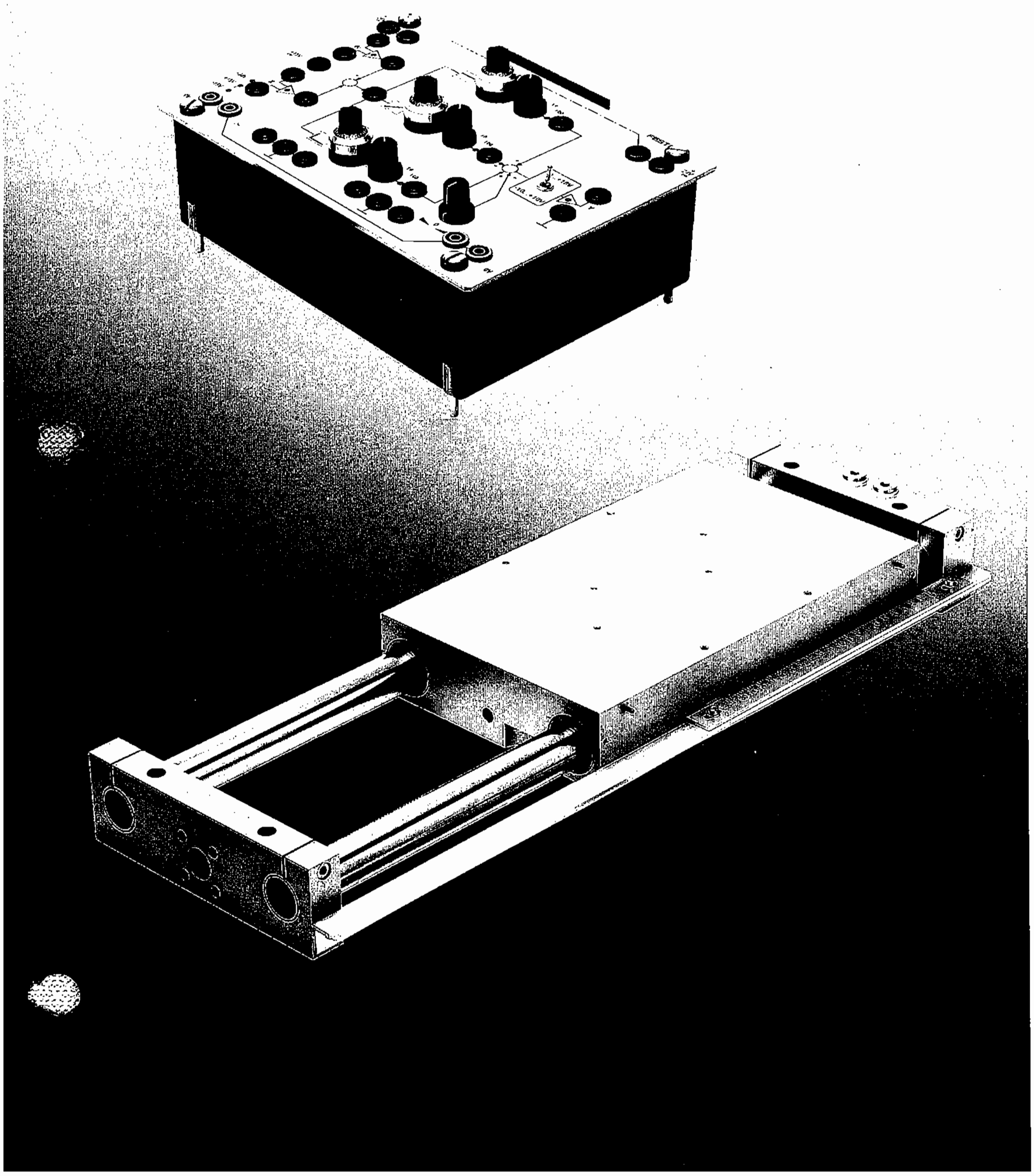
Closed-Loop Hydraulics

FESTO

Workbook TP 511



Festo Didactic
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The Learning System for Automation and Communication has been developed and prepared exclusively for training in the field of automation and communication. The training organisation and / or trainee shall ensure that the safety precautions described in the accompanying Technical documentation are fully observed.

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Preface

Festo Didactic's Learning System for Automation and Communications is designed to meet a number of different training and vocational requirements. The Training Packages are structured accordingly:

- Basic Packages provide fundamental knowledge which is not limited to a specific technology.
- Technology Packages deal with the important areas of open-loop and closed-loop control technology.
- Function Packages explain the basic functions of automation systems.
- Application Packages provide basic and further training closely oriented to everyday industrial practice.

Technology Packages deal with the technologies of pneumatics, electropneumatics, programmable logic controllers, hydraulics, electrohydraulics, proportional hydraulics closed loop pneumatics and hydraulics.

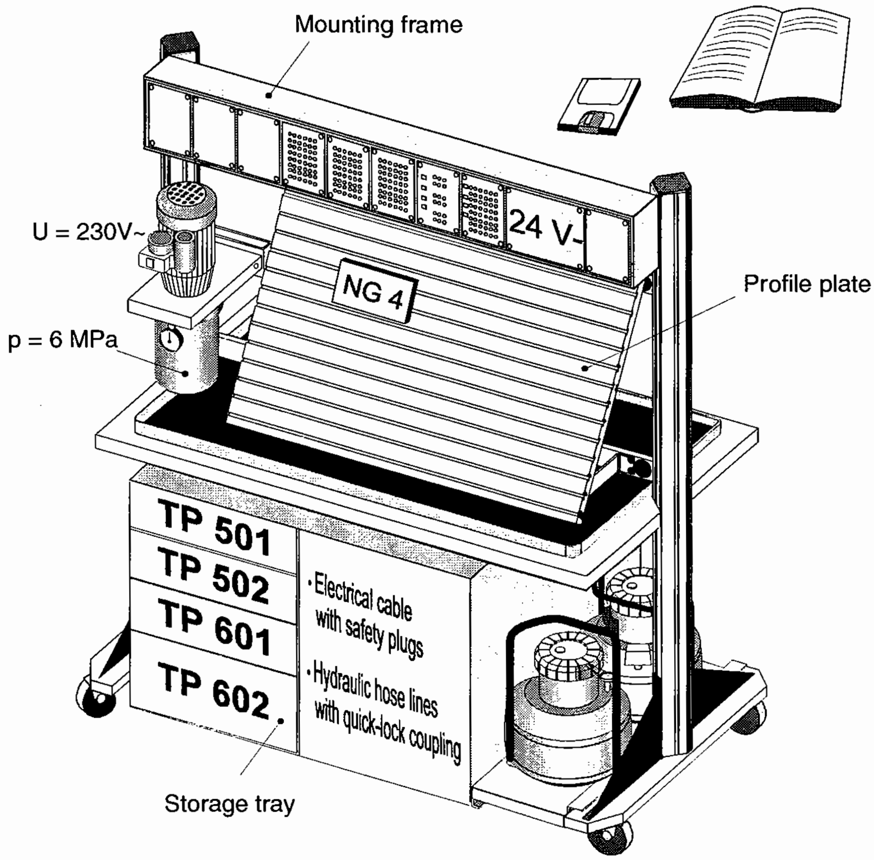

Fig. 1: Example of Hydraulics 2000: Mobile laboratory trolley

The modular structure of the Learning System permits applications to be assembled which go beyond the scope of the individual packages. It is possible, for example, to use PLCs to control pneumatic, hydraulic and electrical actuators.

All training packages have an identical structure:

- Hardware
- Courseware
- Software
- Courses

The hardware consists of industrial components and installations, adapted for didactic purposes.

The courseware is matched methodologically and didactically to the training hardware. The courseware comprises:

- Textbooks (with exercises and examples)
- Workbooks (with practical exercises, explanatory notes, solutions and data sheets)
- OHP transparencies, electronic transparencies for PCs and videos (to bring teaching to life)

Teaching and learning media are available in several languages. They have been designed for use in classroom teaching but can also be used for self-study purposes.

In the software field, CAD programs, computer-based training programs and programming software for programmable logic controllers are available.

Festo Didactic's range of products for basic and further training is completed by a comprehensive selection of courses matched to the contents of the technology packages.

Latest information about the technology package
Closed loop hydraulics TP511.

New in Hydraulic 2000:

- Industrial components on the profile plate.
- Exercises with exercise sheets and solutions, leading questions.
- Fostering of key qualifications:
  Technical competence, personal competence and social competence form professional competence.
- Training of team skills, willingness to co-operate, willingness to learn, independence and organisational skills.

Aim – **Professional competence**

Content

Part A	Course	Exercises
Part B	Fundamentals	Reference to the text book
Part C	Solutions	Function diagrams, circuits, descriptions of solutions and equipment lists
Part D	Appendix	Storage tray, mounting technology and datasheets

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Section A – Course

1. Pressure control loop

2. Position control loop

Section B – Fundamentals

Section C – Solutions

Section D – Appendix

Technology package TP511 "Closed loop hydraulics"

The technology package TP511 "Closed loop hydraulics" forms part of Festo Didactic's Learning System for Automation and Communications.

The training aims of TP511 are concerned with learning the fundamentals of analogue control technology. With electrical control and closed loop elements, hydraulic actuators are activated. A basic knowledge of electrohydraulics and electrical measuring technology is therefore recommended to work with this technology package.

The exercises in TP511 cover the following main topics:

- Pressure control with PID controller (exercise 1 – 11)
- Position control with PID controller (exercise 12 – 18)
- Position control with status controller (exercise 19 – 21)

The fundamentals dealt with in TP511 concern:

- A classification of hydraulic controlled systems
- A description of different controller structures
- Notes regarding the technical implementation of controllers, valves and sensors
- Tips on the assembly and commissioning of hydraulic closed control loops

The components of the equipment set to be used for the individual exercises are listed in the component/exercise table overleaf.

Safety recommendations

The following safety advice should be observed in the interest of your own safety:

- Caution! Cylinders may advance as soon as the hydraulic power pack is switched on!
- Do not exceed the permitted working pressure (see data sheets).
- Use only extra-low voltages of up to 24 V.
- Observe general safety regulations (DIN58126 and VDE100).

Notes on procedure

Construction

The following steps are to be observed when constructing a control circuit.

1. The hydraulic power pack and the electrical power supply unit must be switched off during the construction of the circuit.

2. All components must be securely attached to the slotted profile plate i.e. safely latched and securely mounted.

3. Please check that all return lines are connected and all hoses securely connected.

4. Make sure that all cable connections have been established and that all plugs are securely plugged in.

5. First, switch on the electrical power supply unit and then the hydraulic power pack.

6. Make sure that the hydraulic components are pressure relieved prior to dismantling the circuit, since:

   Couplings must be connected unpressurised!

7. First, switch off the hydraulic power pack and then the electrical power supply unit.

Standard method of representation used in circuit diagrams

The hydraulic circuit diagrams are based on the following rules:

- Clear representation avoiding crossovers as far as possible
- Symbols conforming to DIN/ISO 1219 Part 1
- Circuit diagrams with several loads are divided into control chains
- Identification of components in accordance with DIN/ISO 1219 Part 2:
  - Each control chain is assigned an ordinal number 1xx, 2xx, etc.
  - The hydraulic power pack is control chain 0xx.
  - Identification of components by letters:

    A – Power component

    B – Electrical sensors

    P – Pump

    S – Signal generator

    V – Valve

    Z – Other component

  - The complete code for a component consists of
    - a digit for the control chain,
    - a letter for the component,
    - a digit for the consecutive numbering of components in accordance with the direction of flow in the control chain.

Example: 1V2 = Second valve in control chain 1.

Technical notes

The following notes are to be observed in order to ensure trouble-free operation.

- An adjustable pressure relief valve has been integrated in the hydraulic power pack Pt. No. 152962. For reasons of safety, the system pressure has been limited to approx. 6 MPa (60 bar).
- The maximum permissible pressure for all hydraulic components is 12 MPa (120 bar).

The working pressure is to be at a maximum of 6 MPa (60 bar).

- In the case of double-acting cylinders, an increase in pressure may occur according to the area ratio as a result of pressure transference. With an area ratio of 1:1.7 and an operating pressure of 6 MPa (60 bar) this may be in excess of 10 MPa (100 bar)!

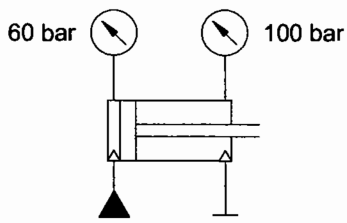


Fig. 2:
Pressure transference

- If the connections are released under pressure, pressure is locked into the valve or device via the non-return valve in the coupling (see Fig. 3). This pressure can be reduced by means of pressure relieving device Pt. No. 152971. Exception: This is not possible in the case of hoses and non-return valves.
- All valves, equipment and hoses have self-sealing couplings. These prevent inadvertent oil spillage. For the sake of simplicity, these couplings have not been represented in the circuit diagrams.

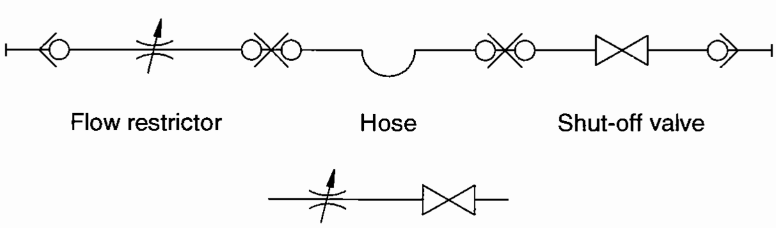


Fig. 3:
Symbolic representation of sealing couplings

Component/exercise table

Description	Exercises 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Power pack (2 l)	1	1	1			1			1	1	1	1									1
Power pack (2 x 4 l)													1	1	1	1	1	1		1	1
Pressure filter	1	1	1			1			1	1	1	1	1	1	1	1	1	1		1	1
Braking cylinder																					1
Linear unit												1		1	1	1	1	1		1	1
Loading weight (5 kg)																	2			2	
Pressure relief valve	1										1		1					1			1
Flow control valve											1							1			1
Shut-off valve																					1
4/3-way regulating valve		1	1			1			1	1	1	1	1	1	1	1	1	1		1	1
Hydraulic motor													1	1							
Flow meter													1	1							
Pressure gauge	1										1			1				1			1
Pressure sensor	1	1	1			1			1	1	1	1		2	2			1			1
Hose, 600 mm	1		2								6	2	2	3	2	2	2	6		2	7
Hose, 1000mm		2	2			2			2	2	2	2	2	2	2	2	2			2	4
Hose, 3000mm			1			1			1	1	1					2				2	
T-distributor	1		1									4		1							4
PID controller	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			
Status controller																			1	1	1
Universal display													1	1							
Digital multimeter	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Oscilloscope			1		1	1	1	1	1	1	1			1	1	1	1	1	1	1	1
Function generator		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Cable, BNC/4 mm		1	2	1	2	2	2	2	2	2	2	1	2	3	2	2	2	2	2	2	2
Cable, BNC/BNC			1	1	1	1	1	1	1	1	1				1	1	1	1	1	1	1
T-piece, BNC			1		1	1	1	1	1	1	1				1	1	1	1	1	1	1
Cable set, universal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Power supply unit	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Workbook concept

The workbook is divided into the following sections:

Section A – Course

Section B – Fundamentals

Section C – Solutions

Section D – Appendix

In **Section A, "Course"**, progressive exercises are used to explain the assembly and commissioning of analogue closed control loops.

The necessary technical knowledge required to complete an exercise is provided at the start of each exercise. Non-essential details are avoided. More detailed information is given in Section B.

Section C, "Solutions" gives the results of the exercises with a brief explanation.

Section B, "Fundamentals" contains general technical knowledge, which complements the training contents of the exercises in Section A. Theoretical relationships are illustrated and the necessary specialist terminology is explained in a clearly understandable way by means of examples.

Section D, "Appendix" is intended as a means of reference. It contains data sheets, a list of literature and an index.

The layout of the book has been structured to allow the use of its contents both for practical training, e.g. in classroom courses, and for self-study purposes.

Equipment set TP511

Equipment set TP511 – Closed loop hydraulics, complete, Order No. 184471

Description	Order No.	Quantity
Components for hydraulics general	091070	1
Components for pressure control	184472	1
Components for position control	184473	1

Components – Hydraulics general Order No.091070

Description	Order No.	Quantity
Pressure filter	152969	1
Pressure relief valve	152848	1
Flow control valve	152842	1
Hydraulic motor	152858	1
Pressure gauge	152841	1
T-distributor	152847	4

Components for pressure control, Order No. 184472

Description	Order No.	Quantity
4/3-way regulating valve	167088	1
PID controller	162254	1

Components for position control, Order No. 184473

Description	Order No.	Quantity
Linear unit	167089	1
Loading weight (5kg)	034065	2
Status controller	162253	1

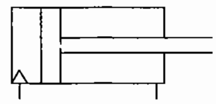
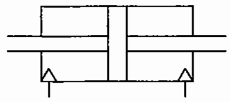
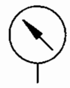
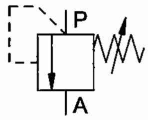
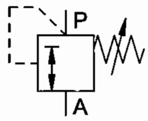
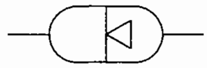
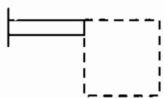
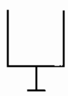
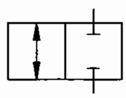
Additional components for exercise 21

Description	Order No.	Quantity
Braking cylinder	152295	1

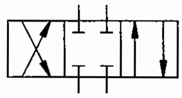
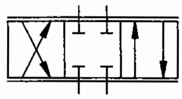
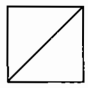
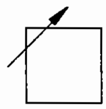
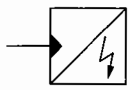
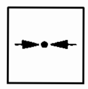
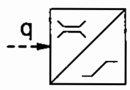
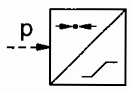
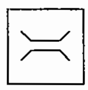
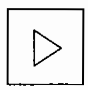
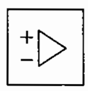
List of additional devices

Description	*Order No.*	*Quantity*
Power pack (1 x 4 l)	152962	1
Power pack (2 x 4 l)	186085	1
Workbook, DE	094460	1
Workbook, GB	094469	1
Digital multimeter	035681	1
Pressure sensor (included in measuring set)	184133	2
Flow meter (included in measuring set)	183736	1
Function generator	152918	1
Cable, BNC/4mm	152919	3
Cable, BNC/BNC	158357	1
Cable set with safety plugs	167091	1
Measuring set	177468	1
Power supply unit (for mounting frame)	159396	1
Table top power supply unit	162417	1
Oscilloscope	152917	1
Profile plate, 550 x 700 mm	159409	1
Hose, 600 mm	152960	7
Hose, 1000 mm	152970	4
Hose, 3000 mm	158352	2
T-piece, BNC	159298	1
Universal display (included in measuring set)	183737	1

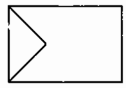
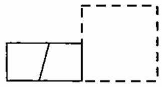
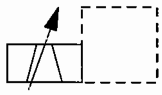
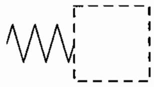
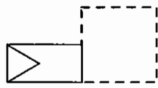
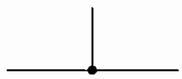
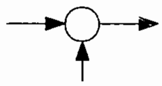
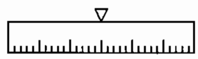
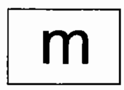
Symbols for the equipment set TP511

Designation	*Explanation*	*Symbol*
Double-acting cylinder	single-ended piston rod	
Double-acting cylinder	double-ended piston rod	
Pressure gauge		
Flow control valve	adjustable	
Pressure relief valve	adjustable	
Pressure regulating valve	adjustable	
Shut-off valve		
Reservoir	Connection at both sides	
Energy source	hydraulic	
Manual operation	general	
Plugged port		
2/2-way valve	Normally closed	

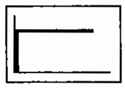
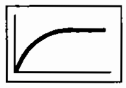
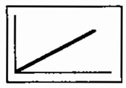
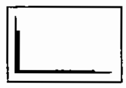
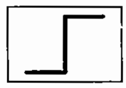
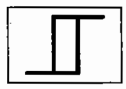
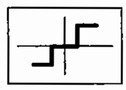
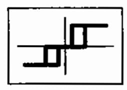
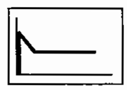
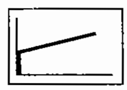
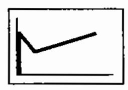
Symbols for the equipment set TP511

Designation	*Explanation*	*Symbol*
4/3- way valve	mid position closed	
4/3- way dynamic valve	mid position closed	
Converter	general	
Adjuster	general	
Sensor	hydraulic / electrical	
Pressure gauge	general	
Flow sensor	electrical	
Limiter	electrical	
Pressure sensor	electrical	
Flow meter	general	
Amplifier	general	
Operational amplifier	general	

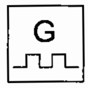
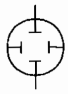
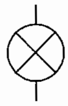
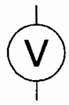
Symbols for the equipment set TP511

Designation	*Explanation*	*Symbol*
Regulator	general	
Electrical actuation	solenoid with one winding	
Electrical actuation	solenoid with two opposed winding, infinitely adjustable	
Manual actuation	by means of spring	
Pilot actuated	indirect by application of pressure	
Switch	detent function	
Working line	line for energy transmission	
Line connection	fixed connection	
Link	collecting or summation point	
Electrical line	line for electrical power transmission	
Linear scale		
Mass		

Symbols for the equipment set TP511

Designation	*Explanation*	*Symbol*
Transmission element	proportional time response	
Transmission element	PT1 time response	
Transmission element	integral time response	
Transmission element	differential time response	
Transmission element	two-step action without hysteresis	
Transmission element	two-step action and hysteresis, different hysteresis	
Transmission element	three-step action	
Transmission element	three-step action with two different hysteresis	
Transmission element	PD time response	
Transmission element	PI time response	
Transmission element	PID time response	

Symbols for the equipment set TP511

Designation	*Explanation*	*Symbol*
Voltage generator	D.C. voltage	
Voltage generator	square-wave voltage	
Voltage generator	sine-wave voltage	
Voltage generator	triangular-wave voltage	
Oscilloscope		
Display	indicator light	
Voltmeter		

Part A – Course

1. Pressure control loop

2. Position control loop

Subject

Closed-loop hydraulics

Title

Pipe-bending machine

Training aim

- To learn about the mode of operation of a pressure sensor
- To be able to record and evaluate a characteristic curve
- To be able to understand the significance of a characteristic curve

Technical knowledge

Sensors

A sensor acquires a physical variable, such as pressure, temperature, flow or speed, and converts this into an electrical or mechanical signal. The form of output signal can be binary, digital or analogue.

- The binary output signal describes two switching statuses, e.g. ON and OFF or 0V and 10V.
- The digital output signal corresponds to a number created by the addition of several pulses of identical size, e.g. increments of a scale or bits.
- The analogue output signal is produced in a continuous curve. Theoretically, it can assume any interim value. For instance, the pointer deflection of a pressure gauge or a voltmeter.

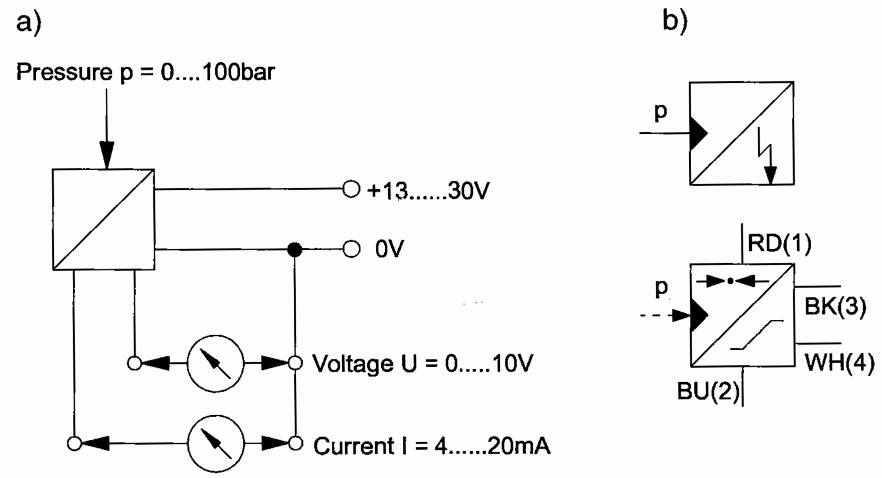
Sensors are also occasionally referred to as signal converters or, in conjunction with closed-control loops as measuring systems and measuring transducers.

Analogue pressure sensor

The sensor used in this case converts the measured variable "pressure" into an analogue, electrical signal. The characteristics of the sensor are:

Supply voltage	*Input variable*	*Output variable*
13V to 30V	0bar to 100bar	0V to 10V or 4mA to 20mA

Fig. A1.1:
Circuit and block diagram of analogue pressure sensor



Characteristic curve

The relationship between the input and output variable of a sensor is described by means of a characteristic curve. The following characteristic data can be read (see also fig. A1.2):

- *Input range or measuring range* between the smallest and largest input value which can be recorded.
- *Output range* between the smallest and largest possible output signal.
- In the *linear range* the characteristic proceeds in the form of a straight line with a constant gradient producing a unique correspondence between the change of the input signal and the change of the output signal. Sensors are particularly suitable for measuring input variables in this range.
- *Transfer coefficient* (frequently referred to as gain) is proportional to the gradient of the characteristic curve in the linear range. It is calculated accordingly from the change of the output signal in relation to the change of the input signal:

$$\text{Transfer coeffizient } K = \frac{\Delta \text{ Output signal}}{\Delta \text{ Input signal}}$$

- *Hysteresis* describes the difference between characteristic curves recorded with rising and falling measured variables, which should be as small as possible. The maximum difference as a percentage in relation to the input range represents the operative characteristics:

$$\text{Hysteresis } H = \left(\frac{\text{max. difference}}{\text{Input range}}\right) \cdot 100\%$$

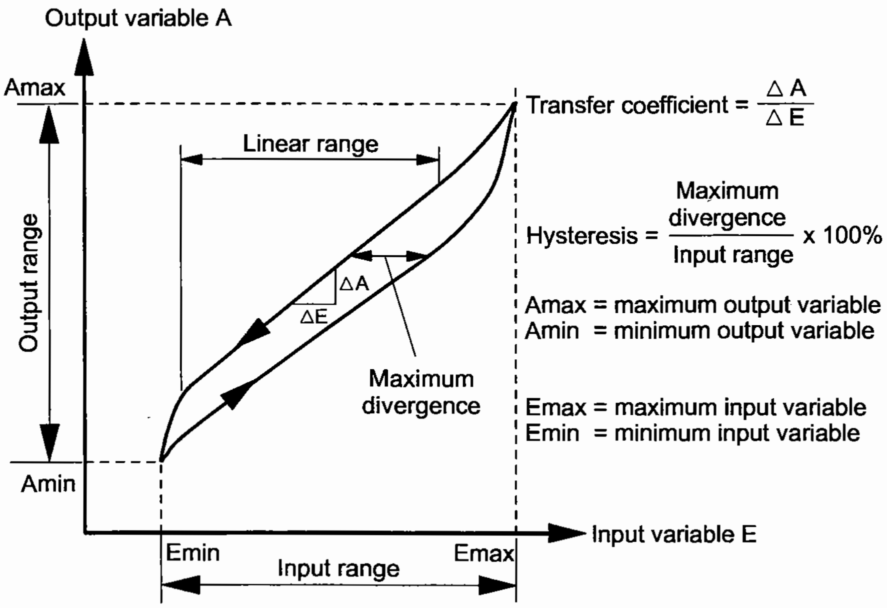
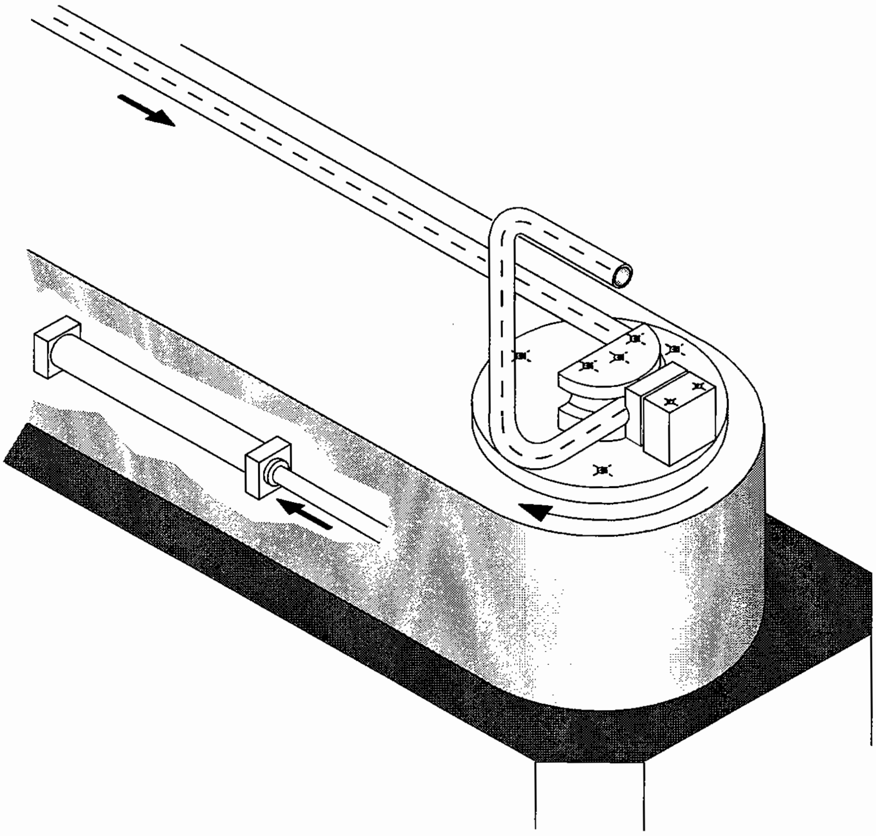


Fig. A1.2: Characteristic curve of a sensor

Problem description

A pipe-bending machine is used to bend pipes of varying diameters, wall thickness and material of different dimensions. The required bending force is produced by a hydraulic cylinder. The pressure in the hydraulic cylinder is maintained constant by means of a pressure control loop. The measuring system in the pressure control loop is a pressure sensor. The closed control loop is to be reset in the course of maintenance work. First of all, the characteristic values of the measuring system are to be checked. To do so, the characteristic curve of the pressure sensor must be recorded.

Positional sketch



Exercise

Characteristic curve of the pressure sensor

1. Designing and constructing the measuring circuit
2. Recording the characteristic curve of the pressure sensor
3. Deriving the characteristics of the pressure sensor from the measuring results

1. Measuring circuit

Execution

Frequently, a characteristic curve has to be recorded on the spot using the devices available. Hence the input variable of the pressure sensor (= pressure in bar) is measured by means of a pressure gauge and the output variable (= voltage in V) by means of a multimeter. The accuracy of a measuring circuit of this type is generally adequate to check the sensor function. A pressure relief valve is built into the hydraulic circuit to set the different pressures. These are displayed by means of a pressure gauge.

The electrical circuit consists of the voltage supply for the pressure sensor and a voltage measuring device for the output signal of the pressure sensor.

2. Characteristic curve

First, the pressure relief valve is opened completely. The entire oil flow returns de-pressurised from the pump to the tank. The pressure sensor display shows 0V. Pressure is then gradually increased by closing the pressure relief valve. The pressure levels and the pressure sensor readout are entered in a values table. Once the maximum pump pressure has been reached, this series of measurements is repeated with falling pressure.

Note the following when recording the characteristic curve

- *accurate setting of pressure values*
- *rising or falling direction of measurement.*

The characteristic curve of the pressure sensor is represented by plotting

- the input variable (pressure p in bar) on the x-axis and
- the output variable (voltage V in Volts) on the y-axis.

3. Characteristics

The most important characteristics of a pressure sensor are:

- Measuring range
- Connection values
- Transfer coefficient
- Hysteresis.

These values can be taken from the data sheet. It is, however, often necessary to carry out a check by means of a series of measurements.

It is not possible to establish the complete measuring range of the pressure sensor with the items of equipment available. Since the pump supplies less than 100bar, it is not possible to traverse the entire input pressure range. It is nevertheless possible to calculate the transfer coefficient in the linear range, which is the most important one for setting a closed control loop. There is no point in calculating hysteresis, since any possible differences are more likely due to the inaccuracy of the pressure gauge rather than the features of the pressure sensor.

WORKSHEET

Characteristic curve of a pressure sensor

1. Measuring circuit

- Familiarise yourself with the required items of equipment.

  What characteristics describe the pressure sensor?

  Input range: ____________________

  Output range: ____________________

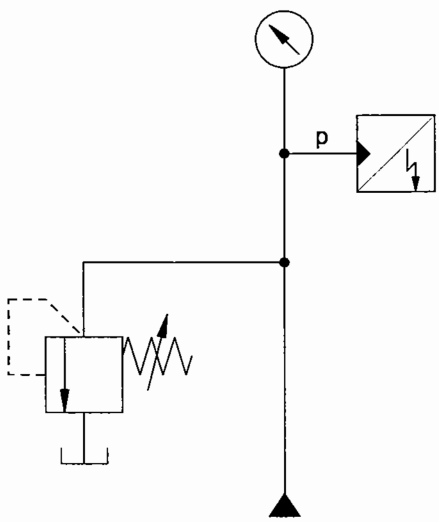
  Supply voltage: ____________________

  Designate the characteristics of the pressure gauge:

  Measuring rang: ____________________

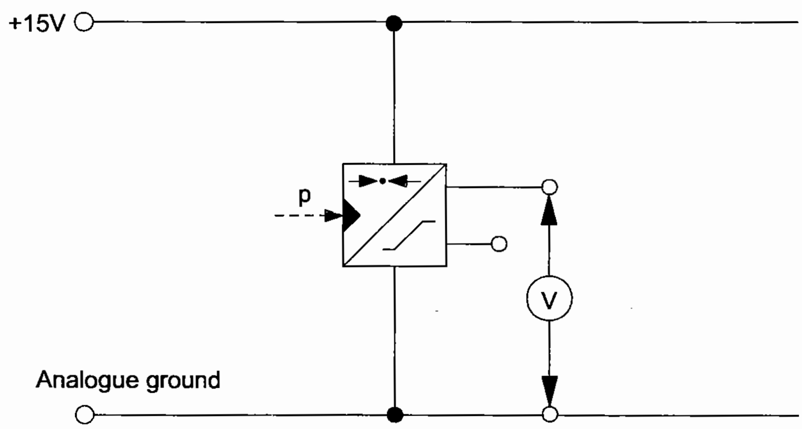
  Measuring accuracy: ____________________

- Construct the measuring circuit, starting with the hydraulic and then the electrical part.



Circuit diagram, hydraulic

Circuit diagram, electrical



2. Characteristic curve

- Open the pressure relief valve completely.
- Switch on the voltage first.
- Then switch on the hydraulic pump.

What output signal does the pressure sensor supply?

____

- Slowly close the pressure relief valve. Traverse the measuring range by way of a test.

WORKSHEET

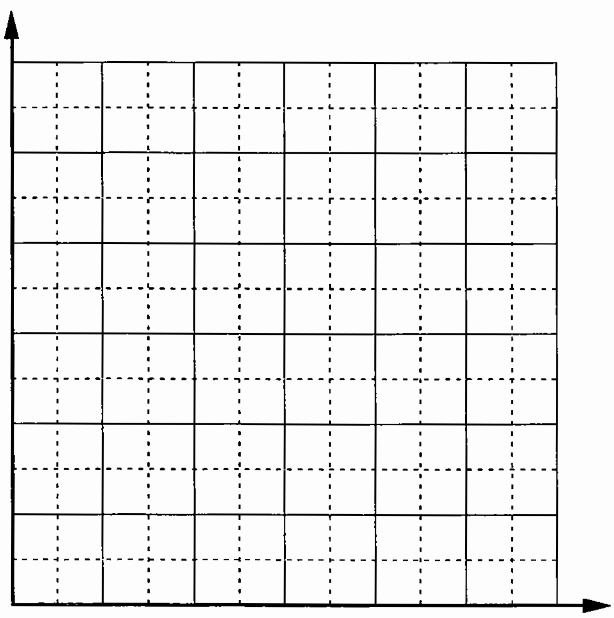
- Record the characteristic curve of the pressure sensor.
  Observe the direction of measurement: rising or falling input variable!

Value table

Measured variable and unit	*Measured values*									*Direction of measurement*
Pressure p in bar	0	10	20	30	40	50	60	70	80	
Voltage V in volts										rising
Voltage V in volts										falling

- Enter the measured values in the diagram. Identify the axes:
  x-axis for input variable
  y-axis for output variable

Diagram



3. Characteristics

- Establish the following characteristics from the diagram:

  Input range: ______________________________

  Output range: ______________________________

  Measuring rang: ______________________________

  Linear range: ______________________________

  Transfer coefficient: ______________________________

  Hysteresis: ______________________________

- How do you evaluate the use of this pressure sensor within the framework of the circuits given with this equipment set?

  State your reasons for this:

____

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Closed-loop hydraulics — *Subject*

Forming plastic products — *Title*

Training aim

- To understand the function of a dynamic directional control valve
- To be able to record the pressure/signal characteristic curve
- To be able to establish important characteristics from the characteristic curve

Technical knowledge

Dynamic 4/3-way valve

A dynamic directional control valve is used to set the pressure control loop used in the following. The most important features of this valve are described below.

Hydraulic connections

A and B: Working lines
P: Pressure supply
T: Return line

Switching positions

Flow from P → A and B → T
Mid-position closed
Flow from P → B and A → T

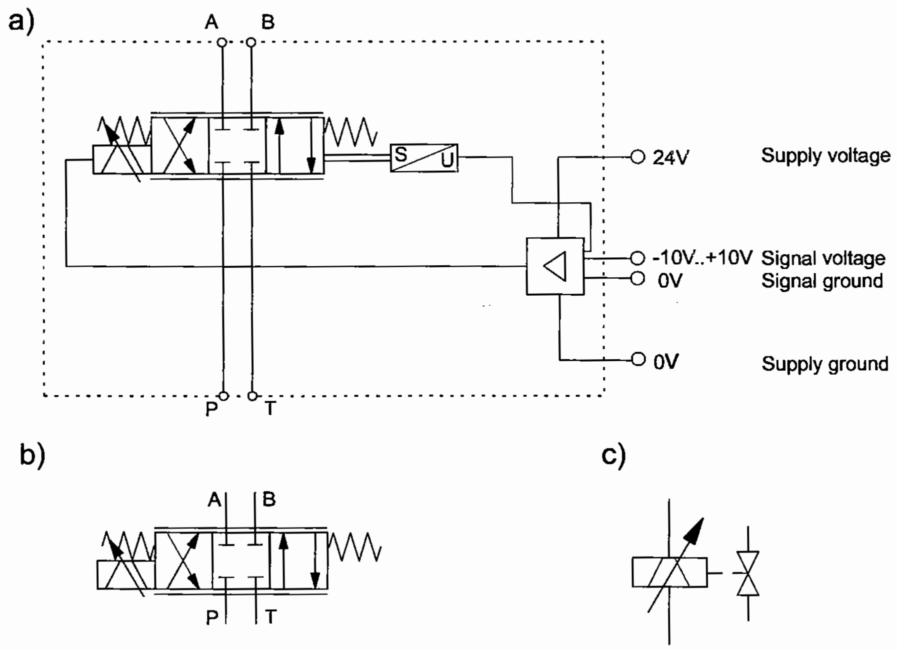
Electrical connections

Voltage supply	*Control voltage (= Input variable)*	*Switching position (= Output variable)*
24V	+10V 0V -10V	P → A and B → T mid-position closed P → B and A → T

Continuously adjustable valve spool

A required intermediate position may be set in addition to the three switching positions; thereby changing the cross sectional opening at the control edges. This simultaneously influences the direction, pressure and flow rate. In this exercise, the control of pressure will be the prime consideration.

Fig. A2.1:
Symbols for dynamic
4/3-way valve



Pressure/signal characteristic curve of a 4/3-way valve

The pressure/signal characteristic curve is created by means of recording

- the control voltage as input signal and
- the pressure at the power port as an output signal.

The working lines are closed during this.

If the valve spool is moved sufficiently in one direction, then one output is opened and the other closed. This results in maximum pressure at the one output and practically nil pressure at the other. Pressure can only build up in the mid-position range on both connections. Thus the pressure/signal characteristic curve is only of significance in the mid-position range.

The pressure/signal characteristic curve consists of two curves, i.e. one each for output A and output B. The following characteristics can be read from this:

Hydraulic zero point

The valve spool covers both outputs equally so that there is zero flow rate. In the diagram, this is the intersection of the two curves.

Electrical zero point

The control voltage is equal to zero. However, the valve spool does not necessarily cover both outputs equally, whereby different pressures may occur at the outputs.

Asymmetry

Asymmetry is the difference between the electrical and hydraulic zero point, which can be compensated by means of an offset added to the control voltage.

Pressure gain

Pressure gain is the ratio of pressure change to voltage change (= output/input). It is specified in bar per volt and should be as large as possible so that even a small change in control voltage results in a large pressure change.

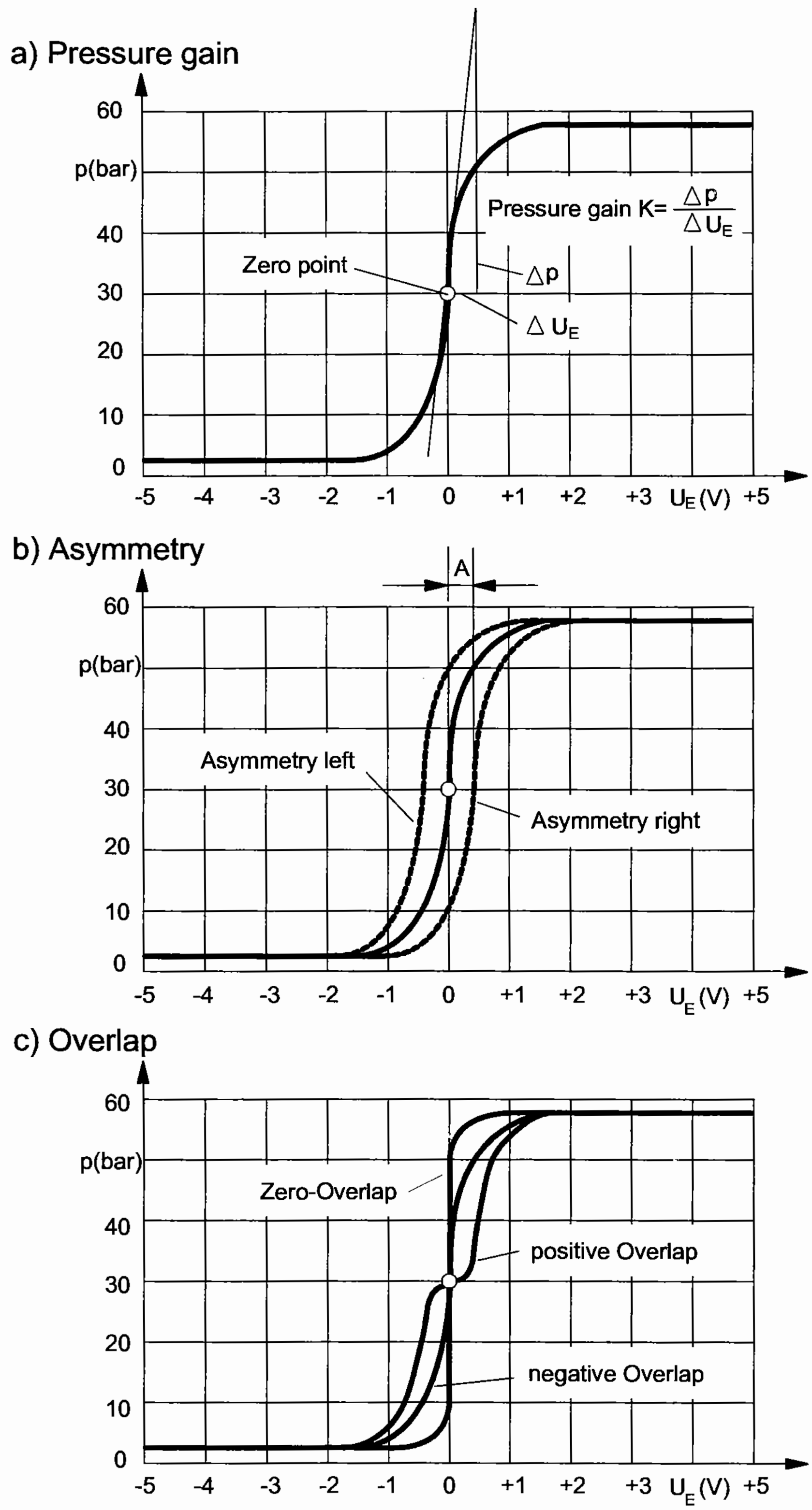
Pressure gain often relates to the signal range of the control voltage and is specified in a percentage stating what percentage of the control signal is required in order to reverse the entire pressure. 10% is required for good valves, but only 1% for excellent valves.

Overlap

This can be seen from the pattern of the characteristic curve at the hydraulic zero point:

- With zero overlap, the characteristic curve is almost vertical.
- Negative overlap produces a continuous steep curve gradient.
- Positive overlap is characterised by a jump: A pressure change is not possible during the closed mid-position. This phenomenon can be compensated electrically by adding the overlap jump automatically to the input signal via the valve pilot.

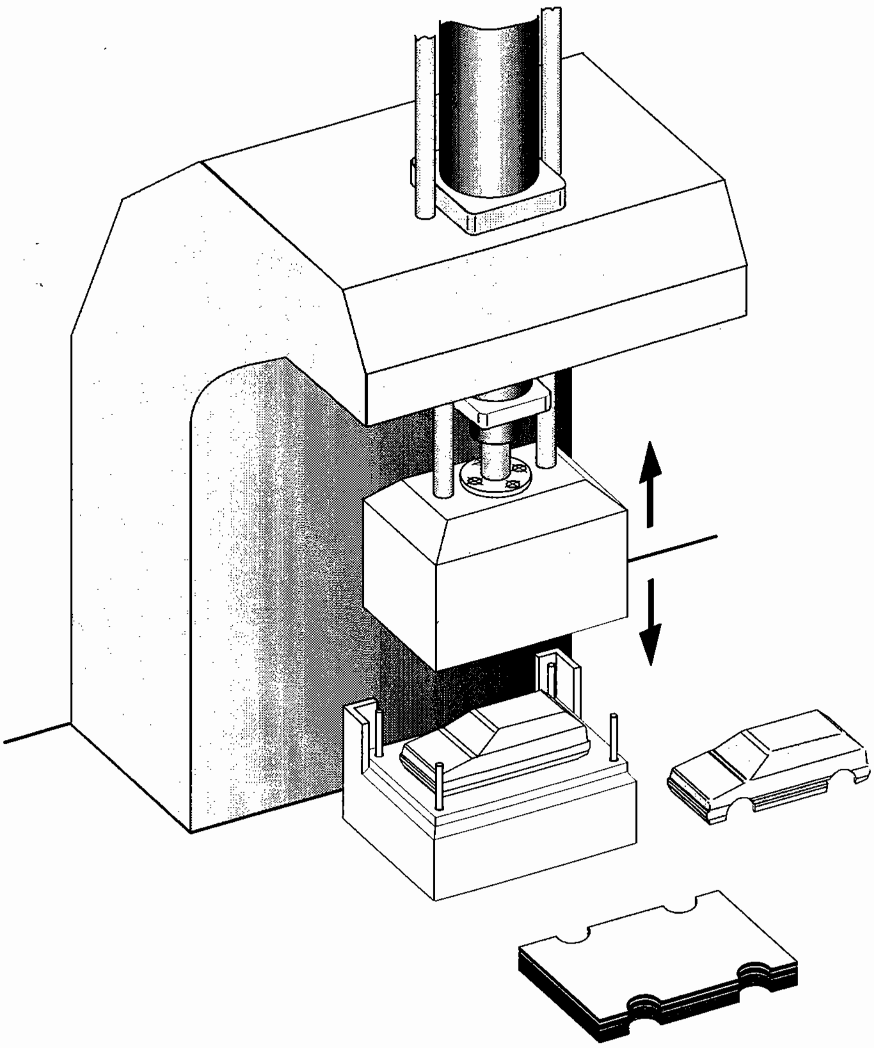
Fig. A2.2: Characteristics of a pressure/signal characteristic curve



Problem description

Plastic plates are to be precisely formed by means of a hot-forming press. The pressure of the press is to be set automatically by means of a pressure control loop. Pressure is to be controlled via a dynamic 4/3-way valve. Some time after start-up, variations occur in the size of the product. One cause may be that the working pressure is no longer constant. This may indicate wear in the directional control valve. The pressure/signal characteristic curve must therefore be recorded and an assessment of the operating status made in comparison with the characteristic curve of a new valve.

Positional sketch



Exercise **Pressure/signal characteristic curve of a dynamic control valve**

1. Constructing a measuring circuit to plot the characteristic curve
2. Plotting and recording the pressure/signal characteristic curve
3. Establishing the characteristics from a characteristic curve

Execution **1. Measuring circuit**

The following are measured for the pressure/signal characteristic curve:

- the control voltage as input signal and
- the pressure at the power port as output signal.

The following devices are required:

- A generator to set the control voltage between - 10V and + 10V.
- A pressure sensor to measure the working pressure.

A second pressure sensor on the other power port facilitates the recording of the characteristic curve.

- A multimeter for the voltage signal of the pressure sensor, from which the pressure is calculated (see exercise 1).
- A voltage supply of 24V for the valve and 15V for the sensor.

These are used to construct the hydraulic and electrical circuits.

2. Pressure/signal characteristic curve

The pressure/signal characteristic curve is only of significance in the proximity of the hydraulic zero point, which is near the mid-position; in this case with a control voltage between - 1V and + 1V.

The valve used here has a very high pressure amplification, i.e. even a small change in control voltage is followed by a measurable change in pressure. This is why as near to a constant a voltage signal as possible is essential.

3. Characteristics

The following characteristics can be seen from the pressure/signal characteristic curve:

- linear range,
- hydraulic zero point,
- electrical zero point,
- asymmetry,
- overlap,
- hysteresis,
- pressure gain.

The hysteresis and pressure gain must be calculated. The hysteresis is described in exercise 1. The pressure gain is proportional to the gradient of the pressure/signal characteristic curve in the linear range. Pressure gain is converted to a percentage share of the signal range according to fig. A2.3 by means of the following steps:

1. Plot the control signal in percentage values in relation to the signal range.
2. Extend the gradient curve of the linear range across the entire pressure range.
3. Draw in the intersections of the gradient curves with maximum and minimum pressure.
4. Read the signal range between the intersections.

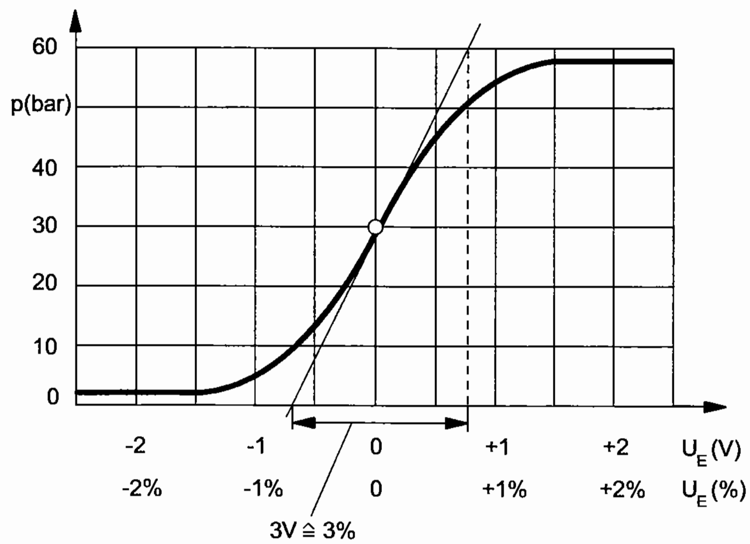


Fig. A2.3: Evaluation of pressure/signal characteristic curve

WORKSHEET

Pressure/signal characteristic curve of a dynamic 4/3-way valve

1. Measuring circuit

- Familiarise yourself with the dynamic 4/3-way valve.

What hydraulic connections does the valve have?

____

Where on the valve body are these connections?

____

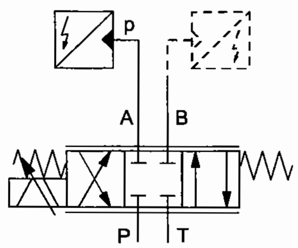
____

What electrical connections does the valve have?

____

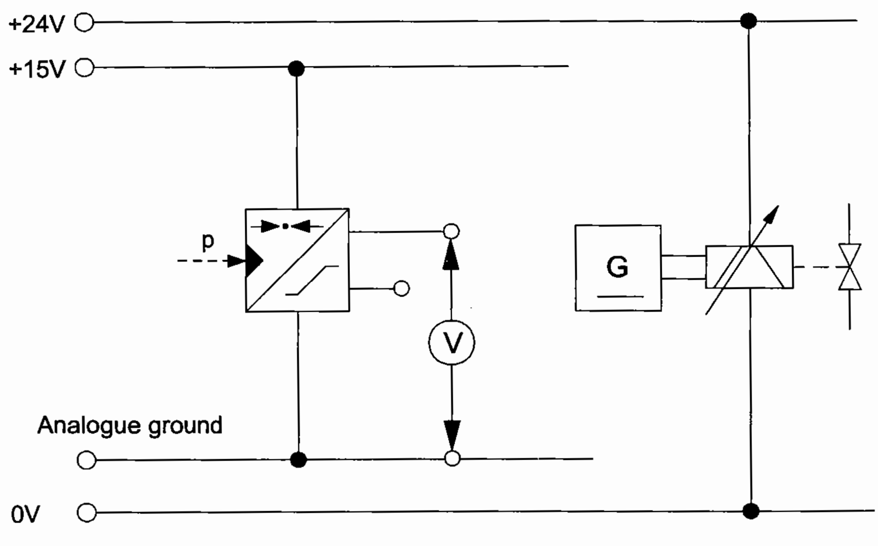
____

- Construct the measuring circuit according to the circuit diagrams.



Circuit diagram, hydraulic

Circuit diagram, electrical



2. Pressure/signal characteristic curve

- First of all switch on the voltage supply.
- Specify a control voltage of 0V.
- Select a setting range of a maximum of 1.5V and as high a resolution as possible.
- Check the pressure sensor display.

  What values will the sensor display in the course of a series of measurements?

  ____

- Select the appropriate measuring range of multimeter.
- Switch on the hydraulic power pack.

  What is the value set on the pressure sensor?

  ____

  ____

- Alter the control voltage.

  At what control voltage does the pressure no longer change?

  ____

WORKSHEET

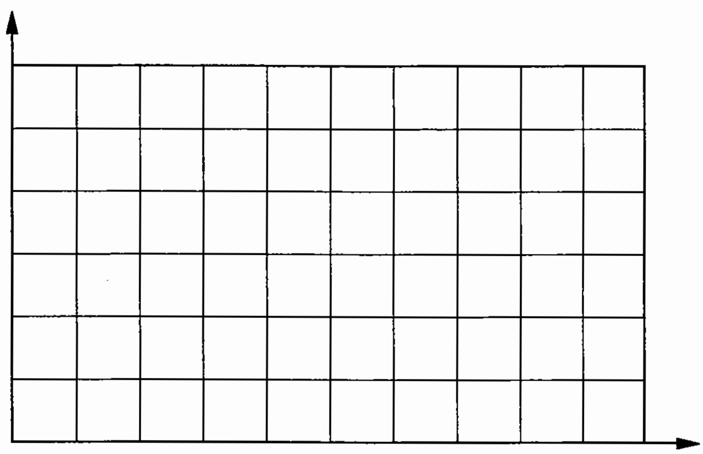
- Record the characteristic curve for both outputs whilst observing the direction of measurement.

Value table

Measured variable and unit	*Measured values*									*Direction of measurement (rising/falling)*
Voltage V_E in V										
Pressure p_A in bar										
Pressure p_A in bar										
Pressure p_B in bar										
Pressure p_B in bar										

- Draw the characteristic curves in the diagram.
- Designate the axes and select suitable scales.

Diagram



3. Characteristics

- Establish the characteristics of the valve from the diagram:

  Linear range: ____________________

  Hydraulic zero point: ____________________ V

  Electrical zero point: ____________________ bar

  Asymmetry: ____________________ V

  Overlap: ____________________

  Hysteresis: ____________________ %

  Pressure gain: ____________________ bar/V

  ____________________ bar/V

  Signal range of pressure gain: ____________________ %

  ____________________ %

- Evaluate the features of this valve with regard to linear range, hysteresis and pressure gain.

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Subject — *Closed-loop hydraulics*

Title — ***Cold extrusion***

Training aim

- To be able to describe the runtime behaviour of a closed control loop
- To be able to create and evaluate transfer functions

Technical knowledge

Controlled system

A closed control loop always consists of the same elements:

- Closed-loop controller,
- Controlled system,
- Measuring system.

Each of these elements can be further subdivided. The controlled system is the point where the controlled variable is physically formed. As far as pressure regulation is concerned, this means that a specific pressure is set as a controlled variable with the actuating signal, in this case a voltage. The controlled system consists of

- a dynamic 4/3-way valve as a final control element and
- a reservoir as a controlled system element.

Runtime performance

When describing the transition behaviour of a controlled system, it is not just the relationship between output and input variables which is of great importance, but also the time characteristics of the output variable following the input variable.
With pressure control, the output variable (= pressure in the reservoir) follows the input variable after a delay. This is known as a “controlled system with delay”.
The pressure in the reservoir does not rise to some random level, i.e. it reaches an limit value. This is characterised by a “controlled system with compensation”. A controlled system without compensation would never reach a limit value. One example of this is the filling of a container: For as long as the supply is maintained, the volume in the container increases. Only when the container overflows or by switching off the supply can a limit value be reached.

The runtime performance of the controlled system is thus described by two characteristics:

1. with or without compensation,
2. with or without time delay.

Transition function

Defined test signals are used as input variables to establish the runtime performance of a controlled system:

- Square signal – produces the step response,
- Triangular signal – produces the ramp response,
- Sine-wave signal – produces a sinusoidal response.

The step response is also known as the transition function..

Fig. A3.1: Forms of signal and their generator symbols

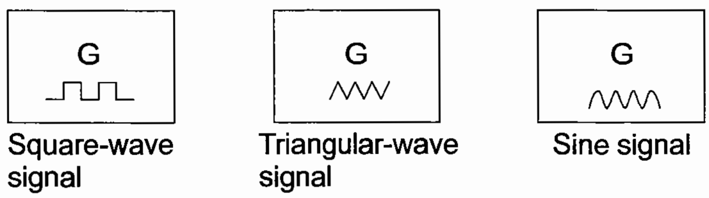
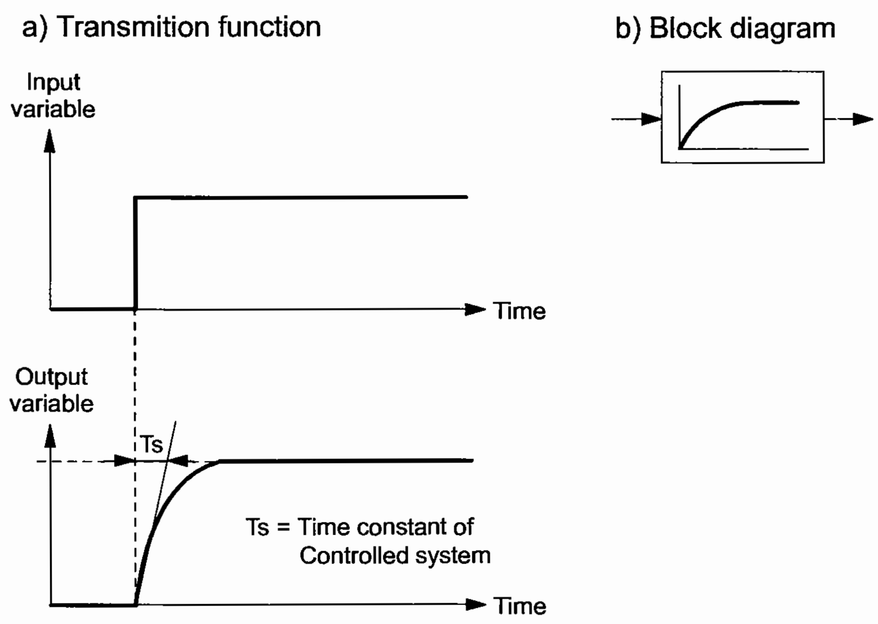


Fig. A3.2 illustrates a typical transition function in a controlled system. The pattern of the transition function enables you to determine the type of controlled system and to establish the time constant:

1. Controlled system type – with compensation and delay,
2. Time constant – T_S

This corresponds to a "controlled system with a high-order delay", i.e. with stored energy.

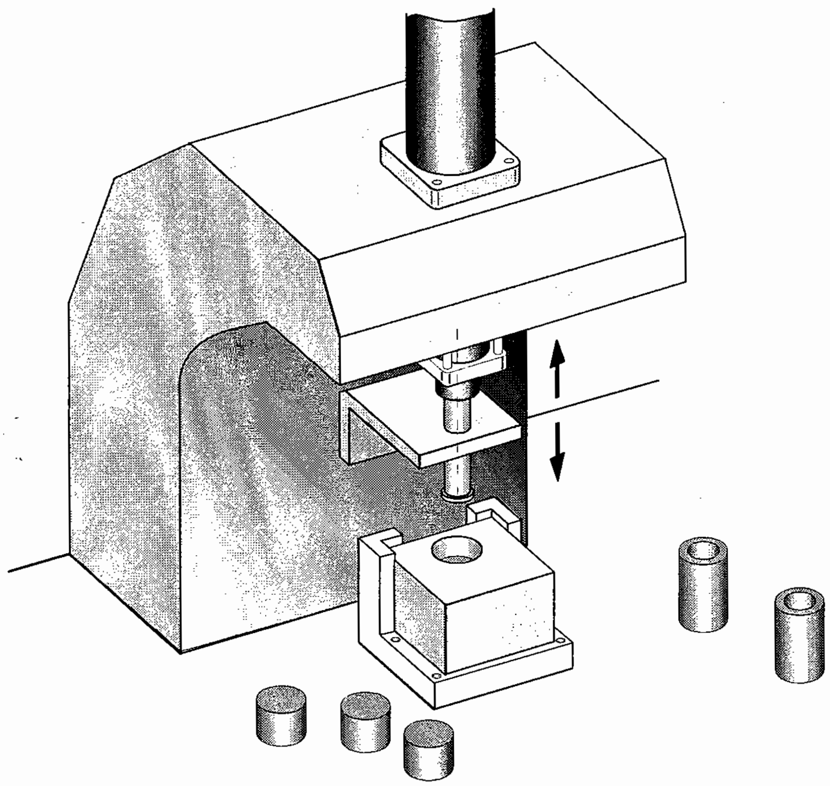
Fig. A3.2: Transition function and block diagram of a controlled system with compensation and delay



Problem description

Blanks are to be reshaped into sleeves by means of cold extrusion, for which a defined press pressure is to be maintained. A hydraulic pressure control loop is to be constructed for this. In preparation, the runtime performance of the controlled system is to be determined.

Positional sketch



Exercise

Transition function of a pressure control loop

1. Constructing a measuring circuit
2. Recording the transition function
3. Describing the controlled system type and determining the time constant

Execution

1. Measuring circuit

The following variables must be measured in order to produce the transition function of a controlled system:

- Correcting variable y as input variable and
- Controlled variable x as output variable.

Both variables are plotted over the time t.

In order to compare different controlled systems, reservoirs of different volumes are installed. Tubing of different lengths is used as reservoirs:

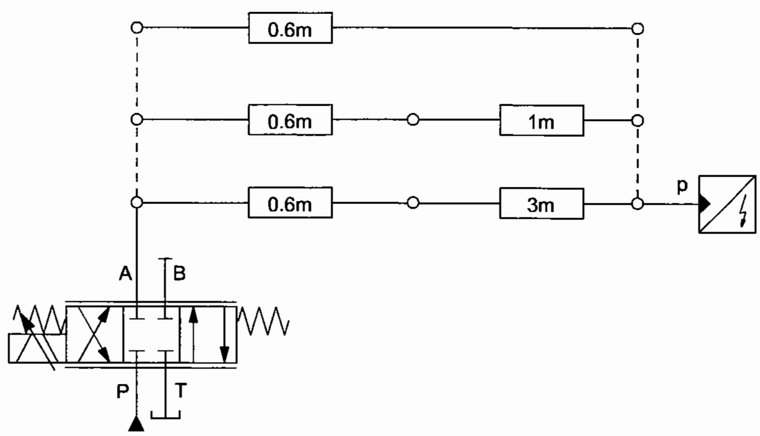
Tubing length L:	0.6m	1.6m	3.6m
Volume V:	0.02l	0.05l	0.1l

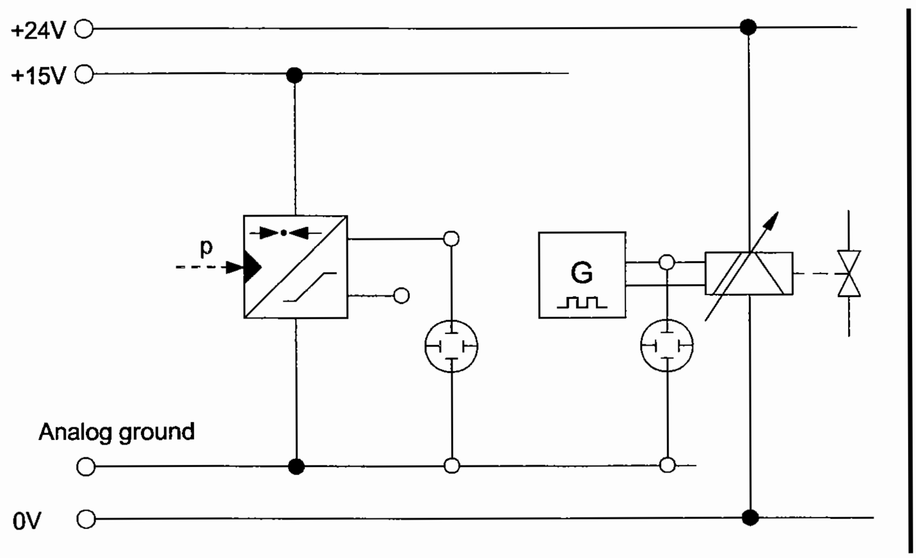
The following devices are required for the measuring circuit:

- a pressure sensor,
- tubing of different lengths,
- a dynamic directional control valve,
- a frequency generator to actuate the directional control valve,
- an oscilloscope to record the transition function,
- voltage supply for valve and sensor.

This results in the following circuit diagrams:

Circuit diagram, hydraulic





Circuit diagram, electrical

2. Transition functions

Since the valve already reverses completely with an actuating signal of $V_E = \pm$ 1V, a setpoint step-change of w = 0V ± 1V is sufficient.

To represent the transition function, correcting variable y and controlled variable x (= pressure) are plotted over the time t. The time scale must be adapted to the reservoir size.

3. Controlled system type and time constant

The pattern of the transition function enables you to establish the controlled system type and to calculate the time constant (see fig. A3.1).

WORKSHEET

Transition function of a pressure controlled system

1. Measuring circuit

- Construct the circuit according to the circuit diagrams. Start with a circuit without reservoir, i.e. attach the pressure sensor directly to the directional control valve initially.

2. Transition function

- Set the following setpoint value:

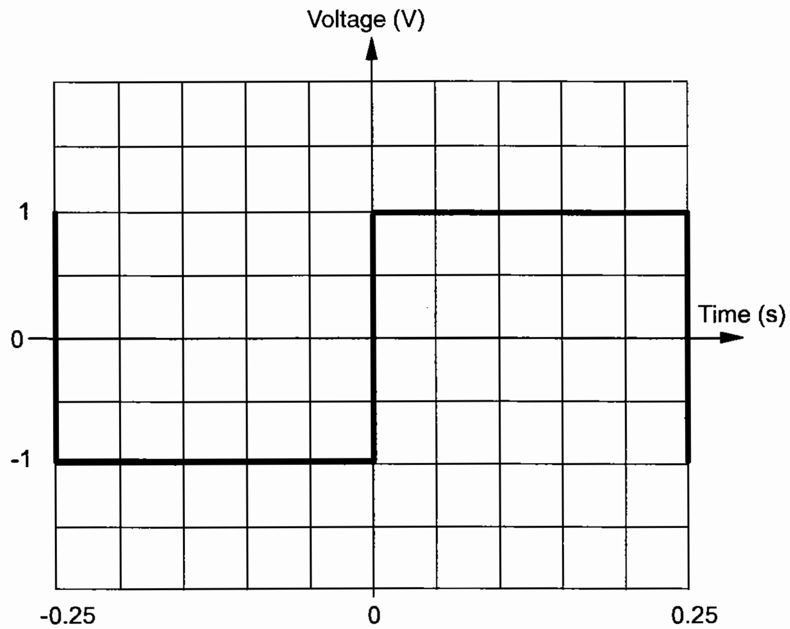
  $w = 0V \pm 1V$, $f = 2Hz$, as square form

- Select the following scale on the oscilloscope:

  Time t: 50 ms/Div.
  Reference variable w: 0.5 V/Div.
  Controlled variable x: 2 V/Div.

- Display a step response on the oscilloscope.
- Plot the transition function on the diagram.
- Insert various tubing lengths as reservoir volumes in the circuit.
- Display a step response for each of these on the oscilloscope.
- Plot the transition functions on the diagram.

Diagram



3. Controlled system type and time constant

■ To what controlled system type do you attribute the controlled system in question?

Compensating: ____

____

Delay: ____

____

■ Establish the time constants T_S of the controlled system and evaluate the change in time constants in relation to the storage reservoir.

Value table

Variable	*Values*				*Tendency*
Tubing length L	0	0.6m	1.6m	3.6m	increasing
Volume V	~ 0	0.02l	0.05l	0.1l	increasing
Time constants T_S					

Closed-loop hydraulics — *Subject*

Thread rolling machine — *Title*

Training aim

- Familiarisation with the configuration of a PID controller
- To be able to check the characteristics of a PID controller card

Technical knowledge

PID controller card

In the case of a PID controller, three closed-loop control elements are connected in parallel:

- one P element with, $y_P = K_P \cdot e$,
- one I element with, $y_I = K_I \cdot \int e \cdot dt$,
- one D element with. $y_D = K_D \cdot \frac{de}{dt}$.

The results of the elements are added together at a summation point:

- $y = y_P + y_I + y_D$

Apart from the closed-loop controller, the following connections are also on the controller card:

- Input variable: Reference variable w, controlled variable x
- Comparator: System deviation e = w - x
- Offset: Control signal $y \pm \Delta U$
- Limiter: Range of control signal y_{min} to y_{max}
- Voltage supply

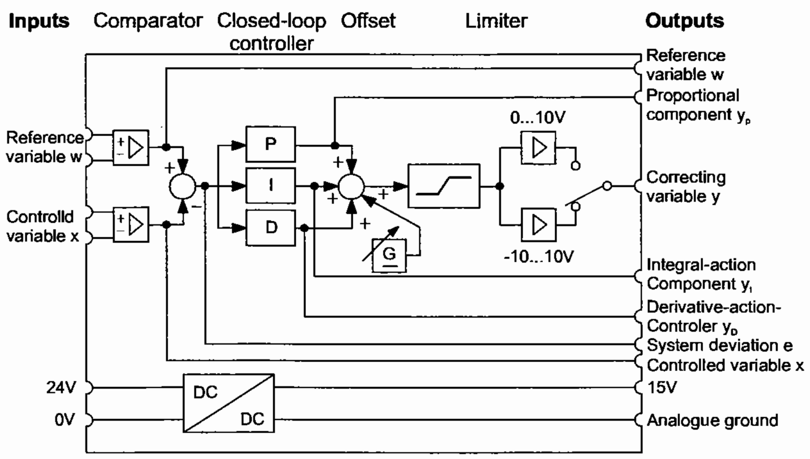


Fig. A4.1:
PID controller card

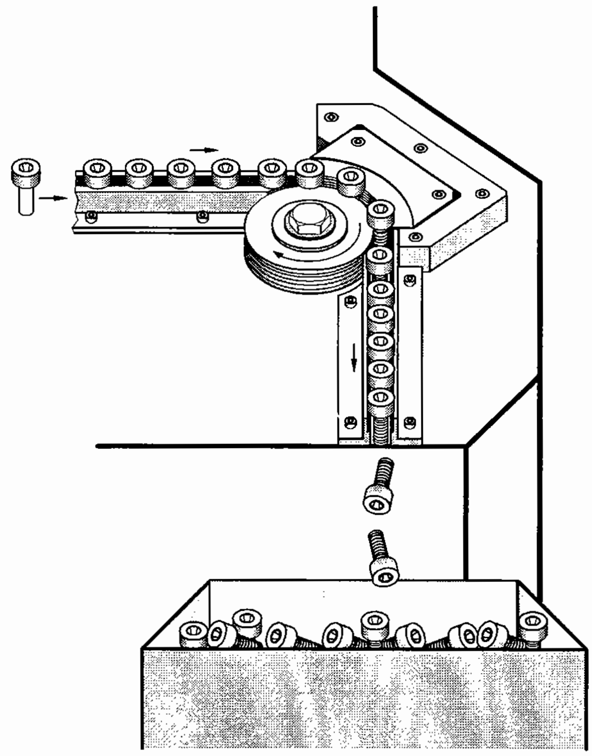
The characteristics of the PID controller card are:

Input variables	Reference variable w	0V - 10V
	Controlled variable x	0V - 10V
Output variable	Correcting variable y	0V - 10V or ± 10V
Other characteristics	Supply voltage	24V
	Voltage connections for sensors	15V or 24V
	Offset	5V ± 3,5V or ± 7V
	Limiter	0V - 10V or ± 10V

Problem description

Screws are to be manufactured on a thread rolling machine. The thread is to be created by means of the impression of a profiled roller. The roller is to turn and press the screw against a guide which is also profiled. The contact pressure of the roller must be maintained at a defined value. This is set via a hydraulic closed control loop. The PID controller used for this is to be checked.

Positional sketch



Exercise

PID controller card

1. Constructing the measuring circuit
2. Establishing the range of the input variables
3. Checking the function of the summation point
4. Setting different output variables

Execution

1. Measuring circuit

The following devices are required to check the function of the controller card:

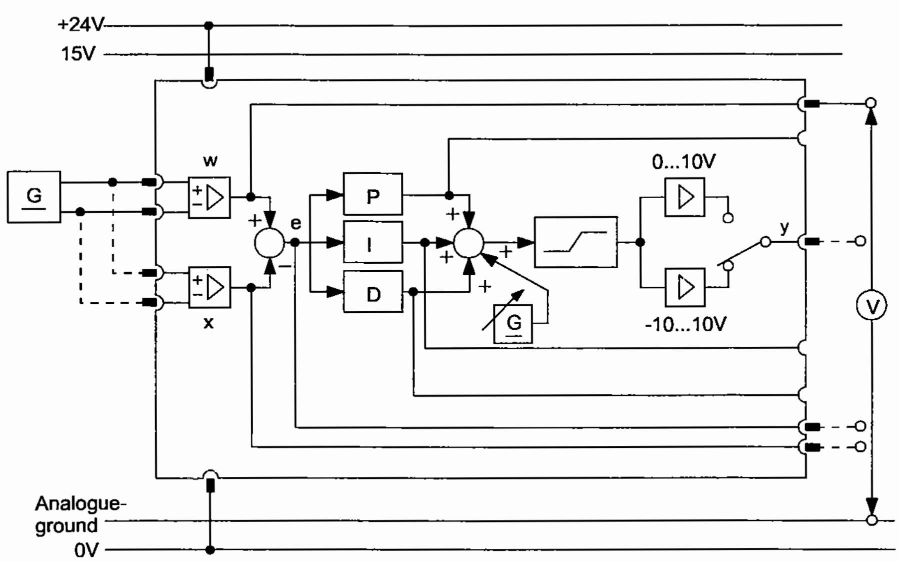
- a voltage supply of 24V for the controller card,
- a generator of input signals of approx. ± 15V,
- a multimeter to measure the output signals.

The controller card is to be brought into the initial position:

- All controller parameters to zero,
- Offset in mid-position,
- Limiter at ± 10V.

This produces the following basic circuit:

Circuit diagram



2. Input variables

Measure the range of the two input variables

- Reference variable w and
- Controlled variable x.

Overload is displayed via an LED.

3. Summation point

Both inputs must be connected to check the summation point:

- Two input variables w and x produce
- the system deviation e = w - x.

4. Output variable

To set the output variable, and the correcting variable y use

- a limiter and
- an offset.

The input variables and controller parameters all are to be set to zero. The output signal is thus y = 0. This signal is shifted and held within a defined signal range by means of the offset.

WORKSHEET

PID controller card

1. Measuring circuit

Familiarise yourself with the PID controller card: How are the following characteristics designated on the card?

Input signals: ______________________________

Summation point: ______________________________

Elements of the controller: ______________________________

Output signal: ______________________________

- Bring the controller to the initial position:
  - All controller potentiometers and selector switches to zero
  - Offset potentiometer to the centre
  - Limiter selector switch to ± 10V
- Construct the basic circuit and connect the voltage supply.

Which LEDs are illuminated? ______________________________

2. Input variables

- Measure the signal range of input variables w and x.
- Compare the result with the characteristics in the data sheet.

Characteristic	*Max. value*	*Min. value*	*Comment*
Reference variable w			
Controlled variable x			

Value table

Always measure analogue signals against analogue load!

3. Summation point

- Check the function of the summation point: $e = w - x$

Value table

Reference variable w	*Controlled variable x*	*Summation point e*	*Comment*
1	0		
1	1		
1	-1		
0	-1		
0	1		
-1	0		

4. Output variable

- Measure the range of the output variable in relation to
  - Offset and
  - Range selection.

Value table

Range	*Max. offset*	*Min. offset*	*Comment*
0V to + 10V			
- 10V to + 10V			

Subject: *Closed-loop hydraulics*

Title: ***Stamping machine***

Training aim

- To learn about the function of a P controller
- To be able to record the characteristic curve and transition function of a P controller
- To be able to derive the characteristics of a P controller

Technical knowledge

Proportional controller (P controller)

The proportional element is an important element of a P controller. It amplifies the input signal e by a specified factor, and transfers the output signal y_P. The amplification factor is described as the proportional action coefficient K_P. The equation of the P element is as follows:

$$y_P = K_P \cdot e$$

The input signal of the P element is the system deviation e, made up of the reference variable w and controlled variable x:

$$e = w - x$$

The output signal y_P is pre-processed as the control signal via the offset and limiter.

The P controller consists of the comparator, P element and limiter (see fig. A5.1). The equation of the P controller is as follows:

$$y = K_P \cdot (w - x)$$

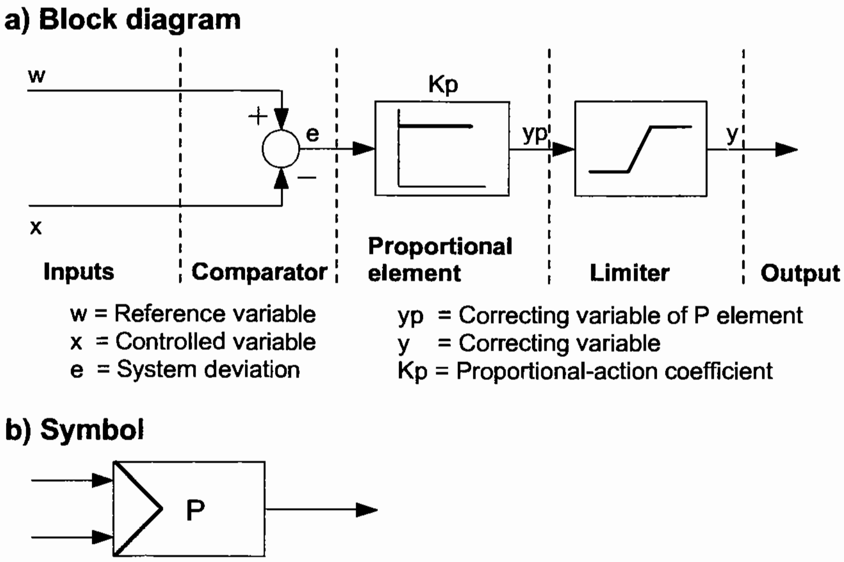


Fig. A5.1: Block diagram and symbol of P controller

Characteristic curve and transition function of a P element

The correlation between input and output variable can be represented in two ways:

1. The *characteristic curve* illustrates the dependence of the output variable on the value of the input variable. The following characteristic generally applies:

$$\text{Transfercoefficient } K = \frac{\Delta \text{ Output}}{\Delta \text{ Input}}$$

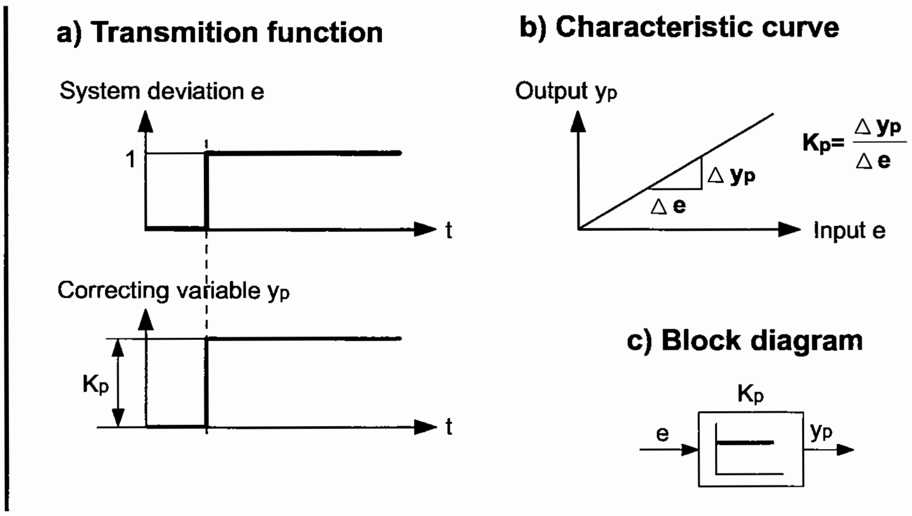
2.1 The *transition function* describes the time characteristic of the output variable in relation to a defined time characteristic of the input variable, whereby a step function is used as an input variable.

2.2 It is also possible to select *a different time characteristic* of the input variable (triangular, sinusoidal). The time characteristic of the output variable changes accordingly.

The following are typical characteristics of a P element:

- The time characteristics of input and output variables are identical.
- The step amplitude (i.e. height) of the output variable is greater by the factor K_P than that of the input variable.

Fig. A5.2: Transition function, characteristic curve and block diagram of P element

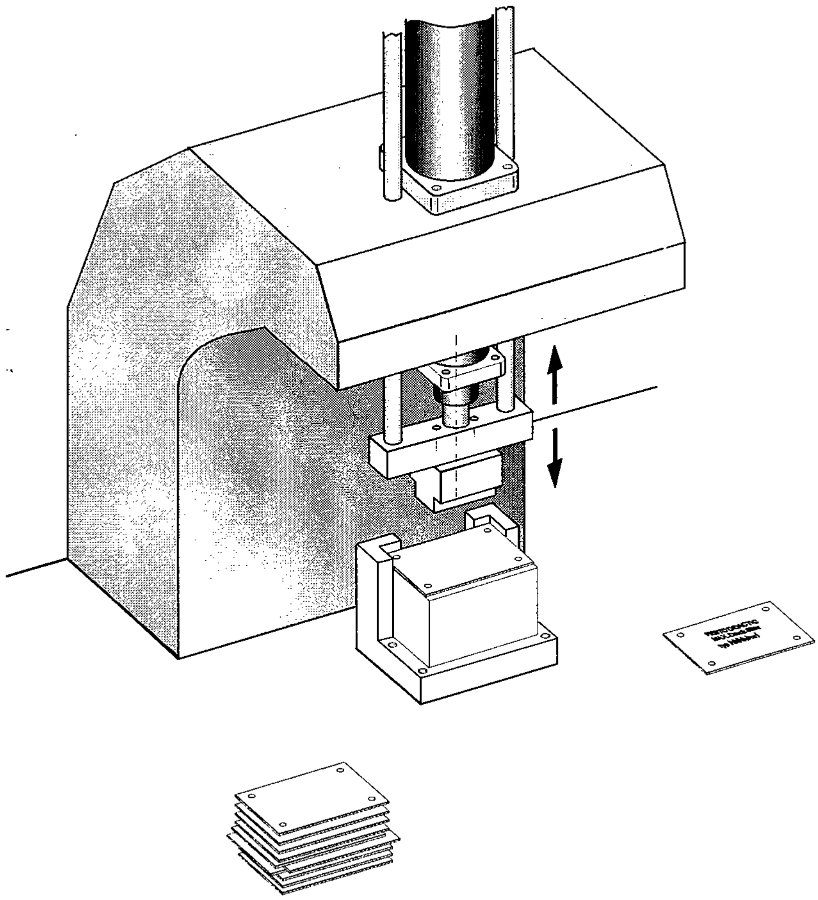


Problem description

The date and serial number are to be stamped on to workpiece identification plates. The stamp is to be moved by means of a hydraulic cylinder. In order to prevent any damage, the force of the stamp is to be set by means of a pressure control loop.

The characteristics of the closed-loop controller are to be established prior to the closed-control loop being constructed.

Positional sketch



Exercise

P controller

1. Constructing and commissioning the measuring circuit
2. Plotting the characteristic curve of the P controller
3. Recording the transition function of the P controller
4. Using other test signals

Execution

1. Measuring circuit

To be measured are

- the reference variable w as input signal of the P controller and
- the correcting variable y as output signal of the P controller.

It is also possible to measure the P element directly:

- the system deviation e as input signal and
- the correcting variable y_P of the P element as output signal.

System deviation e and correcting variable y or y_P are to be measured against analogue measurements!

The following equipment is required:

- the PID controller card with a P controller,
- a generator for test signals from ± 10V as input variable,
- an oscilloscope to record the time characteristics of the output variable,
- a multimeter for the commissioning,
- a power supply unit for the voltage supply of the controller.

The following settings are to be carried out prior to switching on:

- Limiter to ± 10V,
- Offset to centre (= 0),
- Controller coefficient K_P = 1,
- All other controller coefficients to zero.

The setting of controller coefficient K_P results from the value of the potentiometer and the value of the rotary switch.

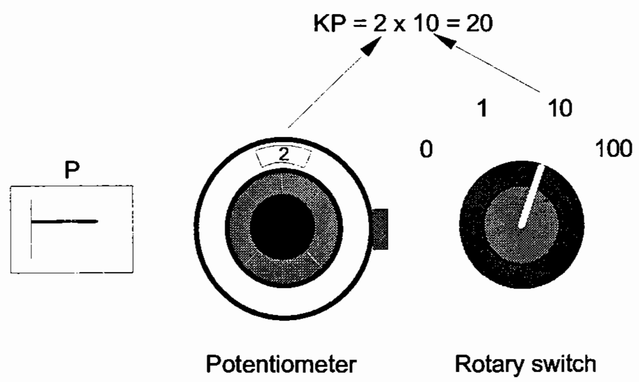
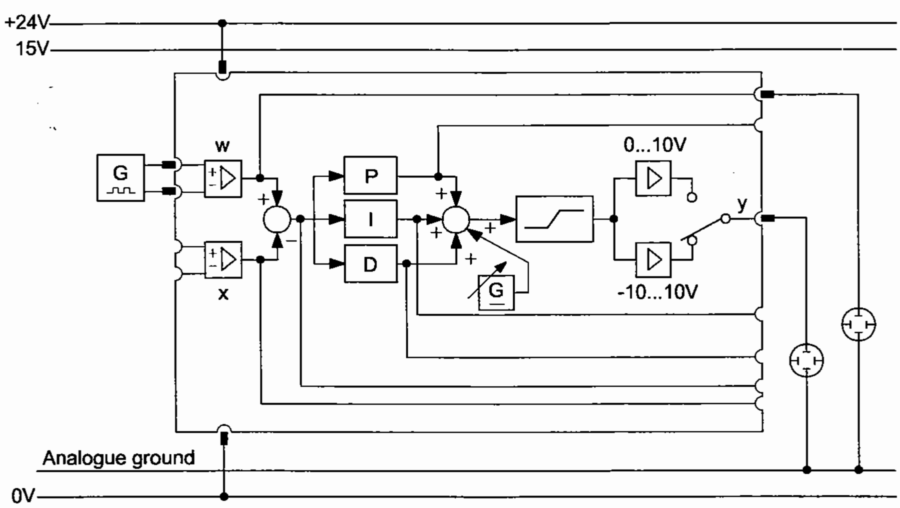


Fig. A5.3: Setting of proportional coefficient K_P

This results in the following circuit diagram:



Circuit diagram, electrical

2. Characteristic curve of a P controller

The characteristic curve plots the output variable y via the reference variable w at a constant controller coefficient K_P. For comparison, a number of characteristic curves are recorded using different controller coefficients.

The controller coefficient K_P corresponds to the transfer coefficient of the P element:

$$K_P = \frac{y}{w} = \frac{y_P}{e}$$

3. Transfer function of P controller

A step-change input signal is specified to record the transfer coefficient. The proportional-action coefficient K_P can be read from the ratio of the step heights:

$$K_P = \frac{\text{Step amplitude output}}{\text{Step amplitude input}}$$

4. Other test signals

Further test signals are the triangular and sinusoidal function, where the controller amplification K_P is shown in relation to the amplitudes from output to input signal:

$$K_P = \frac{\text{Amplitude output}}{\text{Amplitude input}}$$

WORKSHEET

P controller

1. Measuring circuit

- Construct the measuring circuit according to the circuit diagram.
  Carry out the following controller card settings:
  - Limiter to ± 10V,
  - Offset to centre (= 0),
  - Controller coefficient $K_P = 1$,
  - All other controller coefficients to zero.

2. Characteristic curve of P controller

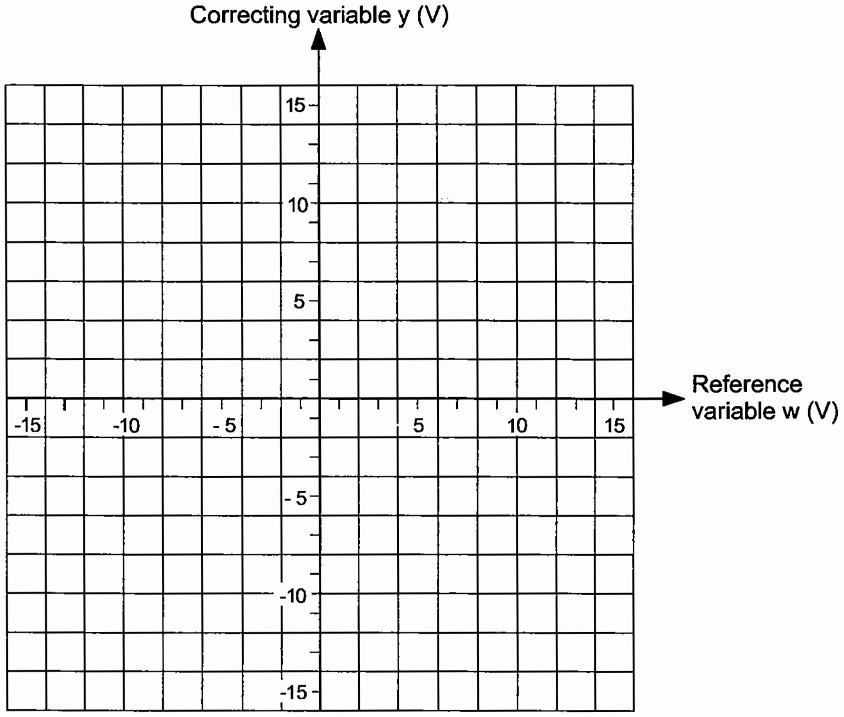
- Specify different reference variables w as input signals.
- Measure the control variable y as output signal of the P controller.
- Carry out a series of measurements using different controller coefficients K_P.

Value table

Input: Reference variable w in V	*Output: Correcting variable y in V with proportional coefficient K_P =*			
	1	*5*	*10*	*0.5*
+10				
+5				
+1				
+0.5				
0				
-0.5				
-1				
-5				
-10				

- Draw the characteristic curves in the diagram.

Diagram



Which feature of the characteristic curve does the amplification factor K_P describe?

___

WORKSHEET

3. Transition function of P controller

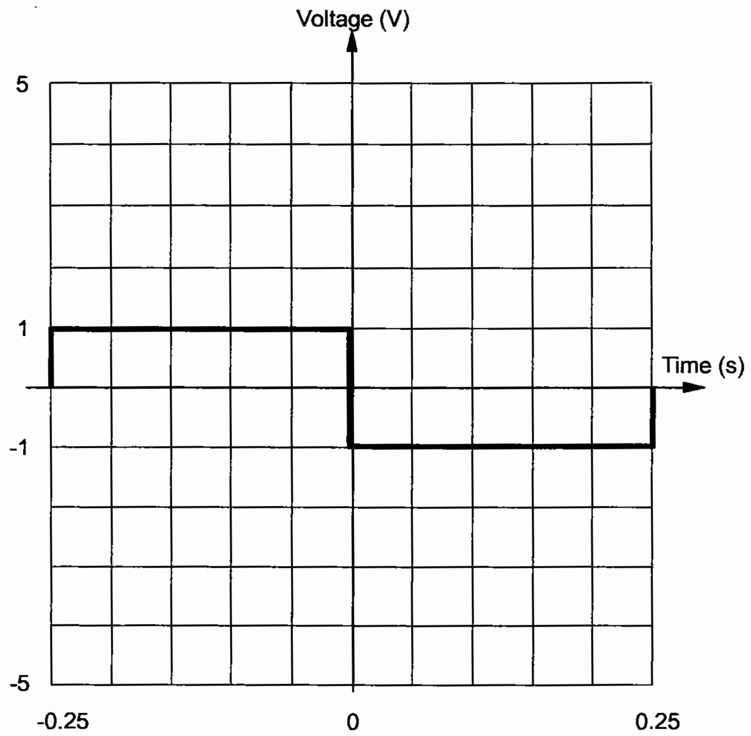
- Specify a step function as input signal:

  $w = 0 \pm 1V$ as square wave form with frequency 2Hz

- Draw the step responses in the diagram for

  $K_P = 1$, $K_P = 2$, $K_P = 5$.

Diagram



What is the equation of the P controller? ____________________

____

Does your measurement agree with the equation? ____________

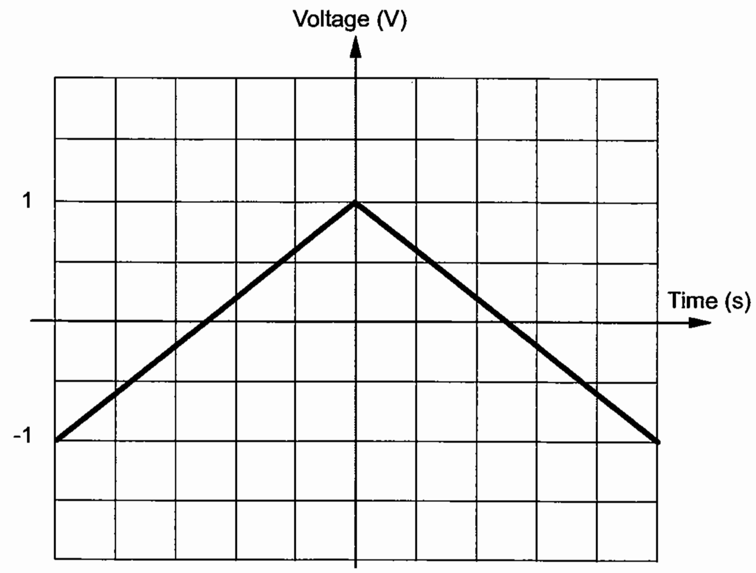
____

4. Other test signals

- Change the input signal to triangular.
- Draw the ramp response of the P controller for

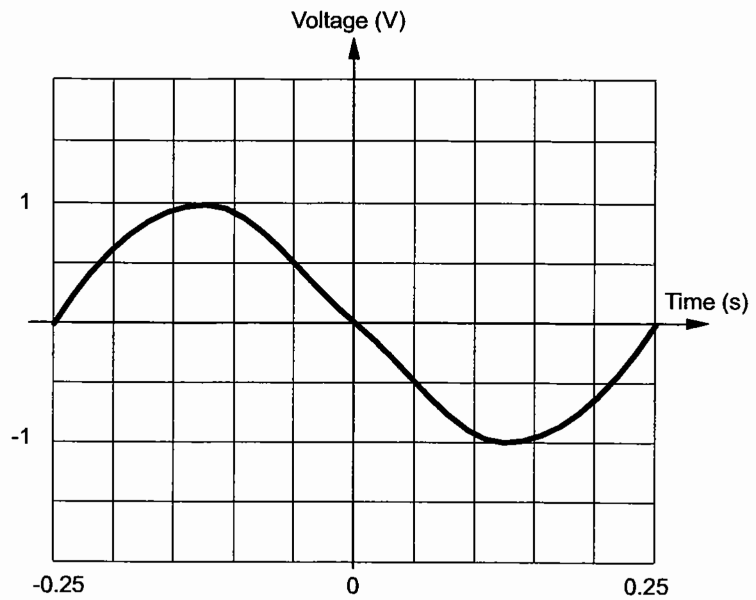
  $K_P = 1$ and $K_P = 2$

Diagram



- What would the pattern of the output signal be with a sinusoidal input signal? Enter the pattern for $K_P = 2$ in the diagram.

Diagram



Subject

Closed-loop hydraulics

Title

Clamping device

Training aim

- To be able to construct a pressure control loop
- To be able to check the control direction
- To be able to set the control quality at optimum level

Technical knowledge

Pressure control loop

The elements in a pressure control loop are:

- the controller — in this case: a P controller,
- the controlled system — in this case: a reservoir,
- the measuring system — in this case: a pressure sensor

Control direction

The above mentioned devices are interconnected in such a way that the following correlation applies:

- increasing reference variable w produces
- an increasing controlled variable x.

Setpoint and actual variable in the closed control loop thus respond in the same direction, i.e. the control direction is correct.

Since the closed control loop is made up of several elements, this results in several interfaces between the elements. The polarity of the signals to be transmitted may be reversed at each interface; this may result in a decreasing controlled variable being generated with an increasing reference variable. The Setpoint and actual variable respond in opposite directions: the control direction is wrong.

When commissioning a closed control loop, the control direction must be correctly set. To do this, the loop is interrupted according to the measuring system and the changes in reference and control variable then compared. If necessary, all interfaces must be re-measured and corrected until the control direction is correct.

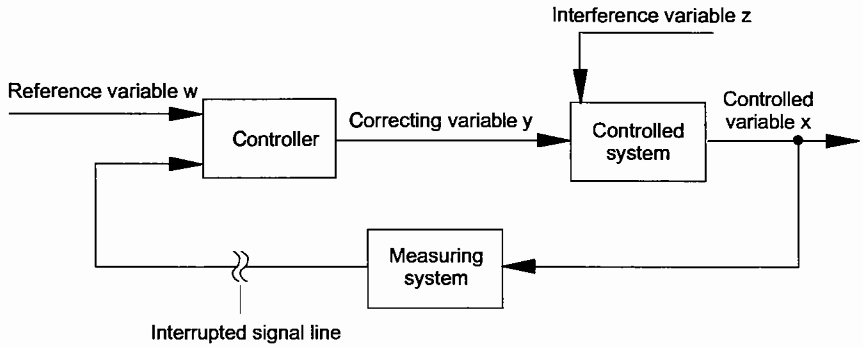


Fig. A6.1: Closed control loop with interruption of control direction setting

Control quality

In the closed control loop, the controller and controlled system are in constant interaction. The interaction of controller and control system are optimised by means of setting the controller coefficients. The control quality describes the quality of closed-loop control. To evaluate the control quality, the transient response of the controlled variable is assessed after a step-change in the reference variable. The following characteristics are determined in detail:

- The *overshoot amplitude* x_m is the greatest temporary deviation of the controlled variable after a step-change in the reference variable. The overshoot amplitude is measured relative to the new steady state.
- The *steady-state system deviation* e_{stat} is the difference between reference variable and controlled variable maintained in the steady state.
- The *settling time* T_a is the time required by the controlled variable x to enter into a new steady state after leaving its steady state.

Generally, a good transient response is obtained when the values of all characteristics are as low as possible.

The above definitions have been quoted DIN 19226.

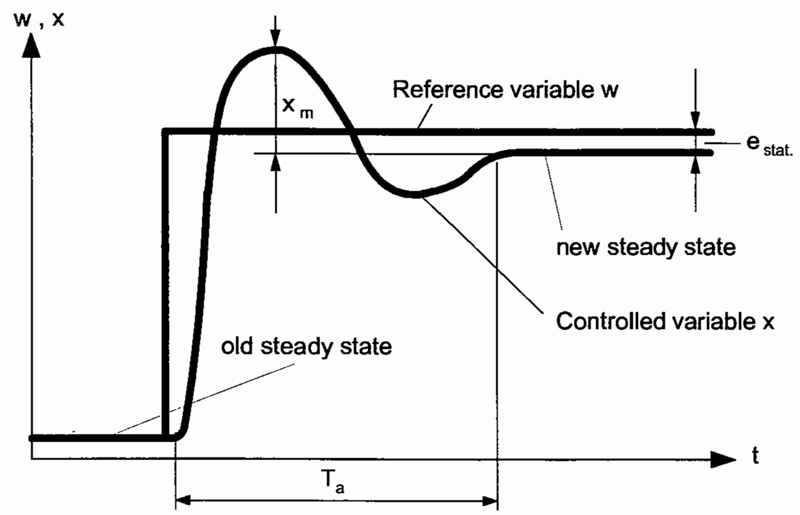


Fig. A6.2: Characteristics of control quality

x_m = overshoot amplitude
$e_{stat.}$ = steady-state system deviation
T_a = setting time

Stability of the closed control loop

A closed control loop operates stable, if the controlled variable assumes a new constant value after a step-change in the reference variable. If this is not the case, i.e. if a new steady state does not occur, then the closed control loop operates unstable. This status is typified by the persistent oscillations of the controlled variable.

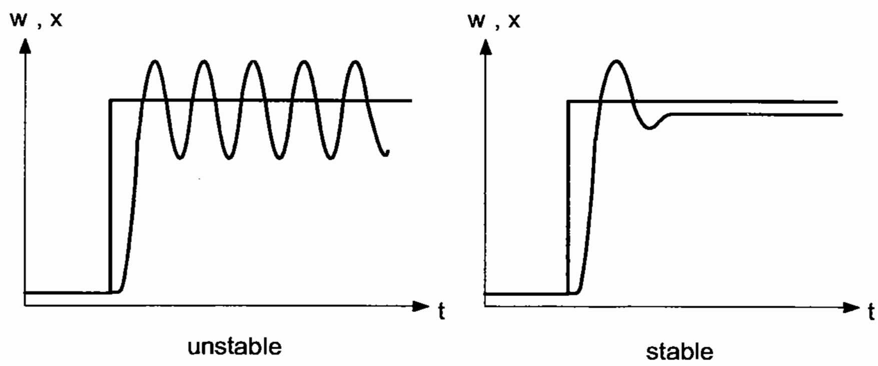
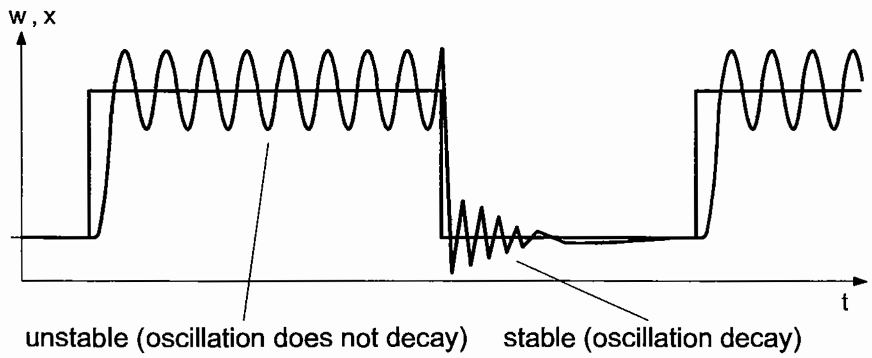


Fig. A6.3: Stability

The stability of a closed control loop depends on the coefficients and time constants of the elements of the closed control loop. Since the controlled system and measuring system are specified here, the limit of stability can only be determined through the proportional coefficient K_P of the P controller. This coefficient is increased until the continuous oscillations occur, whereby the limit of stability has been reached with the critical value K_{Pcrit}.

In many cases, the limit of stability also depends on the reference value. It may occur, that continuous oscillations occur during a step-change pattern of the reference value, whereas the oscillations settle with another value. In that case, it is necessary to determine the limit of stability for the different reference variable step changes.

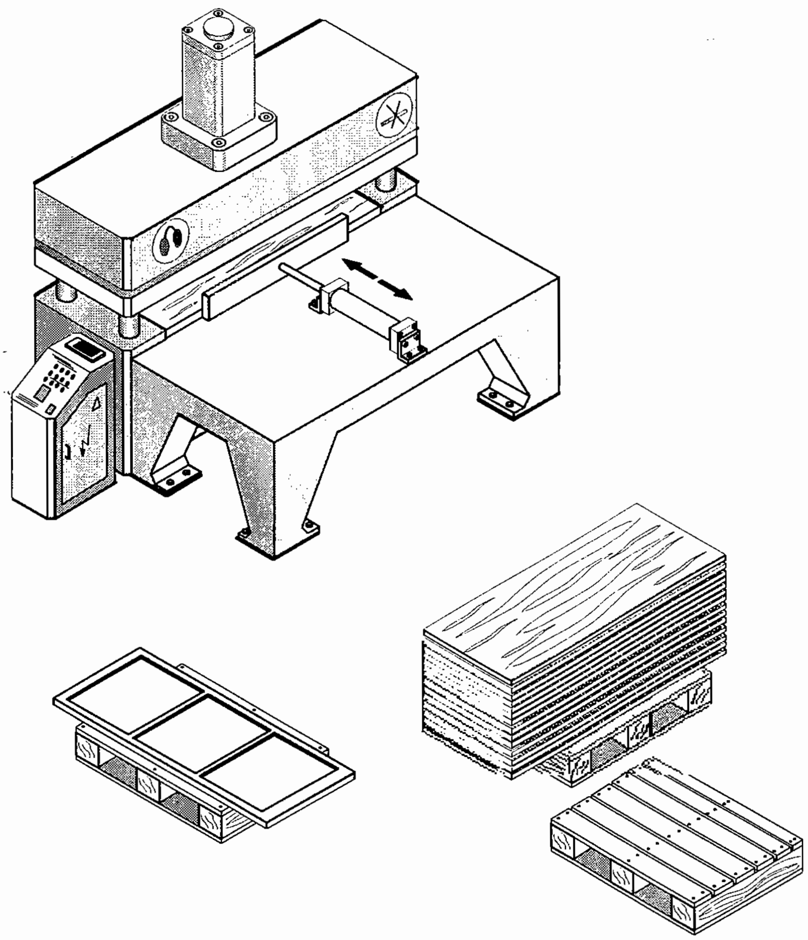
Fig. A6.4: Dependence of limit of stability on reference variable



Problem description

On a veneering press, wooden boards are to be retained by means of a clamping device. Clamping pressure must not exceed a certain level to prevent the wooden boards from being damaged. Equally, pressure must not fall below a minimum variable. For this reason, a pressure control loop is to be constructed and commissioned. The control quality is to be set to an optimum level for the pressures specified.

Positional sketch



Exercise

Pressure control loop

1. Constructing a pressure control loop
2. Checking the control direction
3. Closing the control loop
4. Setting optimum control quality
5. Determining the limit of stability

Execution

1. Pressure control loop

The pressure control loop consists of

- a P controller — as control device,
- a dynamic 4/3-way valve — as final control element,
- a reservoir — as controlled system,
- a pressure sensor — for feedback.

For simplicity's sake, a long piece of tubing is used in place of a reservoir. At a 3 m length, the volume of the tubing is approx. 0.1l (to be accurate: 0.09l).

In order to record transition functions

- step functions are specified as reference variables via the frequency generator,
- and step responses of the controlled variable recorded via the oscilloscope.

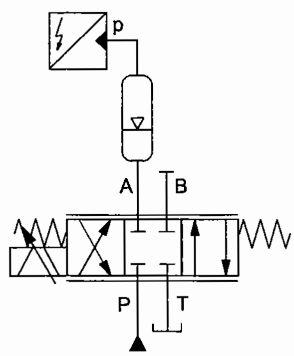
In addition, a multimeter is required for commissioning.

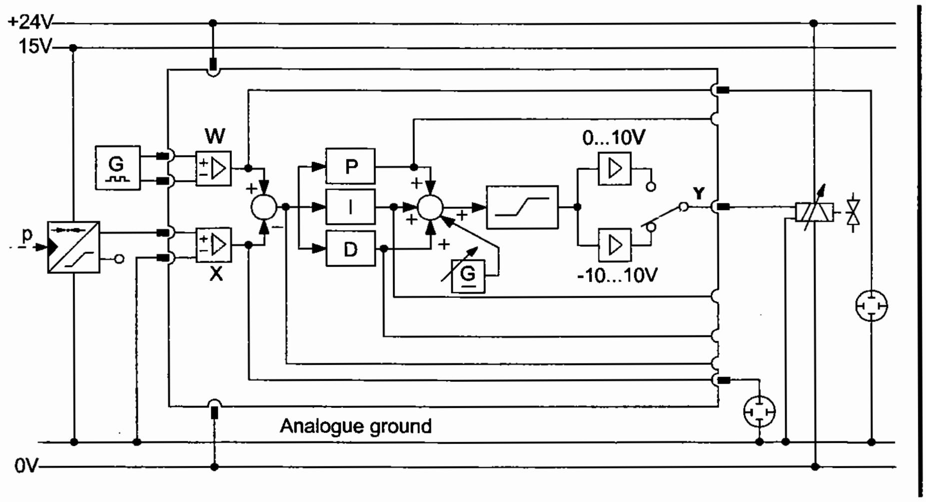
The controller card must be in the initial position prior to switching on the voltage supply:

- Limiter to ± 10V,
- Offset to 0V,
- Proportional coefficient $K_P = 1$,
- Other controller coefficients = 0.

This produces the following hydraulic and electrical circuit diagrams.

Circuit diagram, hydraulic





Circuit diagram, electrical

2. Control direction

The control direction is checked by comparing changes in reference variable and controlled variable. The control direction is correct, if the changes are in the same direction:

- if reference variable w increases, then so does controlled variable x.

If this is not the case, then the interfaces between the elements must be checked:

1. A rising reference variable w produces a rising correcting variable y.
2. rising correcting variable y opens the valve at port A, whereby pressure p_A increases.
3. The rising pressure is measured via the pressure sensor. This results in a rising controlled variable x.

Thus, an increase in the reference variable w will also lead to an increase in the controlled variable x, with the control direction set correctly.

3. Closed control loop

The control loop is closed by connecting the pressure sensor to the controller card. If the polarity is correct, then the correct control direction is maintained. If the polarity is incorrect, this produces typical effects, which can be verified by a comparison of reference and controlled variables.

4. Control quality

A step-change reference variable is to be set. Pressure can be set at between 0bar and 60bar. This corresponds to 0V and 6V on the pressure sensor, producing an appropriate reference value of, say

$w = 3V \pm 2V$ in square wave form

The following characteristics apply for the control quality:

- Overshoot amplitude x_m,
- Steady-state system deviation e_{stat},
- Settling time T_a.

An optimum setting of the controller coefficient K_{Popt} is obtained, if the values of all variables is as low as possible. In addition, the closed control loop should operate stable.

The tolerances for the control quality variables and their priority is to be determined subject to application. In this way, an overshoot amplitude (= pressure above setpoint pressure) may be acceptable in the case of a pressure control which is to set a setpoint pressure as quickly as possible (= short settling time). In the case of position control, overtravelling of the reference position is to be avoided!

5. Limit of stability

The limit of stability K_{Pcrit} is determined by means of increasing the proportional coefficient K_P and is reached when continuous oscillations occur.

To demonstrate the dependence of the limit of stability on the reference variable, a small step of the reference variable is set. By offsetting the mean value, the entire range of potential reference variables is examined.

WORKSHEET

Pressure control loop

1. Pressure control loop

- Construct the pressure control loop. Use the hydraulic and electrical circuit diagrams.
- Set the controller card in the initial position:
  - Limiter to ± 10V,
  - Offset to 0V,
  - Proportional coefficient $K_P = 1$,
  - Other controller coefficients = 0.

2. Control direction

- Interrupt the closed control loop by not connecting the pressure sensor to the controller card.
- Check the control direction:

  Does the controlled variable x increase with rising reference variable w?

  ____

  If "Yes", then the control direction is correct:

  + w equals + x.

- Nevertheless, carry out a check of the interfaces. Make sure that the following conditions are met:

  + w equals + y

  + y equals + x

  + w equals + x

  The control direction is correct when these conditions are met.

3. Closed control loop

- Close the control loop by connecting the pressure sensor to the controller card.
- Check whether the system deviation e becomes smaller.
  - If "Yes", then the connection of the pressure sensor is also in order.
  - If "No", reverse the signal connections of the pressure sensor.

Check the effects of the following polarity reversals:

Value table

Reverse polarity	Change in controlled variable x with increasing reference variable w
Reference variable w	
Correcting variable y	
Feedback r	

WORKSHEET

4. Control quality

- Set a step-change reference variable:

  w = 3V ± 2V   f = 5Hz   in square wave form

- Select the following scales on the oscilloscope:

  Time t: 0,02 s/Div.
  Reference variable w: 1 V/Div.
  Controlled variable x: 1 V/Div.

- Determine the characteristics of the control quality in relation to different proportional coefficients K_P:
  - Overshoot amplitude x_m,
  - Steady-state system deviation e_{stat},
  - Settling time T_a.

Value table

K_P	x_m (V)	e_{stat} (V)	T_a (s)	*Oscillations*	*Evaluation*
1					
3					
5					
8					
10					
12					

- Which controller setting do you consider to be an optimum setting?

  K_{Popt} = ______________________________

- What then are the characteristics of the controller quality:

  Overshoot amplitude $x_{m,opt}$ = ______________________

  Steady-state system deviation $e_{stat,opt}$ = ______________________

  Settling time $T_{a,opt}$ = ______________________

  Stability: ______________________

5. Limit of stability

- Determine the limit of stability by increasing K_P until continuous oscillations occur.

  K_{Pcrit} = ______________________ (with w = 3V ± 2V, 5 Hz)

- Set a step of ± 0.5 V as reference variable and determine the limit of stability for different reference variables.

Value table

Reference variable w	*Limit of stability K_{Pcrit}*	*Evaluation*
1V ± 0.5V		
2V ± 0.5V		
3V ± 0.5V		
4V ± 0.5V		
5V ± 0.5V		

- Which critical proportional coefficient K_{Pcrit} is the most important for the design of a closed control loop?

  ____

Closed-loop hydraulics — *Subject*

Injection moulding machine — *Title*

Training aim

- To learn about the function of I and PI controllers
- To be able to determine the characteristics of I and PI controllers
- To be able to describe the purpose of using I controllers

Technical knowledge

Integral controller (I controller)

The behaviour of the I controller is determined by the integral element.

- The I element adds the input signal e via the time t and
- amplifies it by the factor K_I to the output signal y_I.

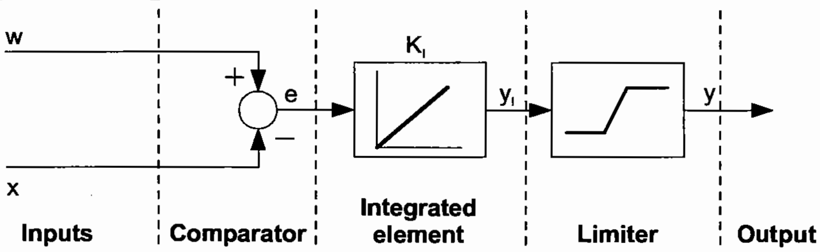
With a constant input signal this results in the following equation:

$$y_I = K_I \cdot e \cdot t$$

A complete I controller consists of

- the comparator to form the system deviation e as input signal of the I element,
- the I element and
- the limiter to form a suitable correcting variable y.

a) Block diagram



w = Reference variable
x = Controlled variable
e = System deviation
y_I = Correcting variable of I element
y = Correcting variable
K_I = Integral-action coefficient

b) Symbol

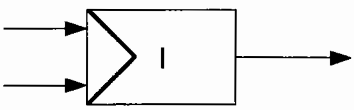


Fig. A7.1:
Block diagram and symbol of integral controller

Characteristics of the I element

The transition function of an I element displays a ramp-shaped pattern since the I element carries out a continuous summation (= integration) of the input signal. The ramp gradient is determined by the integral-action coefficient K_I. The integration time T_I elapses until the output signal y has reached the same value as that of the input signal w, whereby the following applies:

$$T_I = \frac{1}{K_I}$$

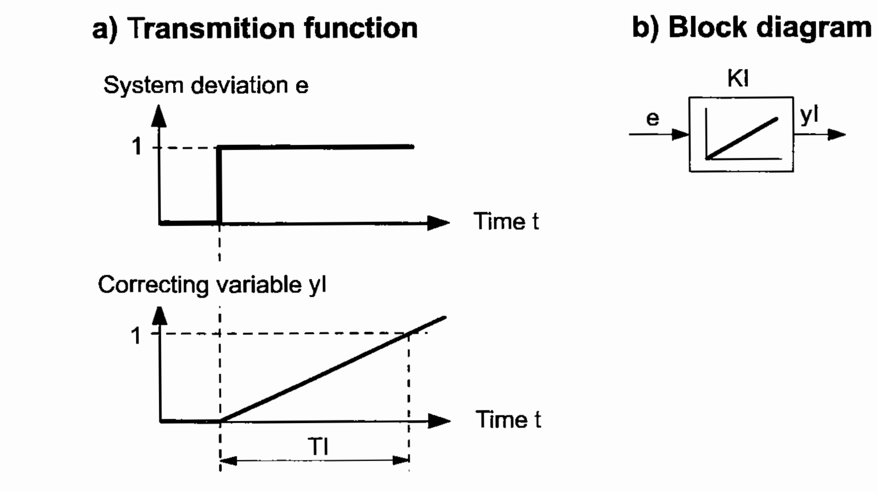


Fig. A7.2: Transition function and block diagram of I element

Use of an I controller:

- The I controller reacts only slowly to changes in the reference variable (in comparison with the P controller) and are therefore rarely used alone.
- The I controller can, however, be used to reduce system deviations to zero, i.e. there is no steady-state system deviation (as in the case of a P controller).

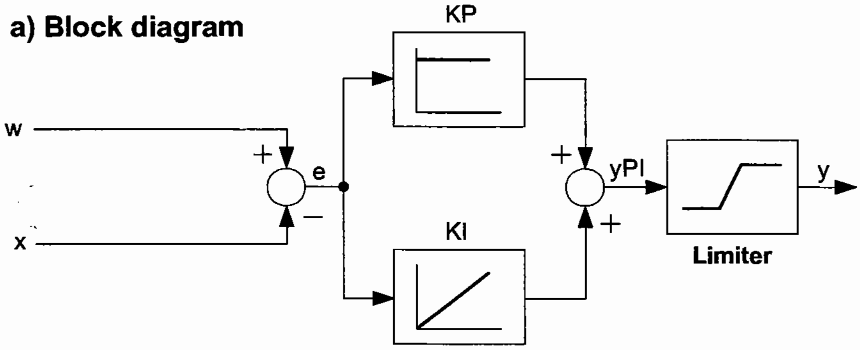
The proportional integral controller (PI controller)

A parallel circuit consisting of a proportional and integral controller forms a PI controller. It combines the advantages of both types of controller, giving a controller which is able both to react quickly and to eliminate system deviations.

A PI controller operates according to the following equation:

$$y_{PI} = e \cdot (K_P + K_I \cdot t) = e \cdot (K_P + \frac{1}{T_I} \cdot t)$$

a) Block diagram



w = Reference variable
x = Controlled variable
e = System deviation
y_{PI} = Correcting variable of PI element
y = Correcting variable
K_P = Proportional-action coefficient
K_I = Integral-action coefficient

b) Symbol

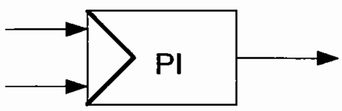


Fig. A7.3: Block diagram and symbol of PI controller

Characteristics of a PI element

The transition function of a PI element consists of:

- the step function of the P element and
- the ramp function of the I element.

The integral-action time T_n is the time required by the I element to generate the same output signal as the P element.

The integral-action time can also be calculated from the coefficients of the PI element:

Output signal of the P element:	$y_P = K_P \cdot e$
Output signal of the I element:	$y_I = K_I \cdot e \cdot t$
Integral-action time T_n:	$y_P = y_I$
And thus:	$K_P \cdot e = K_I \cdot e \cdot T_n$

Hence the following applies for the integral-action time: $T_n = \frac{K_P}{K_I}$

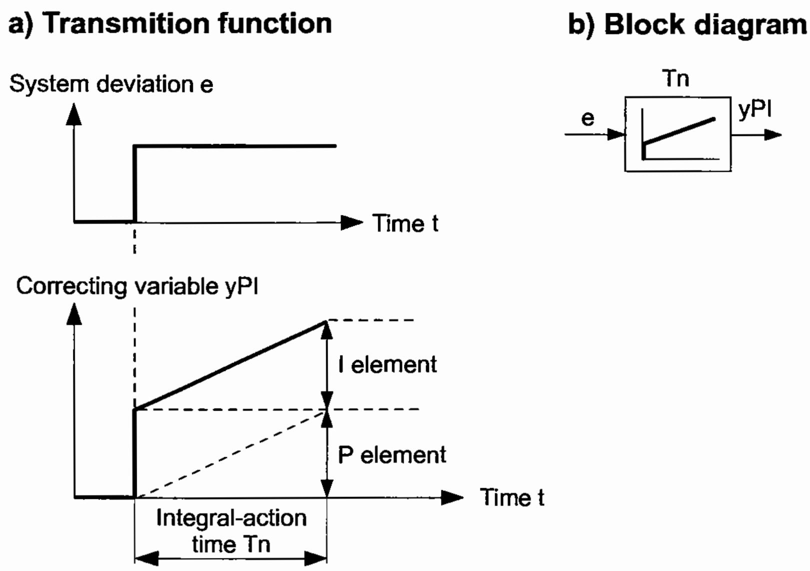
The equation of the PI controller can thus be simplified to:

$$y_{PI} = e \cdot K_P \cdot \left(1 + \frac{t}{T_n}\right)$$

The characteristics of the PI controller specified are:

- either the controller coefficients K_P and K_I,
- or the proportional coefficient K_P and the integral-action time T_n.

Fig. A7.4: Transition function and block diagram of PI element



Combination of P and I controllers

By combining P and I controllers, it is possible to

- minimise the disadvantages of the individual types of controller and
- maximise the advantages of the individual types of controller.

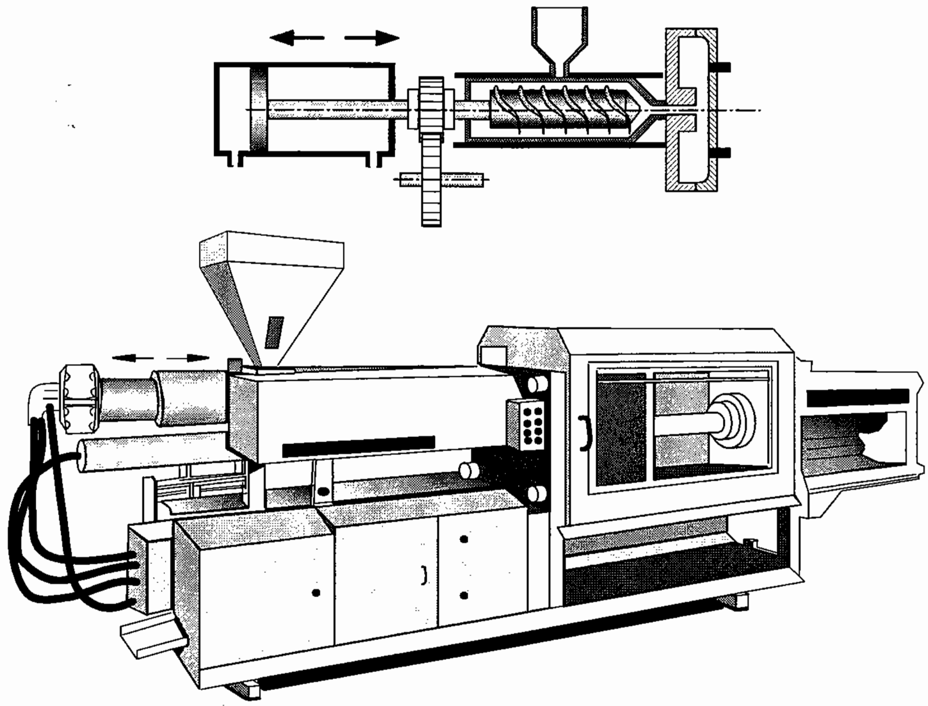
Table A7.1: Advantages and disadvantages of P, I and PI controllers

Controller type	*Advantage*	*Disadvantage*
P controller	fast	inaccurate
I controller	accurate	slow, tendency towards oscillations
PI controller	fast and accurate	tendency towards oscillations

Problem description

Different pressures are to be set on an injection moulding machine: a low charging pressure to fill the mould, a slightly higher forming pressure to fill the entire cavity and a higher calibrating pressure for accurate hardening. A pressure control loop is to be constructed to be able to achieve the required pressure quickly and accurately and to maintain it for the required period of time. You are to examine whether a P controller is adequate or whether a PI controller would give certain advantages.

Positional sketch



Exercise

I controller

1. Constructing and commissioning a measuring circuit
2. Recording the transition function and characteristics of the I controller
3. Determining the transition function and characteristics of the PI controller
4. Comparing the use of the P, I and PI controllers

Execution

1. Measuring circuit

The following are to be measured

- the reference variable w as input signal of the controller and
- the correcting variable y as output signal of the controller.

The following devices are required for this:

- the PID controller card with the I controller,
- a generator for step-change test signals in a range of ± 10V,
- an oscilloscope to record the time characteristic of the output variable,
- a multimeter for commissioning,
- a power supply unit for the voltage supply to the controller.

The following settings are to be made prior to switching on:

- Limiter to ± 10V,
- Offset precisely to zero,
- Integral-action coefficient $K_I = 1$,
- All other controller coefficients to zero.

The setting of the integral-action coefficient K_I is the result of the value of the potentiometer and of the rotary switch.

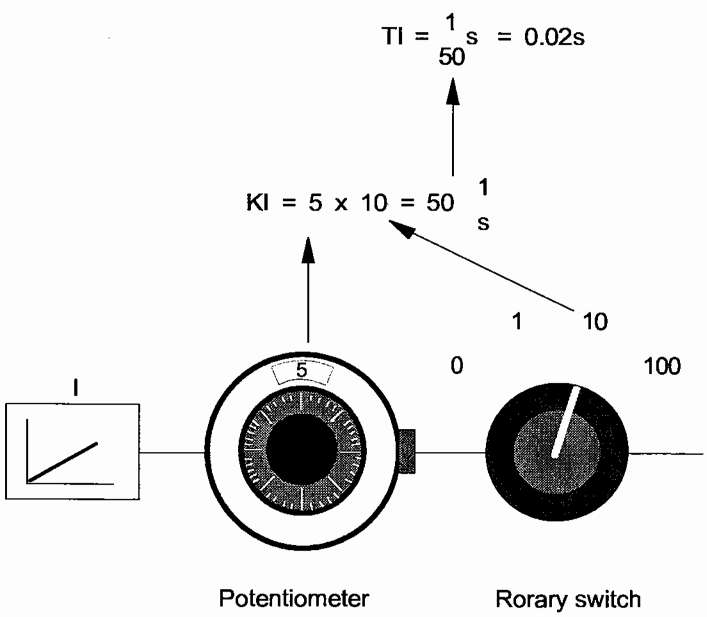
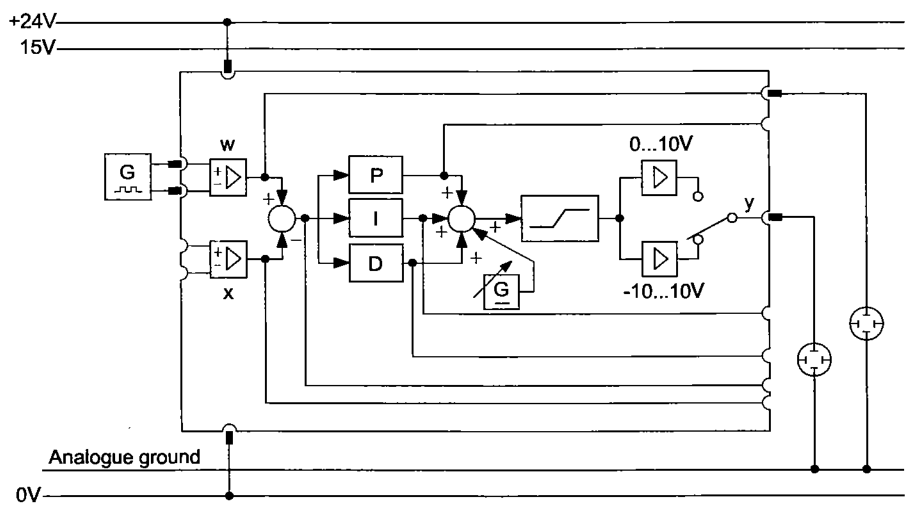


Fig. A7.5: Setting of integral coefficient K_I



Circuit diagram, electrical

2. I controller

The transition function of the I controller is as follows:

- the step-change reference variable w
- results in a ramp-shaped correcting variable y.

Various transition functions are illustrated on the worksheet. The following points must be observed in order to determine the characteristics of an I controller:

1. With a reference variable of w = 0V ± 10V, the magnitude of the step-change w equals = 10V (not 20V!).
2. The integration time T_I is reached when zero of the correcting variable y has risen to the level of the step-change w.
3. The integration coefficient K_I indicates the increase of the transition function. It is therefore a measure for the rate of change of the correcting variable y.

Only by following the above conditions, can the characteristics be correctly established.

The setting of signals for the transition function produces difficulties as a result of the time dependence of the output signal. If the input signal is not exactly symmetrical to zero, then the output signal drifts in one direction until it reaches the limitation. This can be rectified by a slight re-adjustment of the zero.

3. PI controller

The transition function of the PI controller differs from that of the I controller by displaying an initial step-change. After that, it results in the same ramp-shape as the I controller.

To determine the integral-action time T_n, the proportion of the P controller is calculated first:

$$y_P = K_P \cdot w$$

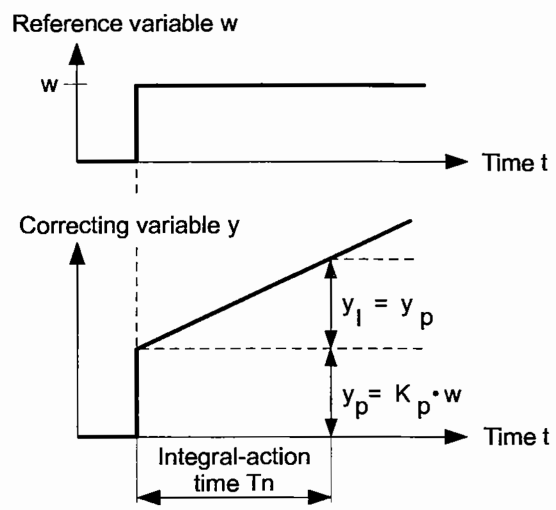
The integral-action time T_n has been reached, when $y_I = y_P$.

When the signals are set, this does not result in the ideal transition function illustrated in the worksheet. This is due to different limitations of the P and I element and the downstream limitation of the correcting variable:

Limitation of P element	$y_P = \pm 10V$,
Limitation of I element	$y_I = \pm 14V$,
Limitation of correcting variable	$y = \pm 10V$.

If the output variable of the I element y_I exceeds 10V, this does not become apparent in the correcting variable y. A subsequently resulting step-change of the P element y_P is therefore incorrectly interpreted. In that case, the transition functions of the individual elements must be measured. The addition of the two signals produces the transition function of the PI controller: $y = y_P + y_I$.

Fig. A7.6: Measuring of integral-action time T_n



Mathematically, the integral-action time is the quotient of the controller coefficient settings:

$$T_n = \frac{K_P}{K_I}$$

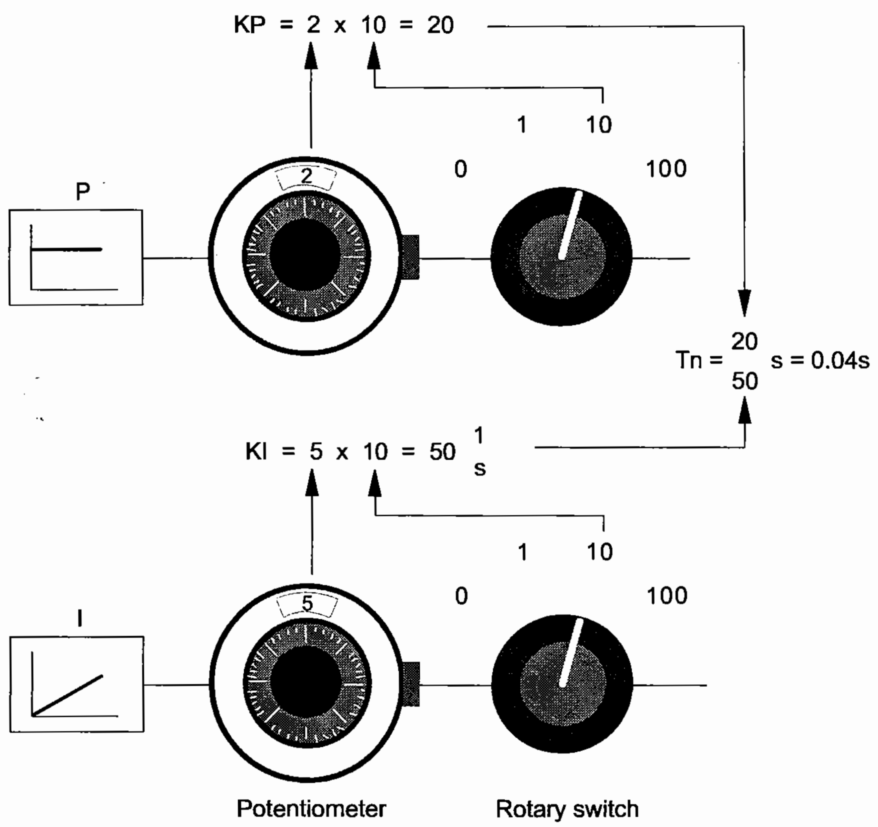


Fig. A7.7: Calculating of integral-action time T_n

4. P-, I and PI controller

Use the table to evaluate the different types of controller relative to the speed and adjustment characteristics of the system deviation.

WORKSHEET

The I controller

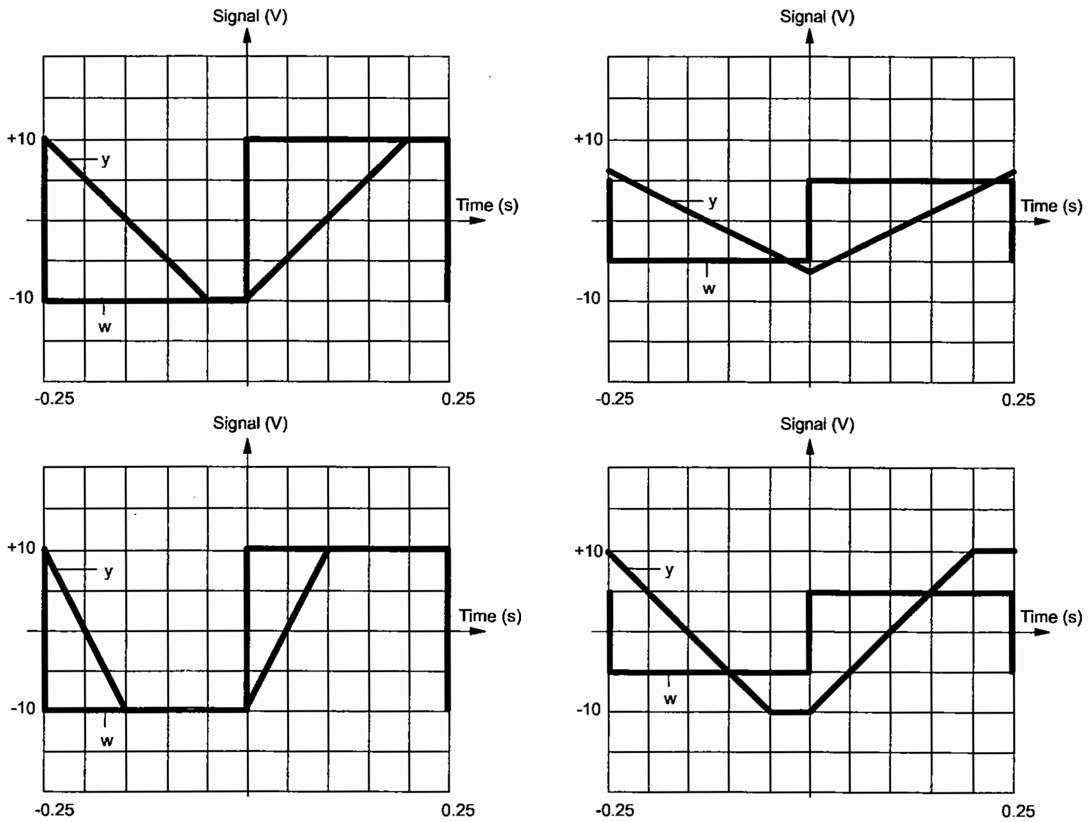
1. Measuring circuit

- Construct the circuit according to the circuit diagram.
- Set the controller card as follows:
  - Limiter to ± 10V,
  - Offset exactly to zero,
  - Integral-action coefficient $K_I = 1$,
  - All other controller coefficients to zero.

2. I controller

- Enter the integration time T_I in the diagrams and calculate the integral-action coefficient K_I.

Diagram



- How does the integration time T_I change with the integral-action coefficient K_I?

___

- Do the integration time T_I and integral-action coefficient K_I change with the reference variable w?

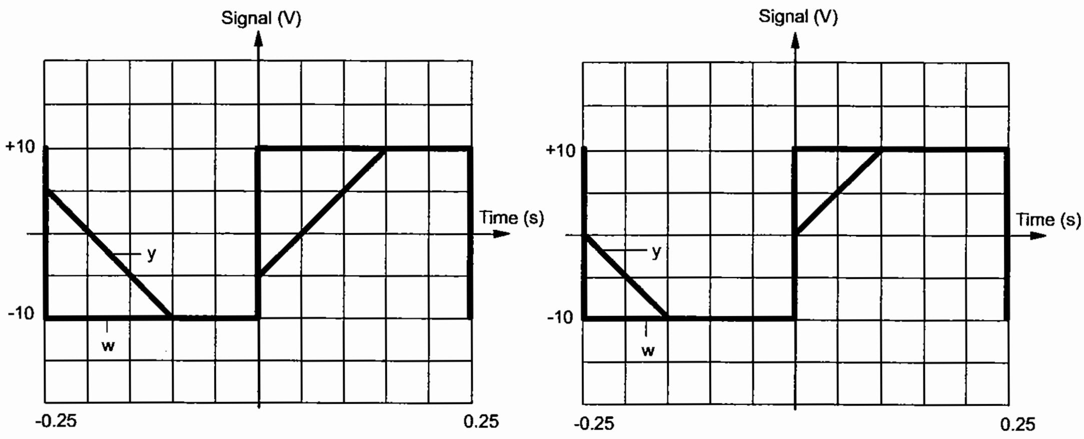
___

- Represent the transition function on the oscilloscope. The settings can be taken from the diagram.

3. PI controller

- The following are to be determined from the diagrams
  - the coefficients of the PI controller: K_P and K_I
  - the integral-action time T_n.

Fig. A7.6: Measuring of integral-action time T_n



WORKSHEET

- Represent the transition functions on the oscilloscope. The settings can be taken from the diagram. Why are there deviations from the ideal representation?

____

____

____

4. P-, I and PI controller

- Evaluate the features of the following types of controller:

Table

Properties	*Controller type*		
	P	*I*	*PI*
Velocity			
Steady-state system deviation			

Subject: *Closed-loop hydraulics*

Title: ***Pressing-in of bearings***

Training aim

- To learn about the function of a D controller
- To be able to determine the characteristics of D and PD controllers
- To be able to describe the transition function of a PID controller

Technical knowledge

Derivative-action controller (D controller)

The derivative-action controller reacts to time changes in the input signal:

- The D element determines the time change in the input variable:

$$\frac{\Delta e}{\Delta t}$$

- and amplifies this with factor K_D.

With an evenly increasing input signal, the D-element operates according to the following equation:

$$y_D = K_D \cdot \frac{\Delta e}{\Delta t}$$

In the case of input signals which can be changed at random, the gradient for infinitely small time increments Δt is calculated (= differentiated) and is described by the following equation:

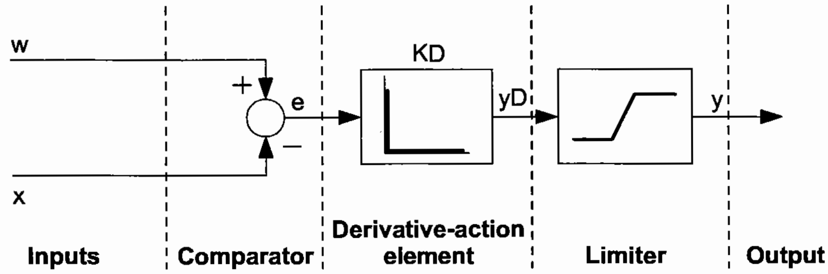
$$y_D = K_D \cdot \frac{de}{dt}$$

The complete D controller consists of:

- the comparator to form the system deviation e as input signal to the D element,
- the D element and
- the limiter to form a suitable correcting variable y.

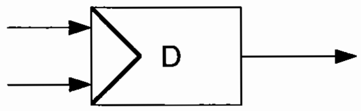
Fig. A8.1: Block diagram and symbol of D controller

a) Block diagram



w = Reference variable
x = Controlled variable
e = System deviation
y_D = Correcting variable of I element
y = Correcting variable
K_D = Derivative-action coefficient

b) Symbol



Characteristics of a D element

The transition function of the D element merely displays a spike pulse: The gradient of the step change function is infinitely great at the time of the change. The input variable does not change after this, the gradient is zero. Since the gradient of the input variable is represented at the output of the D element, this briefly exhibits an infinite value and then returns to a constant zero.

The characteristics of the D element can be measured by means of the ramp response: The triangular function as input variable has a constant gradient $\Delta e/\Delta t$.

This results in a constant correcting variable $y_D = K_D \cdot \Delta e/\Delta t$. The ramp response of the D element is thus a square function, whereby the magnitude of the step change y_D is then determined from the gradient of the input signal and the derivative-action coefficient K_D.

The D controller responds more speedily to changes in system deviation than a P controller (see transition functions). A D controller is, however not able to compensate steady-state system deviations. This is why D controllers are very rarely used on their own in technical applications; instead D controllers are used in combination with P and I controllers.

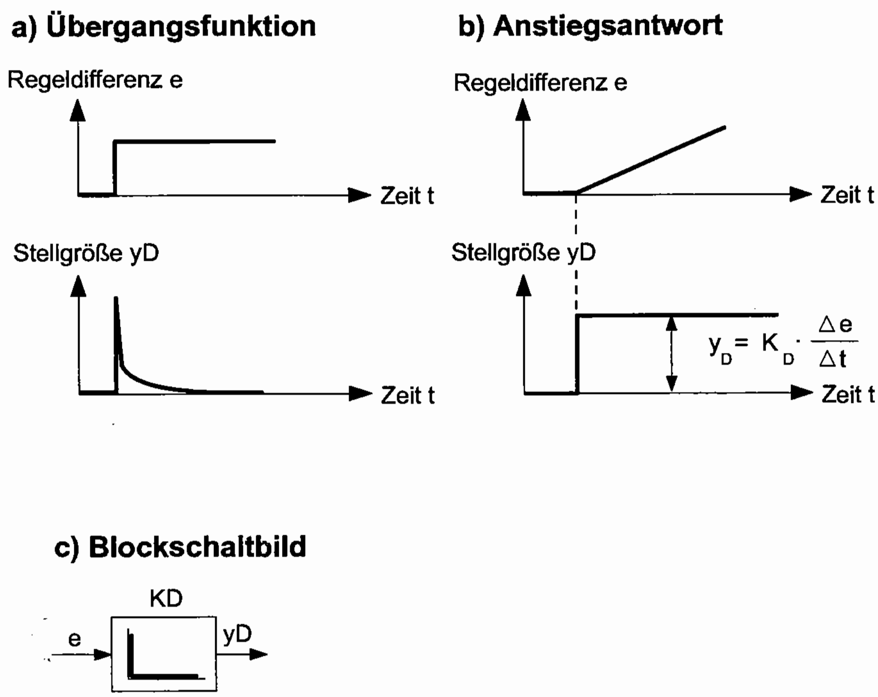


*Fig. A8.2:
Transition function,
Ramp response and
block diagram of D element*

PD controllers

In the case of a PD controller, a P and D element are connected in parallel and then added together. This results in the following equation:

$$y_{PD} = K_P \cdot e + K_D \cdot \frac{de}{dt}$$

The transition function of the PD controller is made up as follows:

- the spike pulse of the D component and
- the step change (square) of the P component.

The ramp response of the PD controller displays

- a step change (square) from the D component and
- a ramp from the P component.

As a result of the step change of the D component, the PD controller reaches a specified correcting variable y_1 sooner than a P controller. This means that the P controller requires a time lead over the PD controller. This time difference between the P and PD controller is described as derivative-action time T_v.

The derivative-action time T_v is the quotient of the coefficients of the PD controller:

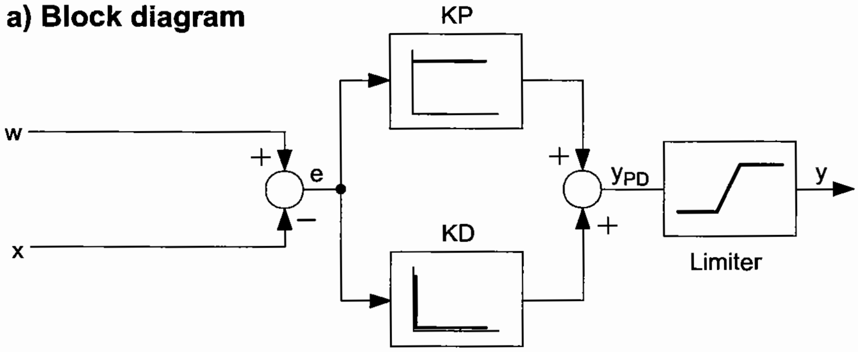
$$T_V = \frac{K_D}{K_P}$$

The following can therefore also apply

$$y_{PD} = K_P \cdot \left(e + T_V \cdot \frac{de}{dt} \right)$$

Fig. A8.3: Block diagram and symbol of PD controller

a) Block diagram



w = Reference variable
x = Controlled variable
e = System deviation
y_{PD} = Correcting variable of PD element
y = Correcting variable

b) Symbol

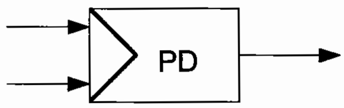
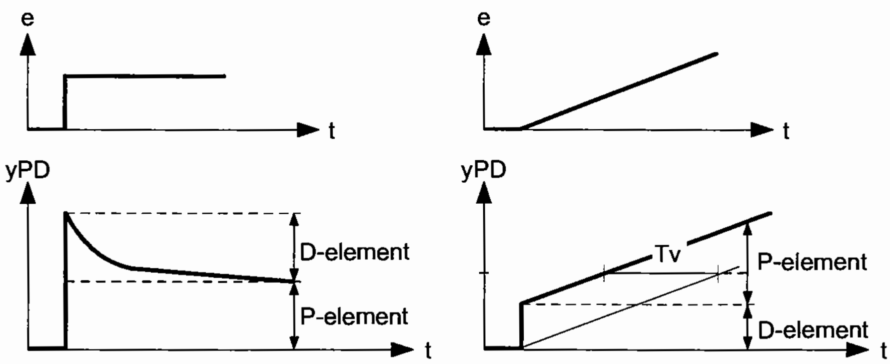
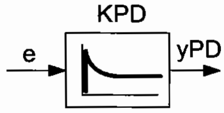


Fig. A8.4: Transition function, ramp response and block diagram of PD element

a) Transmition function **b) Ramp response**



c) Block diagram



PID controller

With the PID controller, three control elements, a P, an I and a D element are connected in parallel and added together. The output signal is:

$$y_{PID} = K_P \cdot e + K_I \cdot e \cdot t + K_D \cdot \frac{de}{dt}$$

The integral-action time $T_n = \frac{K_P}{K_I}$ and the derivative-action time $T_V = \frac{K_D}{K_P}$ result in:

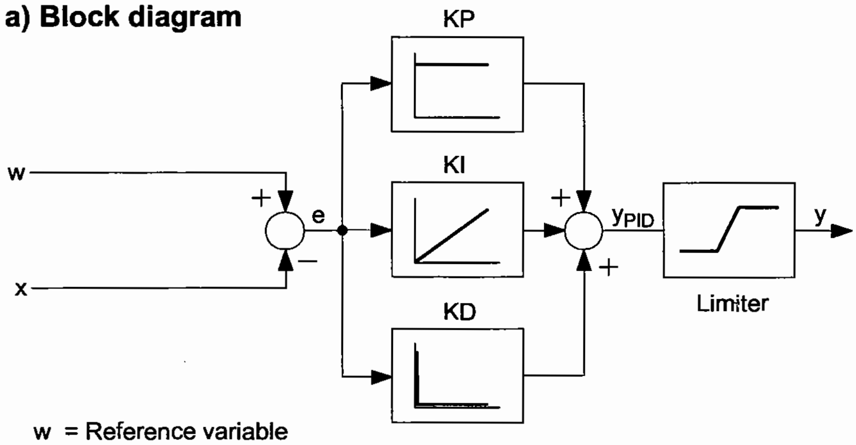
$$y_{PID} = K_P \cdot \left(e + \frac{1}{T_n} \cdot e \cdot t + T_V \cdot \frac{de}{dt} \right)$$

The PID controller can therefore be described by means of the following characteristics:

- either by means of the three coefficients: K_P, K_I, K_D,
- or by means of a coefficient and two time constants: K_P, T_n, T_v.

The integral-action time T_n manifests itself in the transition function, and the derivative-action time T_v in the ramp response!

a) Block diagram



w = Reference variable
x = Controlled variable
e = System deviation
y_{PID} = Correcting variable of PID element
y = Correcting variable

b) Symbol

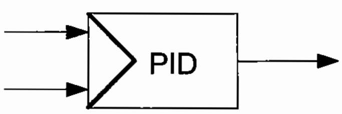


Fig. A8.5: Block diagram and symbol of PID controller

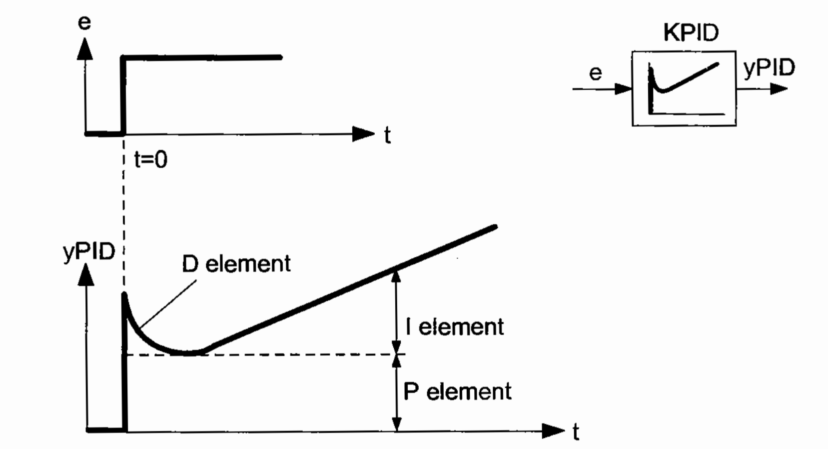


Fig. A8.6: Transition function and block diagram of PID element

Comparison of controller types

The advantages and disadvantages of the different types of controller are set out in table A8.1. An evaluation is made of

- speed,
- steady-state system deviation and
- tendency to oscillation.

Which type of controller is suitable for a controlled system also depends on the type of controlled system. When constructing a closed control loop, it is therefore essential that the type of controller be selected according to the type of controlled system.

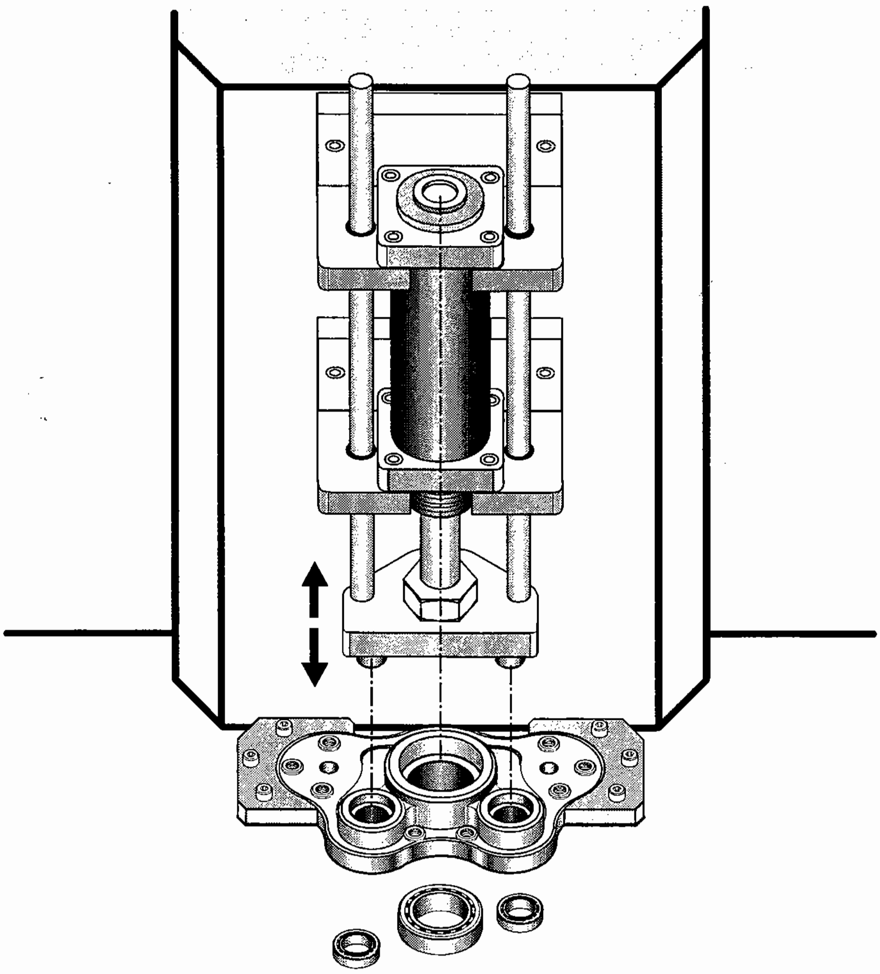
Table A8.1: Comparison of controller types

Controller type	*Advantages*	*Disadvantages*
P controller	fast	steady-state system deviation
I controller	no steady-state system deviation	slow, tendency towards oscillations
PI controller	fast, no steady-state system deviation	tendency towards oscillations
PD controller	very fast	steady-state system deviation
PID controller	very fast, no steady-state system deviation	

Problem description

Bearings are to be pressed into a housing. In order to prevent damage to the bearings, the process must be slow and at constant force. A hydraulic drive unit is required for the high forces. In order to maintain the force at a constant level, a pressure control loop is to be planned. A PID controller is to be used as the control device after an initial investigation has been carried out.

Positional sketch



Exercise

D, PD and PID controller

1. Constructing and commissioning the measuring circuit
2. Recording the transition function and ramp response of the D controller
3. Determining the time constant of the PD controller
4. Establishing the construction of the PID controller from the transition function

Execution

1. Measuring circuit

The following are to be measured

- The reference variable w as input signal of the controller and
- the correcting variable y as output signal of the controller.

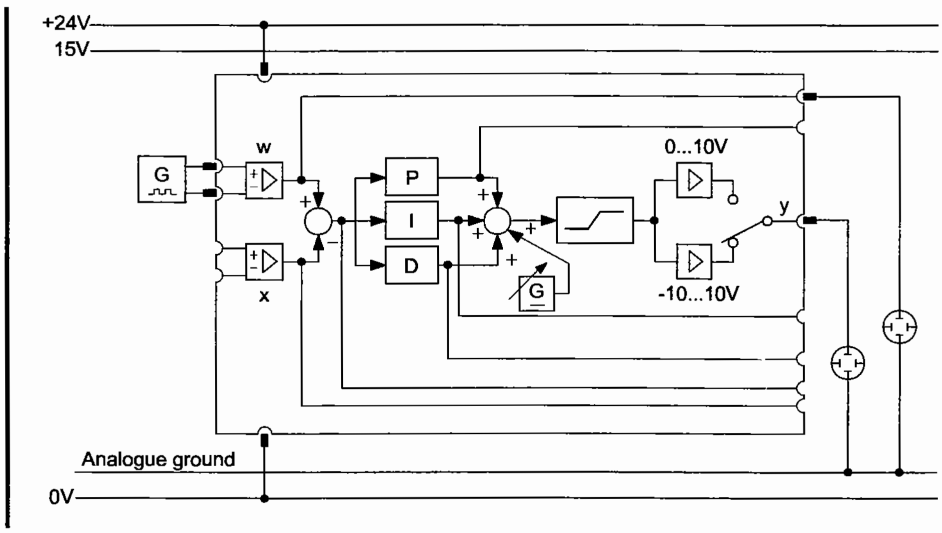
The following equipment is required:

- the PID controller card,
- a generator for test signals in the range of ± 10V,
- an oscilloscope to record the output variable,
- a multimeter for commissioning,
- a power supply unit for the voltage supply to the controller.

The following settings are to be made prior to switching on:

- Limiter to ± 10V,
- Offset to centre (= zero),
- All controller coefficients to zero.

Circuit diagram, electrical



2. D controller

The transition function of the D controller produces

- from a square-wave signal for reference variable w.
- a spike signal for correcting variable y

The ramp response of the D controller produces

- from a triangular-wave signal for reference variable w.
- a square-wave signal for correcting variable y

The magnitude of the step change of the square-wave signal is dependent on the controller coefficient K_D and on the gradient of the triangular-wave signal $\Delta e/\Delta t$.

$$y = K_D \cdot \frac{\Delta e}{\Delta t}$$

The gradient of the reference variable w is calculated from the amplitude A and the frequency f:

$$\frac{\Delta w}{\Delta t} = 4 \cdot A \cdot f$$

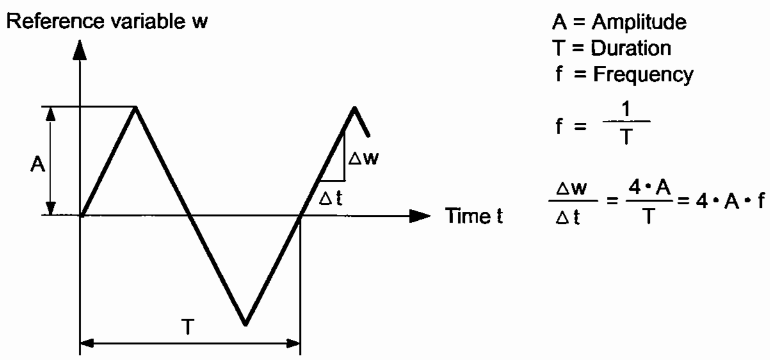


Fig. A8.7: Slope of reference variable w

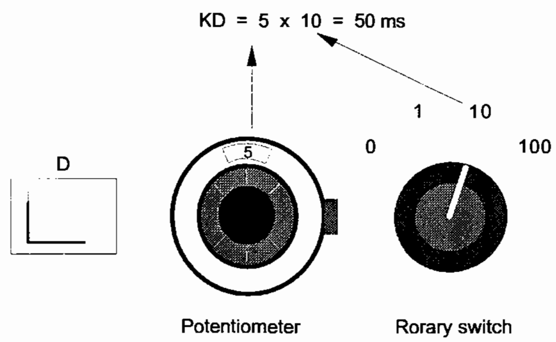


Fig. A8.8: Setting of differential coefficient K_D

3. PD controller

The derivative-action time T_v is the characteristic of the PD controller and is calculated from the ramp response by means of comparison with a P controller (see fig. A8.4).

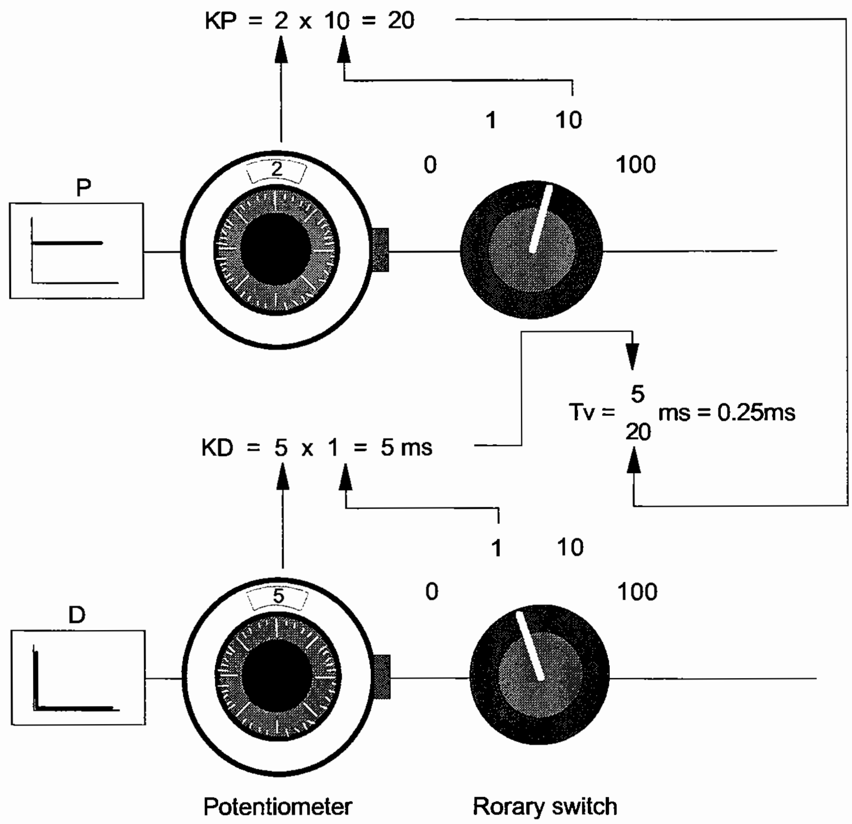


Fig. A8.9: Calculating of derivative-action time T_v

4. PID controller

The transition function of the PID controller is made up of the typical components of the P, I and D element (see fig. A8.6).

WORKSHEET

D, PD and PID controller

1. Measuring circuit

- Construct the circuit in accordance with the circuit diagram.
- Set the controller card as follows:
  - Limiter to ± 10V,
  - Offset to centre (= zero),
  - All controller coefficients to zero.
- Carry out the following settings on the oscilloscope:
  - Signals w and y: 5 V/Div.
  - Time: 20 ms/Div.

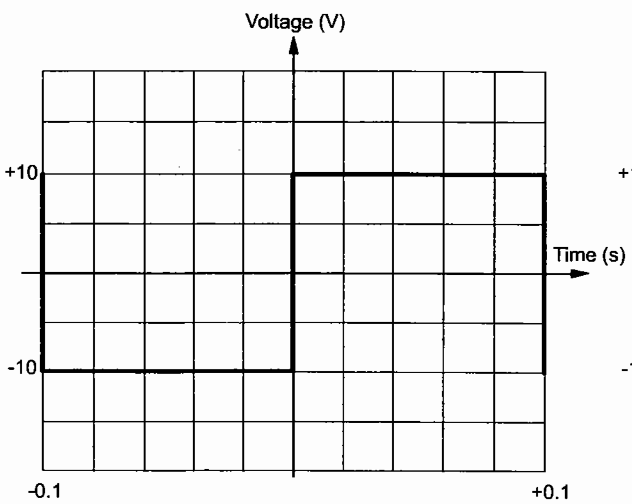
2. D controller

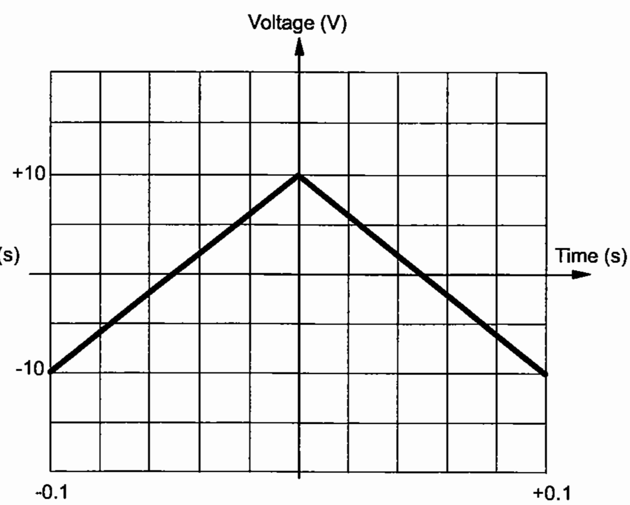
- Record the transition function of the D controller using

  w = 0V ± 10V, f = 5Hz, square wave form

  K_D = 25ms
- Plot the ramp response of the D controller by changing the reference variable to a triangular function.

Diagram





- Calculate the gradient of the reference variable:

$$\frac{\Delta w}{\Delta t} = 4 \cdot A \cdot f = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

- Calculate the correcting variable y:

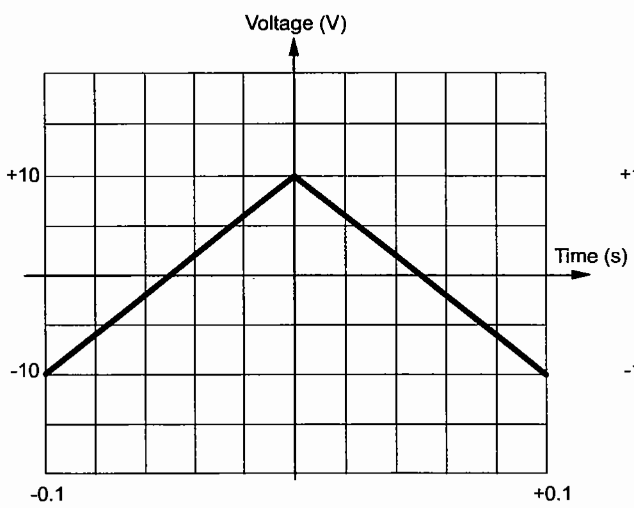
$$y = K_D \cdot \frac{\Delta w}{\Delta t} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

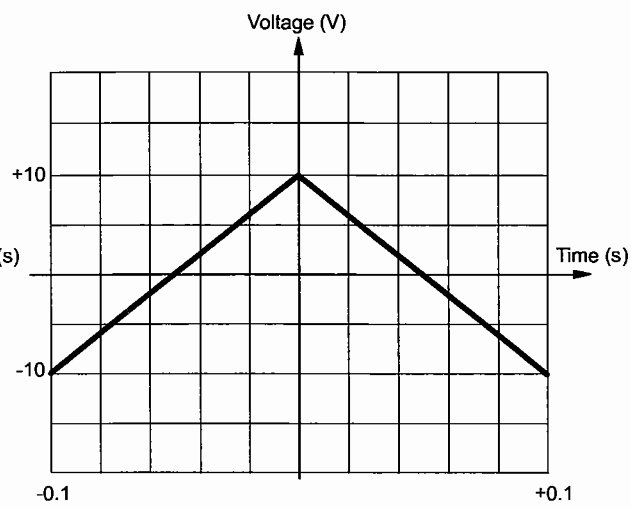
- Does your measurement agree with the calculated correcting variable y? If not, repeat the measurement and closely observe the gradient of the reference variable.

3. PD controller

- Record two jump responses of the PD controller using
  - $w = 0V \pm 10V$, $f = 5Hz$, triangular wave form
  - 1. $K_P = 1$, $K_D = 25ms$
    2. $K_P = 0.5$, $K_D = 25ms$

Diagram





WORKSHEET

Calculate the derivative-action time:

T_{v1} = ____________________

T_{v2} = ____________________

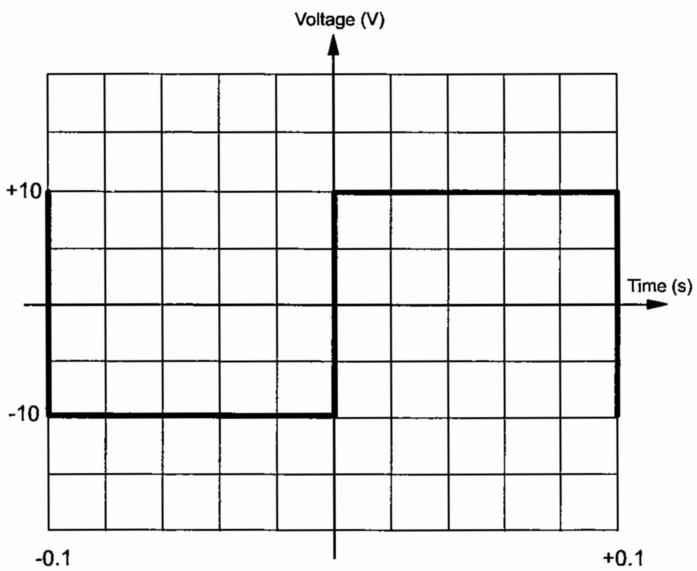
Compare these with your measuring result: do the values agree?

____

4. PID controller

- Record the transition function of the PID controller using
  - $w = 0V \pm 10V$, $f = 5Hz$, square wave form
  - $K_P = 0.5$, $K_I = 25\ 1/s$, $K_D = 25ms$

Diagram



- Designate the components of the P, I and D element in the transition function.

Subject

Closed-loop hydraulics

Title

Welding tongs of a robot

Training aim

- To be able to construct and commission a pressure control loop
- To be able to set the parameters of a PID controller using an empirical method

Technical knowledge

Appropriate combination of controller and controlled system

When constructing a closed-control loop, the controller and controlled system must be harmonised:

- A pressure control loop is a system with compensation and delay (see exercise 3). This is therefore a system with first or higher order compensation and delay.
- P, PI or PID controllers are recommended for such distances.

Empirical parameterisation of a PID controller

A controller is harmonised with the controlled system by setting the coefficients (= parameters). Two methods are basically available for this:

- empirical, i.e. by trial, and
- by calculation, i.e. according to mathematical methods.

With empirical parameterisation, it is essential to proceed systematically; the following method should therefore be adopted:

- change the coefficients consecutively and
- test the effect of the control quality.

The aim of parameterisation is to set the controller so as to achieve

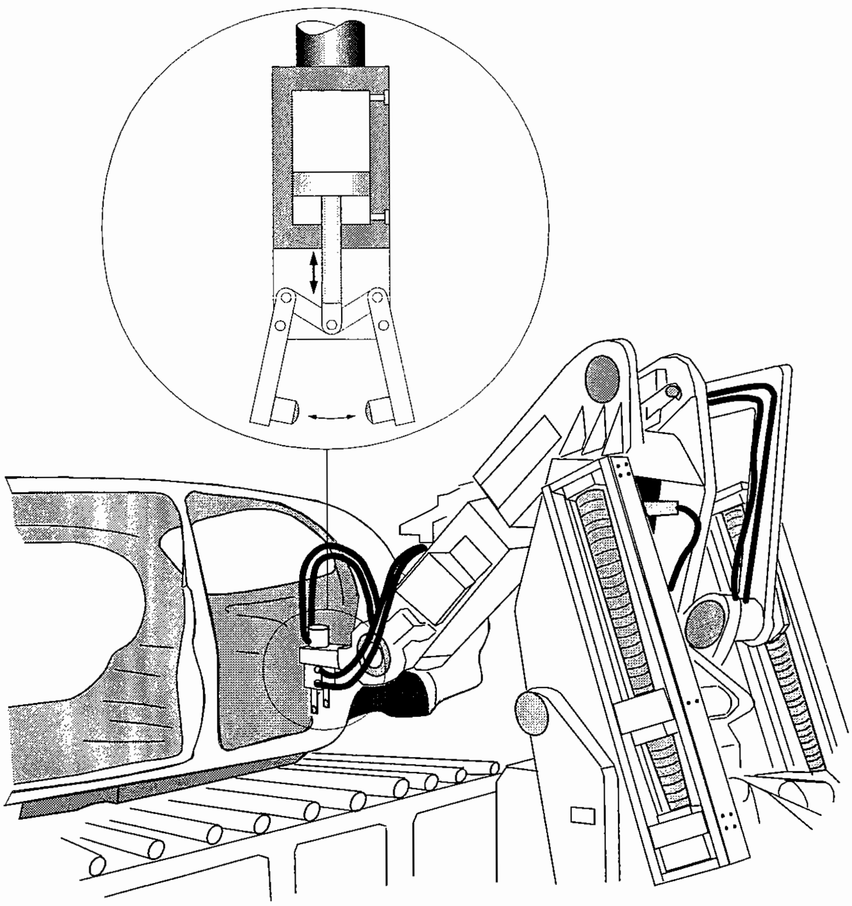
- the best possible control quality
- and to ensure a stable closed control loop.

Problem description

In a car body shop, metal parts are to be joined by means of spot welding. The welding tongs of the robot generate a high contact pressure, which is to last until the welding joint has be made. This is followed by pressure relief, approach of the next position and new pressure build-up. The process is to be as fast as possible to accomplish as many spot welds as possible in a relatively small period of time.

The contact pressure is to be set by means of a pressure control loop. A PID controller is to be used as controller. The pressure control loop is to be constructed and the PID controller set at an optimum level for this application.

Positional sketch



Exercise

Pressure control loop with PID controller

1. Constructing a pressure control loop
2. Commissioning a pressure control loop
3. Setting the parameters of a PID controller using an empirical method

1. Pressure control loop

Execution

A pressure control loop consists of

■ a PID controller	for control device,
■ a dynamic 4/3-way valve	for final control element,
■ a reservoir	for controlled system,
■ a pressure sensor	for feedback.

A long section of tubing is to be used as a reservoir as in exercise 6.

To record transition functions

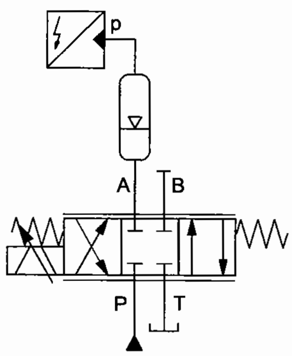
- step functions are to be specified as reference variables by the frequency generator,
- step responses of the controlled variable are recorded via the oscilloscope.

In addition to this, a multimeter is required for commissioning.

The controller card must be in the initial position prior to switching on:

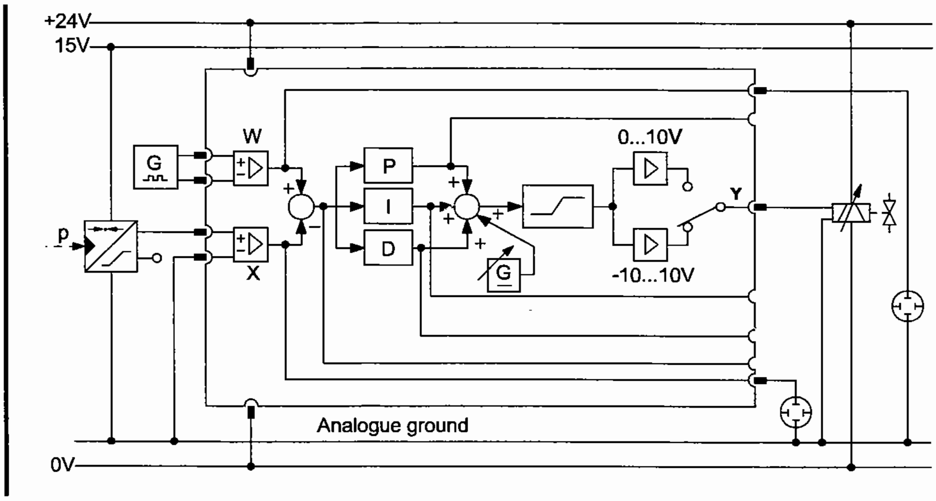
- Limiter to ± 10 V,
- Offset to zero V,
- All controller coefficients = 0.

This produces the following hydraulic and electrical circuit diagrams.



Circuit diagram, hydraulic

Circuit diagram, electrical



2. Commissioning

2.1 Control direction

To check the control direction, set the coefficient $K_P = 1$. The control direction is correct, if the controlled variable x also increases with an increasing reference variable w.

2.2 Limit of stability

The limit of stability is determined via a step-change reference variable w in the mid correcting range. The critical coefficient K_{Pcrit} is reached when steady-state oscillations of the controlled variable x occur.

3. Empirical parameterisation

The aim of setting the controller is to obtain optimum control quality. The characteristics for control quality are:

- Overshoot amplitude x_m,
- Steady-state system deviation e_{stat},
- Settling time T_a

The following procedure is recommended:

1. Set coefficient $K_P < K_{Pcrit}$
2. Increase coefficient K_I
3. Increase coefficient K_D

whereby the effects of the control quality characteristics are to be taken into consideration:

- If the control quality improves, then the coefficient can be further increased.
- If the control quality deteriorates or the closed control loop becomes unstable, then the increase is to be reduced.

The optimum setting has been obtained, if

- the values of all characteristics of the control quality are as small as possible
- and the closed control loop is stable.

This simple procedure must only be used, if the closed control loop can be made to oscillate without causing damage or risk of injury!

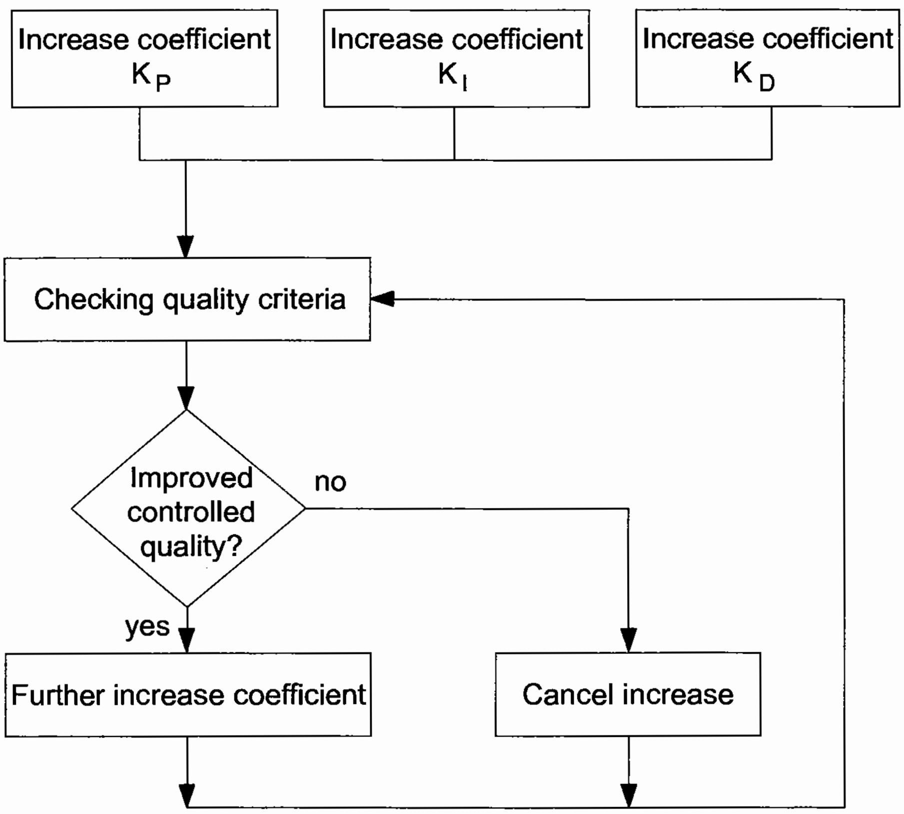


Fig. A9.1: Empirical parameterisation of a PID controller

WORKSHEET

Pressure control loop with PID controller

1. Pressure control loop

- Construct the pressure control loop.
  Use the hydraulic and electrical circuit diagrams.

- The controller must be in the initial position:
  - Limiter to ± 10V,
  - Offset to zero V,
  - All controller coefficients = 0.

2. Commissioning

2.1 Control direction

- Set the coefficient $K_P = 1$, and test the control direction: Does the controlled variable x increase with the reference variable w?

  If not, check the interfaces for correct polarity.

2.2 Limit of stability

- Set a step-change reference variable w:

  w = 3 V ± 2V, 5Hz, square wave form

- Increase the coefficient K_P until steady-state oscillations occur:

  K_{Pcrit} = ______________________________

3. Empirical parameterisation

- Set the PID controller in such as to obtain optimum control quality proceeding step by step. Note the change in control quality after each change of the controller parameter.
- Adjust the frequency of the reference variable w to the settling time T_a, by changing to 1Hz or 0.5 Hz. This enables you to evaluate the characteristics of the control quality correctly.

Value table

Controller coefficient			*Control quality*			*Stability*	*Comment*
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)		

- What are the optimum coefficients of the PID controller?
- What is the control quality obtained?

Value table

Optimum controller coefficients			*Best possible control quality*			*Stability*
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)	

Closed-loop hydraulics — *Subject*

Pressure roller of a rolling machine — *Title*

Training aim

- To be able to set a PID controller using the Ziegler-Nichols method

Technical knowledge

Ziegler-Nichols method

The Ziegler-Nichols method has been developed to provide a middle course between purely empirical and computational methods of parameterisation. Optimum settings of P, PI, PD and PID controllers were established from a wide ranging measuring series using pressure regulation (= controlled system with compensation and delay). Particular attention has been given to the fact that interference can also be compensated. In practice, this method specifies good controller coefficients. Empirical fine-tuning can then still be carried out after this.

The Ziegler-Nichols method can be divided into two steps:

1. Establishing the limit of stability of the closed control loop (empirical),
2. Calculating the controller parameters in accordance with standard formulae.

1. The limit of stability is determined via the P controller. It is reached when steady-state oscillations occur. This produces

- the critical coefficient K_{Pcrit} and
- the critical period of oscillation T_{crit} (see fig. A10.1).

2. The coefficients of the controllers are calculated from this on the basis of the formulae (see fig. A10.2).

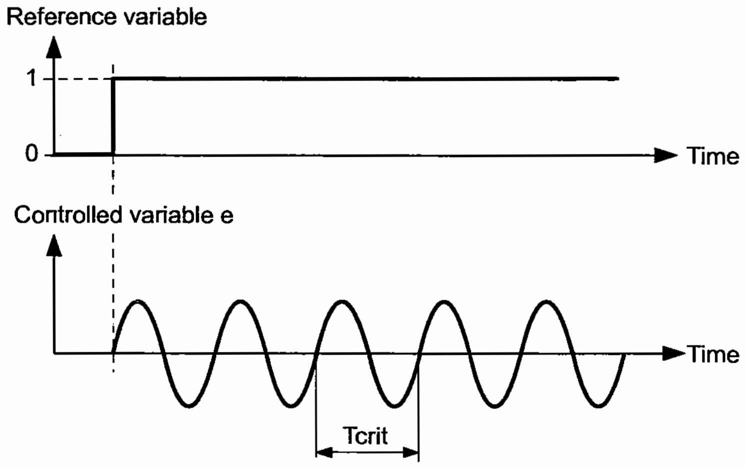


Fig. A10.1: Critical period of oscillation T_{crit}

Fig. A10.2: Controller coefficients according to Ziegler-Nichols method.

Controller type	Calculation of characteristic values				
	K_p	T_n	T_v	K_I	K_D
P	$0.5 \cdot K_{Pcrit}$	-	-	-	-
PD	$0.8 \cdot K_{Pcrit}$	-	$0.12 \cdot T_{crit}$	-	$K_P \cdot T_V$
PI	$0.45 \cdot K_{Pcrit}$	$0.85 \cdot T_{crit}$	-	K_P / T_n	-
PID	$0.6 \cdot K_{Pcrit}$	$0.5 \cdot T_{crit}$	$0.12 \cdot T_{crit}$	K_P / T_n	$K_P \cdot T_V$

Computing example for a closed control loop with PID controller

1. Limit of stability of the closed control loop:

- $K_{Pcrit} = 20$
- $T_{crit} = 100ms$

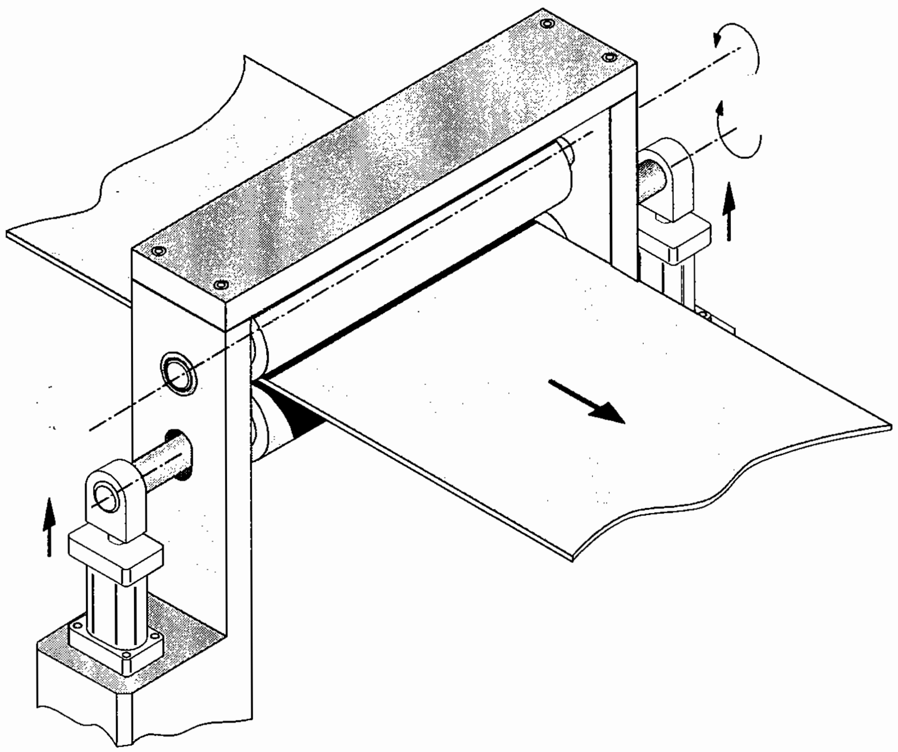
2. Optimum controller coefficients of the PID controller:

- $K_P = 0.6 \cdot K_{Pcrit} = 0.6 \cdot 20 = 12$
- $T_n = 0.5 \cdot T_{crit} = 0.5 \cdot 100ms = 50ms$
- $T_v = 0.12 \cdot T_{crit} = 0.12 \cdot 100ms = 12ms$
- $K_I = \frac{K_P}{T_n} = \frac{12}{0.05s} = 240\frac{1}{s}$
- $K_D = K_P \cdot T_v = 12 \cdot 12ms = 144ms$

Problem description

Metal sheets are to be drawn through two rollers in a rolling machine. One roller has fixed bearings and the other is pressed against this by means of a hydraulic cylinder. The contact force is to be as constant as possible, which is why a pressure control loop with PID controller is used. This PID controller is to be set at its optimum setting.

Positional sketch



Exercise

Ziegler-Nichols method

1. Constructing and commissioning the pressure control loop
2. Setting the PID controller in accordance with the Ziegler-Nichols method
3. Altering the controlled system and resetting it to the optimum level.

Execution

1. Pressure control loop

The closed control loop is to be constructed and commissioned as described in exercise 9:

1. Construct the circuit
2. Set the controller:
   - Coefficients to zero,
   - Offset to zero,
   - Limiter to ± 10V.
3. Check the control direction

2. Ziegler-Nichols method

The Ziegler-Nichols method is divided into two steps:

1. Establishing the limit of stability of the closed control loop by increasing the coefficient K_P until steady-state oscillations occur. This results in the following:
   - critical coefficient K_{Pcrit}
   - critical oscillation time T_{crit} (see fig. A10.1).
2. Calculating the controller parameters in accordance with standard formulae (see fig. A10.2).

The comparison between the empirically determined parameters (solution to exercise 9) and the values calculated here show clear differences:

- regarding the values of the parameters,
- regarding the characteristics of the control quality:
  - Overshoot amplitude x_m,
  - Steady-state system deviation e_{stat},
  - Settling time T_a.
- regarding the oscillations in the closed control loop (stability).

3. Modified controlled system

The pressure control loop is altered by removing the reservoir (tubing), thereby producing different time constants. The controller is reset:

- according to the Ziegler-Nichols method and
- empirically.

The settings are evaluated under point 2 with the help of the control quality obtained.

WORKSHEET

Ziegler-Nichols method

1. Pressure control loop

- Construct a pressure control loop using a PID controller. Use the circuit diagrams from exercise 9.
- The controller must be in the initial setting:
  - Coefficients to zero,
  - Offset to zero,
  - Limiter to ± 10V.
- Set the correct control direction.

2. Ziegler-Nichols method

- Set a step-change reference variable w:

  $w = 3V \pm 2V$, 1Hz, square wave form
- Determine the limit of stability of the closed control loop:

  - K_{Pcrit} = ______________________

  - T_{crit} = ______________________

- Calculate the coefficients of the PID controller using the Ziegler-Nichols method:

  - $K_P = 0.6 \cdot K_{Pcrit}$ = ______________________

  - $T_n = 0.5 \cdot T_{crit}$ = ______________________

  - $T_v = 0.12 \cdot T_{crit}$ = ______________________

  - $K_I = \frac{K_P}{T_n}$ = ______________________

  - $K_D = K_P \cdot T_v$ = ______________________

- Set the calculated coefficients of the PID controller.

  Is the closed control loop stable? ____________________

- Check the control quality:

  - Overshoot amplitude x_m = ____________________

  - Steady-state system deviation e_{stat} = ____________________

  - Settling time T_a = ____________________

- Compare with the empirically obtained control quality (see solution to exercise 9).

  Which controller setting do you consider to be better? ____________

  ____

  ____

3. Modified controlled system

- Remove the tubing (= reservoir) from the hydraulic circuit.
- Determine the limit of stability of the closed control loop:

  K_{Pcrit} = ____________________

  T_{crit} = ____________________

- Calculate the coefficients of the PID controller using Ziegler-Nichols method:

  - $K_P = 0.6 \cdot K_{Pcrit}$ = ____________________

  - $T_n = 0.5 \cdot T_{crit}$ = ____________________

  - $T_v = 0.12 \cdot T_{crit}$ = ____________________

  - $K_I = \frac{K_P}{T_n}$ = ____________________

  - $K_D = K_P \cdot T_v$ = ____________________

WORKSHEET

- Set the coefficients according to the Ziegler-Nichols method and check the control quality.

Controller coefficient according to Z.-N.			Control quality			Stability
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)	

Value table

- Carry out the empirical parameterisation of the PID controller and check the control quality.

Controller coefficients empirical			Control quality			Stability
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)	

Value table

- Which PID setting do you consider to be better?

Closed-loop hydraulics — *Subject*

Edge-folding press with feeding device — *Title*

Training aim

- To be able to carry out the commissioning of a pressure control loop
- To be able to set the parameters of a pressure control loop with interference

Interference in the closed control loop

Technical knowledge

Each element in a closed control loop can be affected by interference; this changes the behaviour of the closed control loop overall, which manifests itself in a change in control quality. It is often not possible to attribute the cause of interference to one device in particular, in which case the closed control loop must be examined systematically.

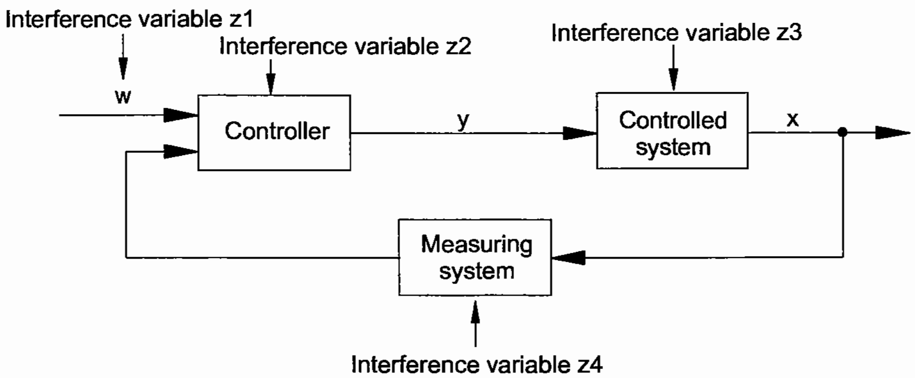


Fig. A11.1: Disturbance variables in the closed control loop

Table A11.1: Examples of interference variables and their effects

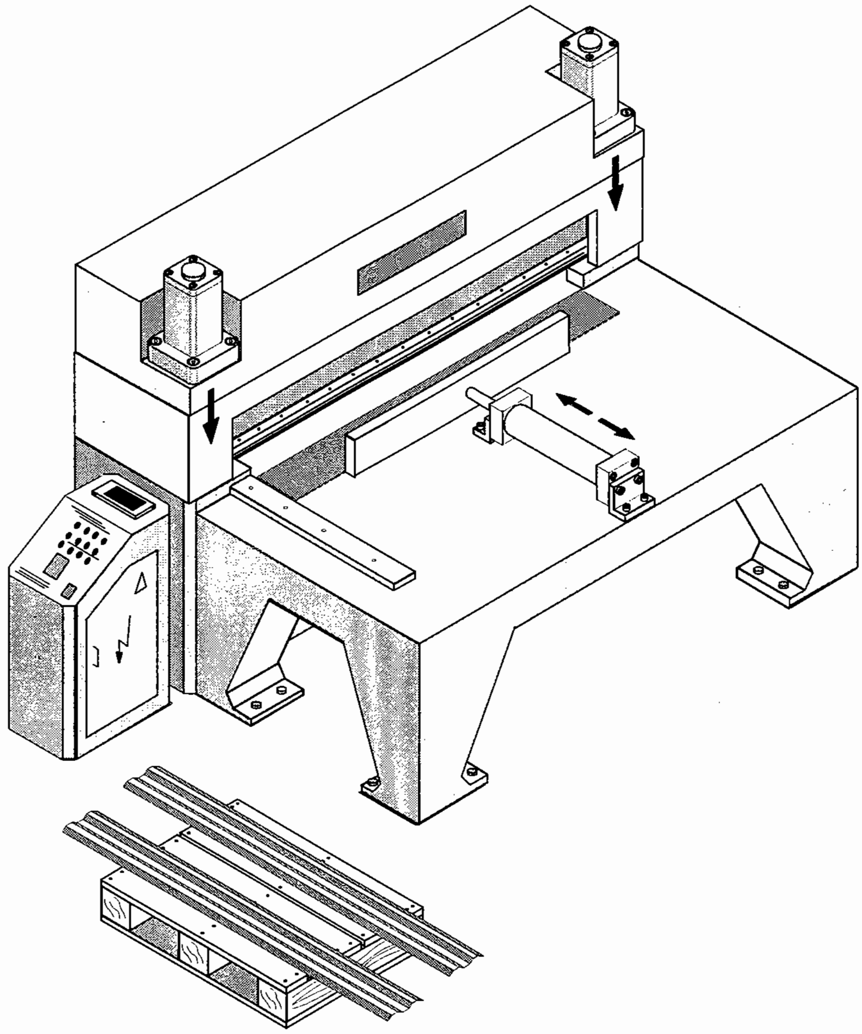
Type of interference	*Effect on control behaviour*
Noisy signals as a result of electrical fields	Electrical signal lines without screening act as antennae for interference signals from adjacent electrical equipment
Hysteresis	Hysteresis in closed control loop elements leads to asymmetrical transmission behaviour. For example the hysteresis effect on a dynamic valve results in different flow characteristics for the two directions of opening.
Offset	Offsets shift the operating points of closed control loop elements. This can lead to steady-state system deviations.
Supply networks, electrical supply networks	Under-sized hydraulic or voltage networks cause fluctuations in the transmission lines. This impairs the follower behaviour of the control loop.
Leakage	Leakage loss in hydraulic components can reduce the line pressure.
Forces, moments	Forces or Moments acting upon the closed control loop cause changes in the runtime performance of closed control loop elements.
Measuring errors	Incorrectly installed or unsuitable measuring devices lead to falsified signals. Signal delays may result, which impair the stability of the closed control loop

Problem description

A hydraulic edge-folding device is to be expended by means of a hydraulic feeding device. The feeding device is operated by the same power pack as the edge-folding press. This may lead to temporary overloading of the power pack and moreover result in eventual leakage due to component wear.

Either situation can lead to interference in the pressure control loop of the edge-folding device. The extent of interference is to be reduced to a minimum by means of appropriate measures.

Positional sketch



Exercise

Pressure control loop with interference

1. Constructing a pressure control loop
2. Commissioning a pressure control loop
3. Optimum setting of a PID controller
4. Examining the effect of interferences

Execution

1. Pressure control loop

The pressure control loop consists of

- a PID controller — for control device,
- a dynamic 4/3-way valve — for final control element,
- a reservoir — for controlled system,
- a pressure sensor — for feedback

As in all the other exercises, a long section of tubing is used as a reservoir.

The most frequent interferences in hydraulics are

- Pressure drop and
- Leakage.

The interferences are to be simulated by means of

- a pressure relief valve and
- a flow control valve.

Both are connected to the hydraulic power pack via a by-pass. This permits the simulation of a pressure drop in the hydraulic power pack and a leakage in the pressure control loop.

The pressure drop at connection P of the valve is measured by means of

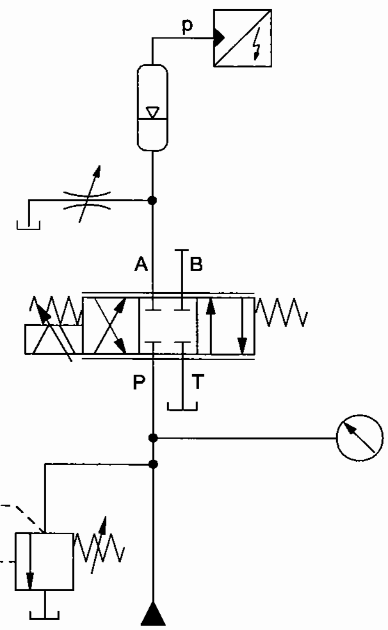
- a pressure gauge or a pressure sensor.

To record the transition function

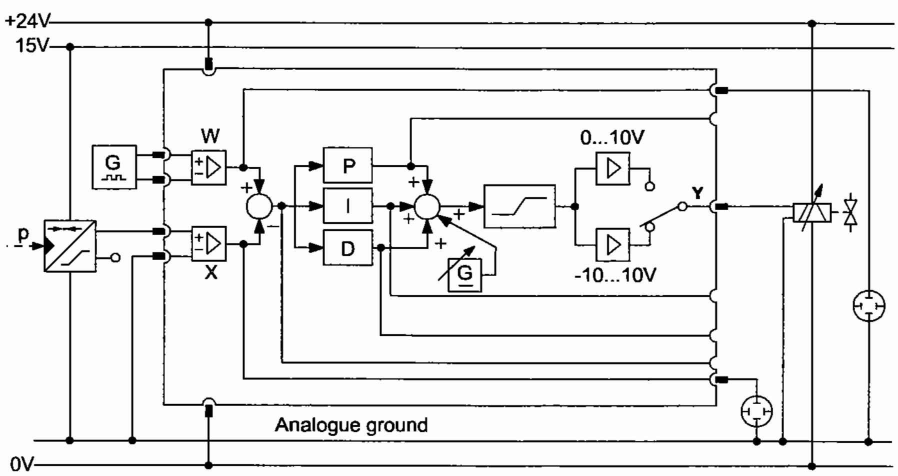
- a step function is specified as reference variable w and
- the step response of the controlled variable x recorded on the oscilloscope.

In addition, a multimeter is required for commissioning.

This results in the following hydraulic and electrical circuit diagrams.



Circuit diagram, hydraulic



Circuit diagram, electrical

2. Commissioning

The controller card must be in the initial position prior to switching on:

- Limiter to ± 10V,
- Offset to zero V,
- All controller coefficients = 0.

The interferences are switched off in the hydraulic section, i.e. the pressure relief valve and the flow control valve are closed completely.

Coefficient $K_P = 1$ is set to check the control direction. The control direction is correct, if the controlled variable x increases with an increasing reference variable.

To check the hydraulic circuit, the flow control valve and the pressure relieve valve are slightly opened. The effect on the transition function can be seen even with minor changes: The pattern changes and the target pressure can no longer be reached.

3. PID controller

First, the limit of stability of the control loop is established without interference. A step-change reference variable w in the mean correcting range is used. The limit of stability having been reached, steady-state oscillations of the controlled variable x occur. This produces:

- the critical coefficient K_{Pcrit} and
- the critical period of oscillation T_{crit}.

The optimum coefficients of the PID controller are then calculated from these according the Ziegler-Nichols method.

The setting is evaluated on the basis of the characteristics of the control quality.

The best possible control quality is set by means of empirical parameterisation.

This results in two settings for the PID controller:

- calculated according to the Ziegler-Nichols method and
- empirically determined.

4. Effect of interferences

The following interferences are investigated in sequence:

- leakage and
- drop in supply pressure.

The computational and empirical coefficients of the PID controller are set and compared on the basis of the control quality.

WORKSHEET

Pressure control loop with interference

1. Pressure control loop

- Construct the pressure control loop with a flow control and a pressure relief valve in the by-pass according to the circuit diagram.

2. Commissioning

- The controller must be in the initial setting:
  - Limiter to $\pm$ 10V,
  - Offset to 0V,
  - All controller coefficients = 0.
- Close the flow control valve and the pressure relief valve completely.
- Connect the electrical and hydraulic power.
- Set $K_P = 1$, and check the control direction:

  Does the controlled variable x increase with the reference variable w?

  ____

- If "No", then check the interfaces between the devices for correct polarity.
- In addition, check whether a pressure drop is created if the flow control valve or pressure relief valve is opened.
- Make sure that both valves are completely closed again.

3. PID controller

- Optimise the coefficient of the PID controller for an interference-free closed control loop.
- Set a step-change reference variable:

  w = 3 V $\pm$ 1V, 1Hz, square wave form
- Determine the limit of stability:

  K_{Pcrit} = ______________________________

  T_{crit} = ______________________________

- Calculate the coefficients of the PID controller using the Ziegler-Nichols method:

  - $K_P = 0.6 \cdot K_{Pcrit}$ = ______________________

  - $T_n = 0.5 \cdot T_{crit}$ = ______________________

  - $T_v = 0.12 \cdot T_{crit}$ = ______________________

  - $K_I = \frac{K_P}{T_n}$ = ______________________

  - $K_D = K_P \cdot T_v$ = ______________________

- Evaluate the control quality using the calculated coefficients:

Value table

Controller coefficients to Z.-N.			*Controller quality without interference*			*Stability*
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)	

- Determine the optimum coefficients empirically:

Value table

Controller coefficients empirical			*Controller quality without interference*			*Stability*
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)	

- What settings of the PID controller do you consider to be better?

____

WORKSHEET

4. Effect of interferences

- Investigate the effect of a leak by slightly opening the flow control valve.
- Determine the limit of stability with leakage:

  K_{Pcrit} = ______________________

- Compare the control quality for the two controller settings
  - calculated using the Ziegler-Nichols method and
  - empirically determined.

Controller coefficients to Z.-N.			*Controller quality with leakage*			*Stability*	*Value table*
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)		

Controller coefficients empirical			*Controller quality with leakage*			*Stability*	*Value table*
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)		

- Which PID controller settings do you consider to be better?

  ____

- Close the flow control valve completely again.

- Investigate the effect of a pressure drop by setting a supply pressure of 45bar via the pressure relief valve.
- Establishing the limit of stability with pressure drop:

  K_{Pcrit} = ____________________

- Compare the control quality for the two controller settings
  - calculated using the Ziegler-Nichols method and
  - empirically determined.

Value table

Controller coefficients to Z.-N.			*Control quality with pressure drop*			*Stability*
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)	

Value table

Controller coefficients empirical			*Control quality with pressure drop*			*Stability*
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)	

- Which PID controller setting do you consider to be better?

  ____

Closed-loop hydraulics — *Subject*

Table feed of a milling machine — *Title*

Training aim

- To learn about the function of a displacement sensor
- To be able to record and evaluate the characteristic curve of a displacement sensor

Technical knowledge

A slide is to be moved to a specified position within a position control loop. The position of the slide is measured by means of a displacement sensor. Displacement sensors operate according to different physical principals. The displacement sensor used in this exercise is a linear potentiometer.

Linear potentiometer

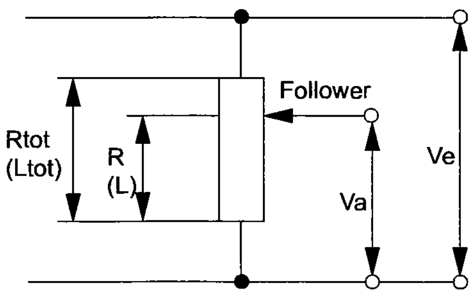
A linear potentiometer converts the physical "displacement" variable into an electrical voltage according to the principle of a voltage divider: the output signal V_a is tapped on an ohm resistance R_{tot} with the input voltage V_e at a given point via the resistance R:

$$V_a = V_e \cdot \frac{R}{R_{tot}}$$ Voltage divider formula

Since the resistance is proportional to length L of the potentiometer, this results in:

$$V_a = V_e \cdot \frac{L}{L_{tot}}$$

Resistance R changes by moving a slider across length L. This also changes the output voltage V_a, which is used as the measured value for the slide in the position control loop.



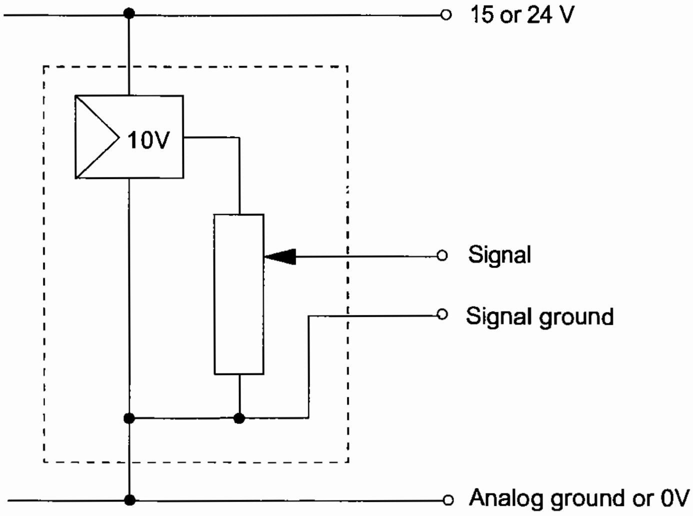
Ve = Inputvoltage
Va = Outputvoltage
Rtot = Total resistance
R = Partial resistance
Ltot = Total length
L = Follower position

Fig. A12.1: Voltage divider principle of linear potentiometer

The linear potentiometer used in this exercise has the following characteristics:

Supply voltage	*Measuring length (= input variable)*	*Output variable*
15V to 24V	200mm + 1mm	0V to 10V

Fig. A12.2: Electrical connection diagram of a linear potentiometer



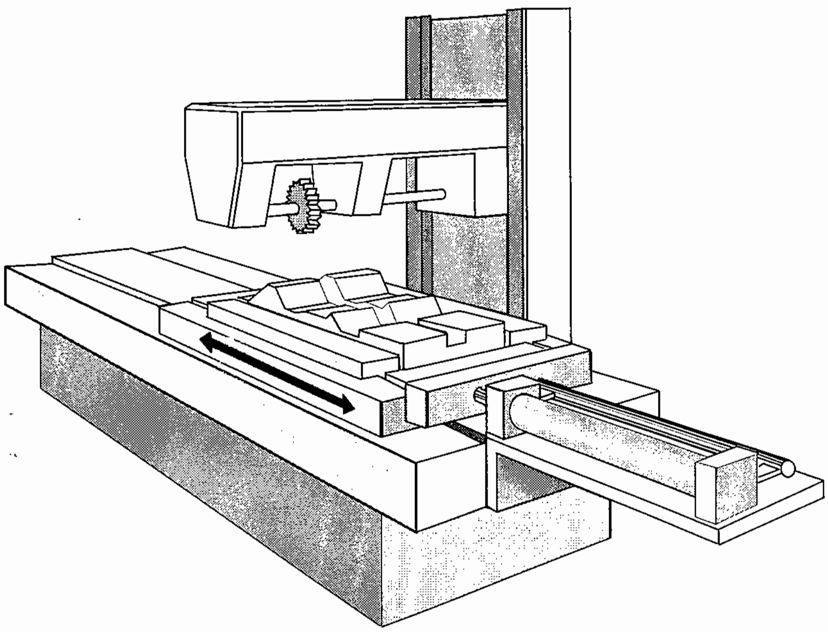
Linear unit

The displacement sensor is a preassembled linear unit. A follower is permanently connected to the slide. In this way, the displacement sensor can be tested by traversing the slide. A scale is to be attached parallel to the slide on the linear unit for comparison. The linear unit is hydraulically operated by means of a directional control valve and a double-acting cylinder. A detailed description is given in exercise 14.

Problem description

The feed axis of a milling machine is to be operated via a hydraulic position control loop. A displacement sensor is to be used for detecting the actual position. The characteristic curve of the displacement sensor is to be recorded as part of maintenance work.

Positional sketch



Exercise

Displacement sensor

1. Constructing a measuring circuit with hydraulic linear unit
2. Recording the characteristic curve of the displacement sensor
3. Deriving the characteristics of the displacement sensor from the measured values

Execution

1. Measuring circuit

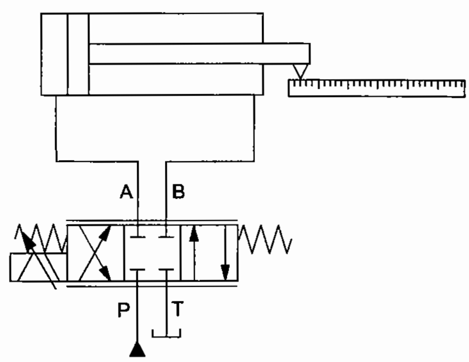
The following points must be observed for the measuring circuit:

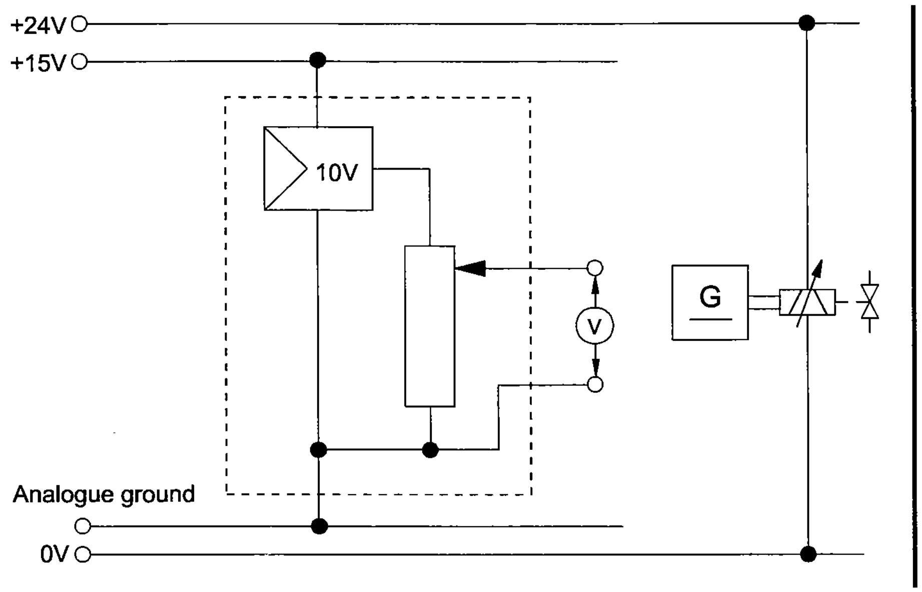
- The input variable for the displacement sensor is the slide position, which is measured by means of a scale graduated in millimetres. The scale is to be attached to the linear unit.
- The output signal of the displacement sensor (= V in volts) is measured by means of a multimeter.
- The displacement sensor is attached to the linear unit, hence this is to be assembled and securely attached as a complete unit.
- The linear unit is operated via a double-acting cylinder. A retracted piston rod represents the zero position.
- The double-acting cylinder is actuated via a dynamic 4/3-way valve with mid-position closed.
- The directional control valve is actuated via the voltage level set by means of a generator.
  The voltage levels are between - 10V and + 10V. With 0V, the valve is in mid-position.

Note

A certain amount of practice is required to be able to approach positions accurately via valve voltage. A simpler method would be to use a P controller with K_P = 10. This would, however pre-empt the next exercises. Hence this note.

Circuit diagram, hydraulic





Circuit diagram, electrical

2. Characteristic curve

The characteristic curve of the displacement sensor is created by recording the

- the output voltage V in volts via
- the length L in mm for the input variable.

3. Characteristics

The most important characteristic can be determined from the characteristic curve of the transfer coefficient K of the displacement sensor:

$$K = \frac{\text{Output}}{\text{Input}} = \frac{\Delta V}{\Delta L}$$

Within a closed control loop, the displacement sensor should be regarded as a P element with the amplification K; as such, it can be represented by means of a block symbol.

Additional criteria to be observed for evaluation are:

- Measuring range,
- Linear range,
- Hysteresis.

WORKSHEET

Displacement sensor

1. Measuring circuit

- Familiarise yourself with the equipment required for the circuit.

  - What are the characteristics of the displacement sensor

  Input range: ____________________

  Output range: ____________________

  Supply voltage: ____________________

  - Where is the displacement sensor built into the linear unit ________

  ____

- Attach the scale whilst observing the zero position.

  - How accurately can you read the positions from the scale? ________

  ____

  - What are the connections of the linear unit? ____________________

  - What are the connections of the 4/3-way valve? ____________________

- Construct the hydraulic and electrical circuit in accordance with the circuit diagrams.

Make sure that the linear unit is securely attached!

2. Characteristic curve

Risk of injury!
Make sure that no one is within the operating range of the slide prior to switching on!

- First of all, switch on the power supply.
- Set a valve voltage of e.g. - 10V on the generator to position the slide at an end stop.
- Switch on the hydraulic power pack.
- Check the signal flow of the circuit design and set this correctly by correcting the polarity of the signal lines.
- Practice the approaching of a position: Re-adjustment of the voltage generator controls the valve and causes the slide to move. Move the slide to and from once between the end stops and then to an intermediate position.
- Record the characteristic curve of the displacement sensor and enter the measured values in the value table.
- For safety's sake, do not approach the extreme end positions.

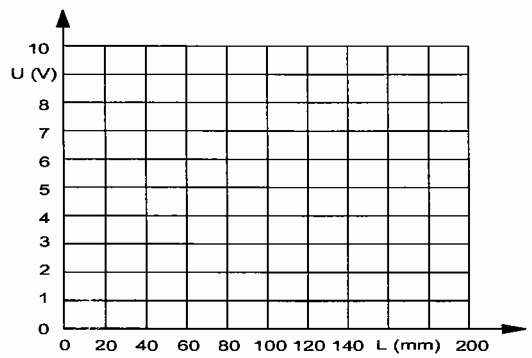
Value table

Measured variable and unit	*Measured values*							*Direction of measurement*
Length L in mm	*(0)*	*10*	*50*	*100*	*150*	*190*	*(200)*	
Voltage V in V								rising
Voltage V in V								falling

WORKSHEET

- Enter the characteristic curves of the displacement sensor in the diagram.

Diagram



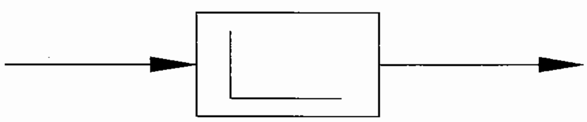
3. Characteristics

- Determine the transfer coefficient of the displacement sensor:

  K = ______________________

- Draw the displacement sensor as a block symbol identifying the input and output signals and the transition function.

Block symbol



- Evaluate the use of the displacement sensor within the framework of this equipment set. State your reasons with the help of the measuring results (e.g. relative to linear range and hysteresis):

Subject

Closed-loop hydraulics

Title

X/Y-axis table of a drilling machine

Training aim

- To understand the function of a dynamic directional control valve for flow control
- To be able to record the flow/signal characteristic curve
- To be able to demonstrate the effect of differential pressure and actuating signal
- To be able to calculate the characteristic data from standard diagrams

Technical knowledge

Flow control by means of a dynamic 4/3-way valve

Flow rates are to be determined by changing cross sections of the opening of the 4/3-way valve described in exercise 2. A full opening produces maximum flow rate. If the cross section of the opening is partially closed, then the flow rate is correspondingly reduced.

A reduced cross section of the opening represents a hydraulic resistance, which manifests itself in a differential pressure. The greater the flow passing through the same cross section, the higher the differential pressure.

Flow characteristic curves of a dynamic 4/3-way valve

The flow is dependent on two variables:

- the position of the valve spool set via the actuating signal, and
- the differential pressure created during the flow through the narrow section.

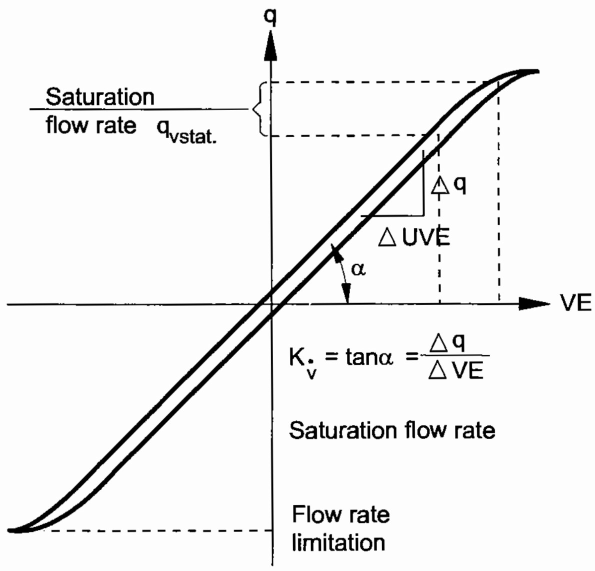
Two flow characteristic curves are thus created (see fig. A13.1):

- the flow/signal characteristic curve with constant differential pressure and
- the flow range/pressure characteristic curve with constant actuating signal.

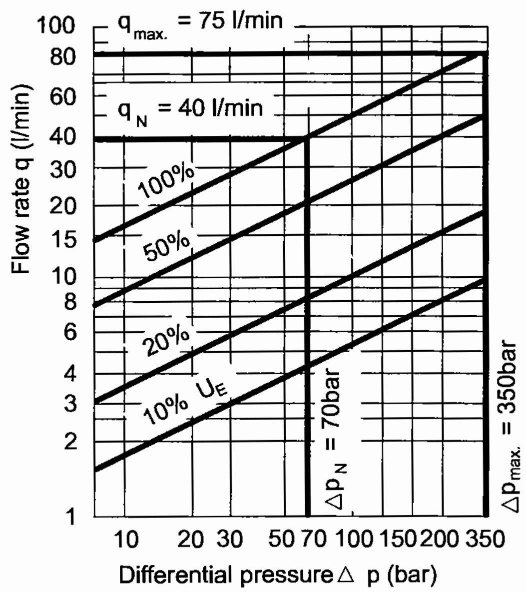
If several characteristic curves are entered in the diagram, then a set of curves are created (see fig. A13.1). This proves that the flow increases with the differential pressure and the actuating signal.

Fig. A13.1:
Flow characteristic curves of a dynamic directional control valve

a) Flow/signal characteristic curve



b) Flow/pressure characteristic curve



Characteristics of a dynamic 4/3-way valve

Flow/signal amplification

The slope of the flow/signal characteristic curve remains constant across a wide range of the actuating signal. The characteristic curve drops off slightly towards the ends, where the flow saturation q_{vsat} has been reached. The slope of the characteristic curve represents the flow/signal amplification:

$$K_V = \frac{\Delta q}{\Delta V_E} \quad \text{in} \quad \frac{\frac{l}{\min}}{V}$$

Overlap

The overlap can be read at the zero crossover of the flow/signal characteristic curve (see fig. A13.2):

- With overlap, the gradient remains constant.
- With positive overlap the slope is zero, i.e. there is a signal range with zero flow rate.
- With negative overlap, there is a flow rate in both directions.

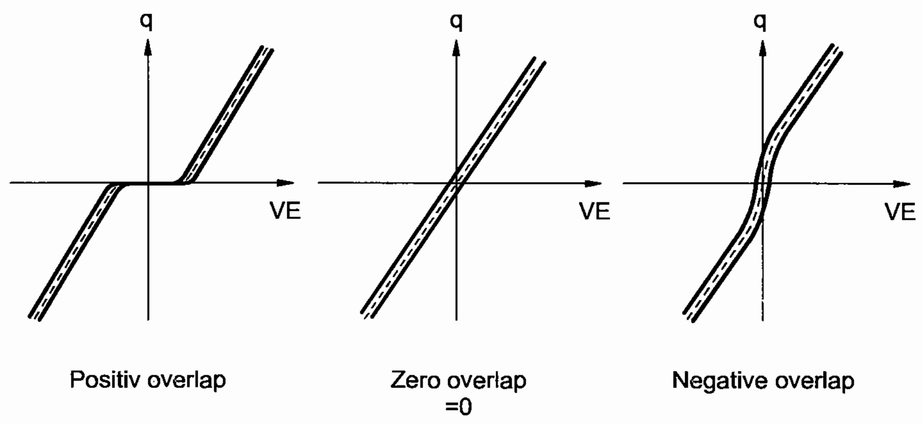


Fig. A13.2: Overlap in flow/signal characteristic curve of a dynamic directional control valve

Nominal flow rate

The nominal flow rate qN is the volumetric flow rate during

- maximum valve opening, i.e. also maximum actuating signal and
- nominal differential pressure.

Nominal differential pressure

According to DIN 24 311, the following is applicable for nominal differential pressure:

- 5bar per control edge with proportional valves and
- 35bar per control edge with servo valves.

Control edges

According to DIN 24 311, the flow rate must be measured via a control edge. The differential pressure is then e.g. $\Delta p_1 = p_0 - p_A$.

The differential pressure is often specified via two control edges, in which case working lines A and B are connected together. The differential pressure is then $\Delta p_2 = p_0 - p_T$.

Since the resistances are added together, double the differential pressure is obtained for an identical flow rate via two control edges.

Flow rate at the operating point

At the operating point, both the differential pressure and the actuating signal deviate from the nominal value. Assuming that the control edges can be regarded as sharp-edged orifices by approximation, the flow rate q can be calculated at any differential pressure Δp and any actuating signal V_E:

$$q = q_N \cdot \frac{V_E}{V_{Emax}} \cdot \sqrt{\frac{\Delta p}{\Delta p_N}}$$

Often, an actuating signal is also specified in percentages of V_{Emax}. The following then applies:

$$q = q_N \cdot \frac{V_{\%}}{100\%} \cdot \sqrt{\frac{\Delta p}{\Delta p_N}}$$

Nominal sizes of the directional control valve in question

Activating signal *V_{Emax}* *(= input variable)*	*Flow* *q_N* *(= output variable)*	*Differential pressure Δp_2* *across 2 control edges* *(= marginal condition)*
± 10V	5 l/min	70bar

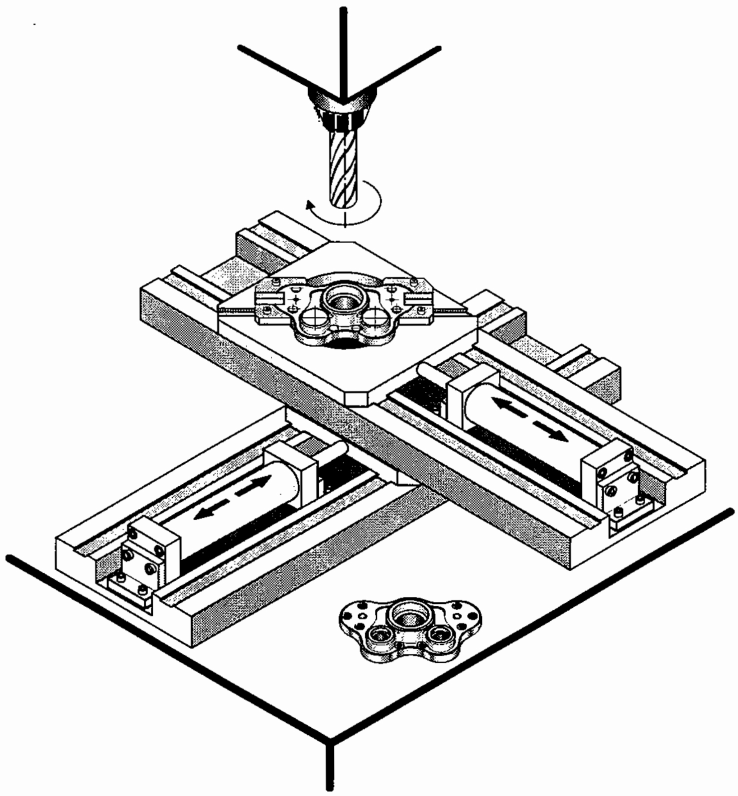
Problem description

A housing cover is to be machined on a drilling machine. Different positions are approached in automatic sequence for several drilled holes. This requires a position control via a dynamic directional control valve.

After a number of hours in operation, problems occur with regard to the clock pulse of the machining process. This means that the positioning process takes too long. Since the speed depends on the flow rate amongst other things, the flow characteristic curves are to be recorded.

The problem described above, can be due to different causes. In this instance, just one possibility is to be investigated as an example.

Positional sketch



Exercise

Flow characteristic curve of a dynamic 4/3-way directional control valve

1. Constructing and commissioning the measuring circuit
2. Recording the flow/signal characteristic curve
3. Deriving the flow/pressure characteristic curve
4. Comparison with the nominal data

Execution

1. Measuring circuit

The flow characteristic curves are to be recorded via a control edge; three variables must be measured for this:

- the control voltage V_E for input variable,
- the flow rate q_A for output variable and
- the differential pressure Δp_1 as a constant parameter.

The following devices are required:

- A generator for the control voltage V_E in the range of ± 10V.
- A flow measuring device for ± 5 l/min. In this instance, a hydromotor with tachometer is used (see measuring case). The universal display indicates the flow value directly in l/min.
- Two pressure sensors for the input pressure p_P and the pressure p_A at the working port.
- Several multimeters for the control voltage and the pressure sensors.
- Voltage supply 24V for the valve and the tachometer as well as 15V for the pressure sensors.
- In order to be able to maintain a constant differential pressure Δp_1 with different flow rates, the supply pressure p_P must be changed. A pressure relief valve is to be connected in the by-pass for this purpose.

☞ *The differential pressure can be maintained at a constant level automatically by means of a pressure control loop consisting of a further dynamic directional control valve and a P controller. This considerably reduces the time required to record the characteristic curves.*

This results in hydraulic and electrical circuits.

2. Flow/signal characteristic curve

Several steps are to be carried out to prepare the series of measurements:

1. Zero point setting:
   - Pressure relief valve open (supply pressure $p_P = 0$),
   - Valve in mid-position (control voltage $V_E = 0$).
2. Checking the signal direction: the flow rate q_A at output A must also increase with the increasing actuating signal V_E.
3. Checking the measuring range by re-adjusting the control signal across the entire range and measuring the flow rate by alternatively setting a higher and then a lower supply pressure to determine the differential pressure range.

Following this, the characteristic curve is recorded, whereby care should be taken that the measuring points are approached from the same direction.

Pressures p_P and p_A as well as the flow rate q_A are to be measured in relation to the actuating signal V_E. The differential pressure $\Delta p_1 = p_P - p_A$ is to be kept constant. A higher supply pressure p_P must be set with increasing flow q_A.

With small differential pressure, it is possible to record the entire characteristic curve. With differential pressure in excess of 20bar, the characteristic curve is broken off owing to the fact that pump power is being exceeded.

It is also useful to carry out a comparative measurement at output B in order to demonstrate that the course of the characteristic curve is symmetrical whereby deviations in flow values of 10% are permissible.

3. Flow/pressure characteristic curve

It is also possible to plot the flow/pressure characteristic curve from the measured values of the flow/signal characteristic curve, in which case the following applies:

- the differential pressure Δp_1 for input variable,
- the flow rate q_A for output variable and
- the control voltage V_E for a constant parameter.

4. Comparison with nominal data

The following nominal values are specified by the manufacturer:

- Nominal flow rate q_N = 5 l/min, at a
- Differential pressure via two control edges Δp_2 = 70bar and
- maximum actuating signal V_{Emax} = + 10V or - 10V.

A comparison between the measured values and the nominal values is made by means of the basic equation:

$$q = q_N \cdot \frac{V_E}{V_{Emax}} \cdot \sqrt{\frac{\Delta p}{\Delta p_N}}$$

whereby the number of control edges is to be taken into account.

The percentage deviation q_f between measured flow rate q_m and calculated flow rate q_r is:

$$q_f = \frac{q_m - q_r}{q_r} \cdot 100\%$$

Sample calculation:

- Actuating signal $V_{\%}$ = 50%, i.e. V_E = 5V, and
- Differential pressure via a control edge $\Delta p1$ = 20bar

produces:

$$q_r = q_N \cdot \frac{V_E}{V_{Emax}} \cdot \sqrt{\frac{\Delta p_1}{\Delta p_{1N}}}$$

$$q_r = 5\,\text{l/min} \cdot \frac{5V}{10V} \cdot \sqrt{\frac{20bar}{35bar}}$$

- Flow rate q_r = 1.9 l/min

This measuring point can be entered in the diagrams.

If the resulting measured flow rate is for example q_m = 2.0 l/min, then the deviation is

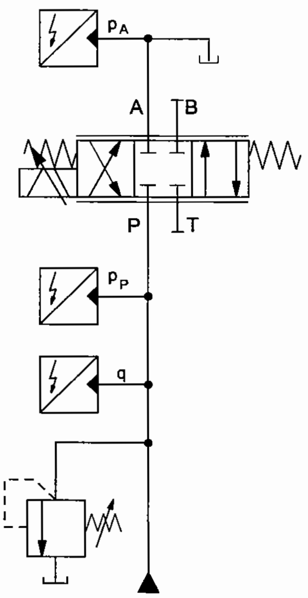
$$q_f = \frac{2.0\,\text{l/min} - 1.9\,\text{l/min}}{1.9\,\text{l/min}} \cdot 100\% = +5.3\%$$

WORKSHEET

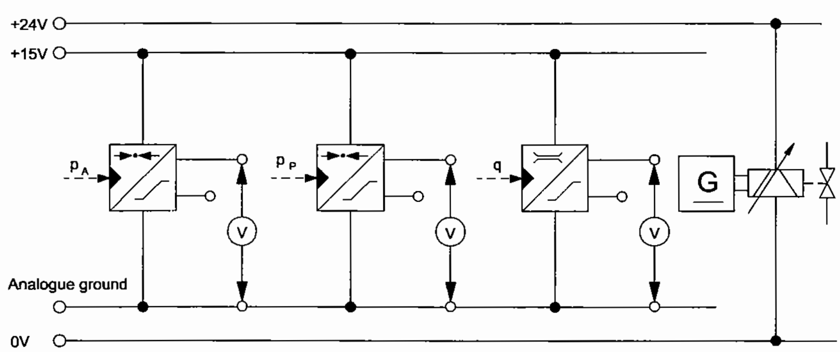
Flow characteristic curves of a dynamic 4/3-way valve

1. Measuring circuit

- The following are to be measured for the flow characteristic curve of a dynamic 4/3-way valve:
  - the flow rate q_A in supply,
  - the supply pressure at port P,
  - the working pressure p_A at output A,
  - the actuating voltage V_E.
- Construct the hydraulic and electrical circuits for this.



Circuit diagram, hydraulic



Circuit diagram, electrical

2. Flow/signal characteristic curve

Zero position

- Open the pressure relief valve completely.
- Set the directional control valve in mid position ($V_E = 0$).
- Check the sensor displays:

p_P = ______________________________

p_A = ______________________________

Δp_1 = ______________________________

q_A = ______________________________

Setting the pressure

- Slowly bring the pressure relief valve to a complete close.
  How do the pressure and flow rate change?

p_P = ______________________________

p_A = ______________________________

Δp_1 = ______________________________

q_A = ______________________________

Setting the actuating signal

- Increase the actuating signal to $V_E = 2V$.
  How do the sensor displays alter?

p_P = ______________________________

p_A = ______________________________

Δp_1 = ______________________________

q_A = ______________________________

WORKSHEET

Check the signal direction

- Check the signal directions on your circuit. Make sure that the flow rate q_A rises with the increasing actuating signal V_E.

Determining the measuring range

- Set a high supply pressure p_P.
  At which actuating signal V_E does the flow rate no longer change?

  V_{Elimit} = ______________________

  q_{Amax} = ______________________

- What is differential pressure Δp_1 now?

  Δp_1 = ______________________

- Record the flow/signal characteristic curve at port A.

Value table

Differential pressure Δp_1 = 5bar

V_E in V	*0*	*1*	*3*	*5*	*7*	*9*	*10*
q_A in l/min							
p_P in bar							
p_A in bar							

Differential pressure Δp_1 = 10bar

V_E in V	*0*	*1*	*3*	*5*	*7*	*9*	*10*
q_A in l/min							
p_P in bar							
p_A in bar							

Value table

Differential pressure Δp_1 = 20bar

V_E in V	0	1	3	5	7	9	10
q_A in l/min							
p_P in bar							
p_A in bar							

Differential pressure Δp_1 = 35bar

V_E in V	0	1	3	5	7	9	10
q_A in l/min							
p_P in bar							
p_A in bar							

- Record a characteristic curve at output B.

  Do the flow values q_B roughly coincide with output A?

  ____

Value table

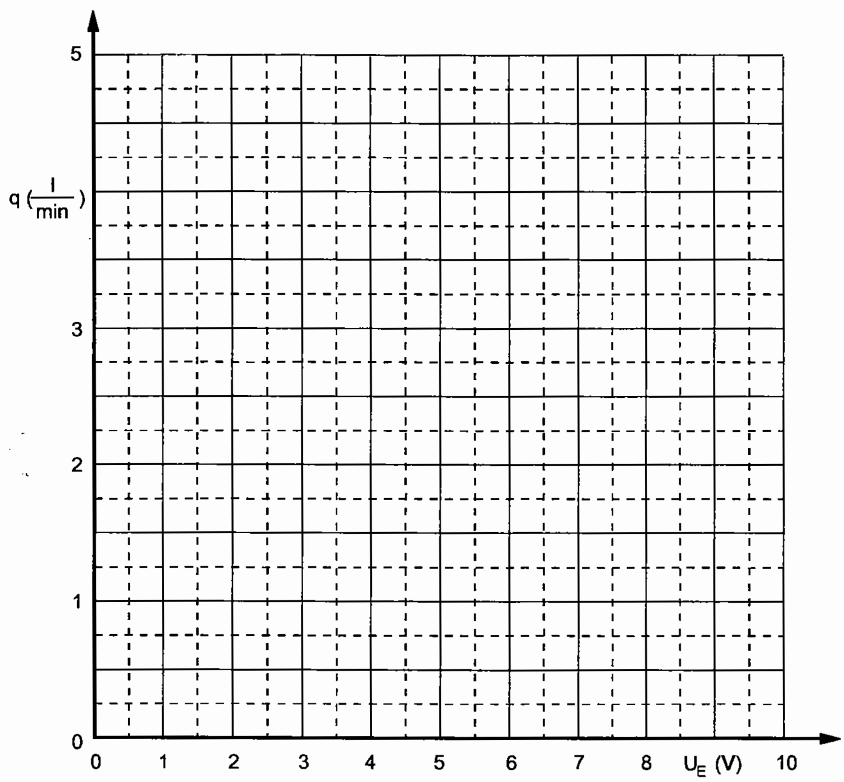
Differential pressure Δp_1 = 20bar

V_E in V	0	- 1	- 3	- 5	- 7	- 9	- 10
q_B in l/min							
p_P in bar							
p_B in bar							

WORKSHEET

■ Enter the flow/signal characteristic curves for output A in a diagram.

Diagram



■ Evaluate the characteristic curves by answering the following questions:

- What is the extent of the linear range?

____

- Can a hysteresis be detected?

____

- What is correlation between flow/signal amplification and differential pressure that can be seen from the diagram?

____

- Calculate the flow/signal amplification at Δp_1 = 35bar.

  K_V = ______________________________

3. Flow/pressure characteristic curve

- Convert the values table:

Value table

Activating signal V% = 100%, i.e. V_E = 10V

Δp_1 in bar	5	10	20	35
q_A in l/min				

Activating signal V% = 90%, i.e. V_E = 9V

Δp_1 in bar	5	10	20	35
q_A in l/min				

Activating signal V% = 70%, i.e. V_E = 7V

Δp_1 in bar	5	10	20	35
q_A in l/min				

Activating signal V% = 50%, i.e. V_E = 5V

Δp_1 in bar	5	10	20	35
q_A in l/min				

Activating signal V% = 30%, i.e. V_E = 3V

Δp_1 in bar	5	10	20	35
q_A in l/min				

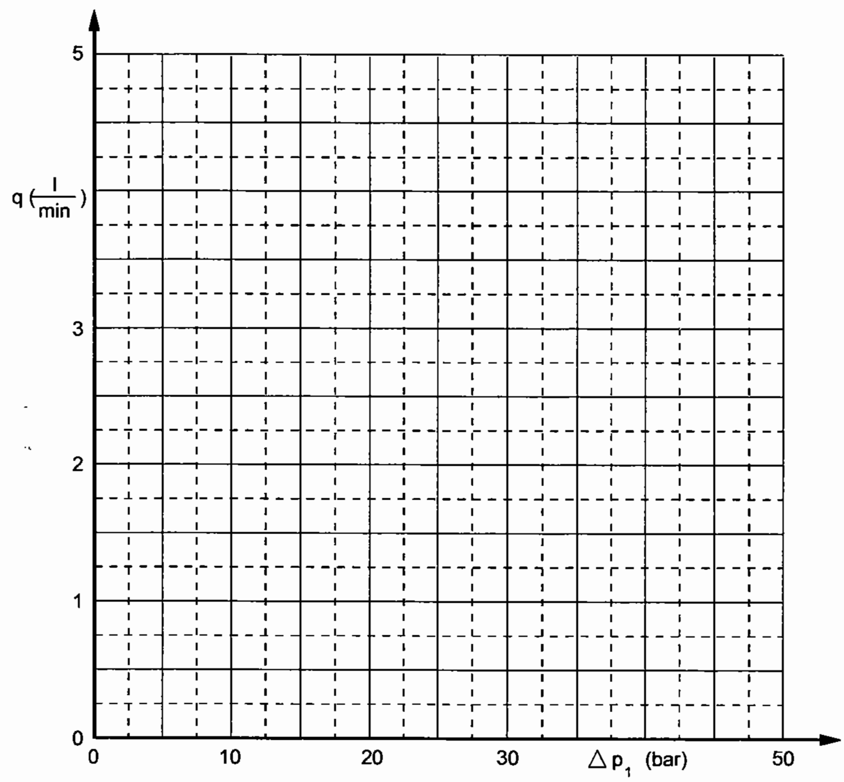
Activating signal V% = 10%, i.e. V_E = 1V

Δp_1 in bar	5	10	20	35
q_A in l/min				

WORKSHEET

- Enter the flow/pressure characteristic curve in the diagram.

Diagram



4. Comparison with nominal values

- What are the nominal values for the dynamic 4/3-way valve?

  Nominal flow rat q_N: ______________________

  Differential pressure Δp: ______________________

  Number of control edges: ______________________

  Actuating signal V_E: ______________________

- Can you enter the measuring point described by the nominal values in your diagram?

  ☐ Yes

  ☐ No

- Why is the measured value beyond the set of curves determined?

  ____

  ____

  ____

- Calculate the flow rate q_r for an actuating signal V_E in the linear range of the characteristic curves, e.g. at Δp_1 = 35bar and V_E = 30%.

  p_r = ______________________

- Draw the arithmetic value in a diagram.
- What is the flow rate q_A you have measured ?

  q_A = ______________________

- What is the deviation q_f resulting between the arithmetic and measured flow rate?

  q_f = ______________________

Subject

Closed-loop hydraulics

Title

Feed unit of an assembly station

Training aim

- To learn about the assembly and function of a linear unit
- To be able to describe the linear unit as a controlled system
- To be able substantiate the correlation between the hydraulic characteristics

Technical knowledge

Linear unit

The linear unit is made up of

- a traversable slide,
- two parallel longitudinal guides,
- a hydraulic linear cylinder and
- a displacement sensor.

Function and characteristics of a displacement sensor are described in exercise 12. In this exercise, it is intended as a measuring system for the actual position of the slide.

A hydraulic linear cylinder is to be used as a drive unit for traversing the slide and is actuated via a dynamic 4/3-way valve. The slide is to be moved to a position of your choice. This should be done as quickly and accurately as possible. A closed control loop is to be built to monitor the position, wherein the linear unit is to be regarded as a controlled system.

Important characteristics of this controlled system are:

- the course of the transition function and
- the controlled-system gain.

Transition function and controlled-system gain

The significance of the transition function or step response is already known from exercise 3. The speed of the slide can be read from the transition function and is to be regarded as an output variable of the closed control loop. It is dependent on the variable of the activating signal, which influences the directional control valve in the form of an input signal. This results in the ratio of

- velocity speed v
- actuating signal V_E.

This transition factor is described as controlled-system gain:

$$K_S = \frac{V}{V_E}$$

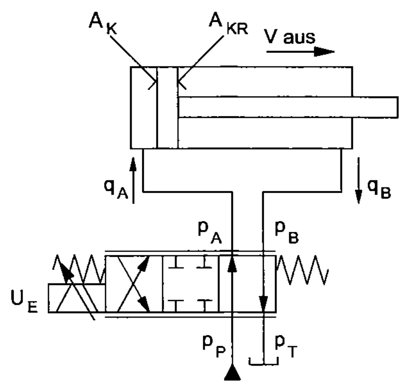


Fig. A14.1: Hydraulic circuit diagram of a controlled system

Table A14.1: System variables inside hydraulic circuit

Variable	*Symbol*	*Value / Formula*
Pump supply pressure	p_P	$= p_{max}$ = constant
Valve activating signal	V_E	$\leq V_{Emax}$
Flow valve, Inlet control edge	q_A	$= q_N \cdot \frac{V_E}{V_{Emax}} \cdot \sqrt{\frac{(p_P - p_A)}{\Delta p_N}}$
Working pressure inside cylinder	p_A	$= \frac{p_P}{1 + \left(A_K / A_{KR}\right)^3}$
Forward velocity of piston	v_{out}	$= \frac{q_A}{A_K} = \frac{q_B}{A_{KR}}$
Volumetric flow inside cylinder	q_B	$= q_A \cdot \frac{A_{KR}}{A_K}$
Back pressure inside cylinder	p_B	$= p_A \cdot \frac{A_K}{A_{KR}}$
Flow, valve, outlet control edge	q_B	$= q_N \cdot \frac{V_E}{V_{Emax}} \cdot \sqrt{\frac{(p_B - p_T)}{\Delta p_N}}$
Feedback pressure	p_T	≈ 0

Signal flow in the hydraulic circuit

The hydraulic circuit of the controlled system is illustrated in fig. A14.1. The table shows the arithmetic correlation between the variables in the circuit. This merely represents the fundamental requirements for extending of the cylinder. Load and friction have not been taken into account.

The arithmetic correlations are not required to carry out this exercise. To give you a better understanding, these are however explained in the following.

Constant pressure system

A constant pressure system should be used as a basis for a servo system:

- Within the operating range, the flow rate of the pump is greater than that of the valve:

  $q_p > q_{vmax}$

- The maximum pump supply pressure is:

  $p_P = p_{Pmax} = \text{constant}$

- A pressure drop is created via the control cross section of the valve, which results in a reduced flow rate:

  $$q_A = q_N \cdot \frac{V}{V_{max}} \cdot \sqrt{\frac{\Delta p}{\Delta p_N}}$$

- The piston area A_K produces a forward speed:

  $$v_{out} = \frac{q_A}{A_K}$$

- Due to the force equilibrium in the cylinder, the pressure on the piston side must be less than that on the piston rod side:

  $p_A < p_B$

- Hence the drop on the valve is greater during actuation of the piston side than during actuation of the piston rod side:

  $\Delta p_{out} = p_P - p_A$ and $\Delta p_{in} = p_P - p_B$ results in: $\Delta p_{out} > p_{in}$

- Thus, advancing from the greater differential pressure produces a greater flow rate:

  $q_{out} > q_{in}$

- The speed during advancing is greater than the speed during retracting (with an identical actuating signal):

$$v_{out} > v_{in}$$

Exactly the reverse effect can be observed with switching valves, which operate on the basis of a constant flow system:

- The pump supplies the maximum flow rate:

$$q = q_{max} = \text{constant}$$

- When the valve is reversed, the entire cross section of the opening is released: Full flow passes to the cylinder.

$$q = q_A = q_B = q_{max}$$

- The piston area A_K produces the forward speed:

$$v_{out} = \frac{q_A}{A_K}$$

- Since the annular area A_{KR} is smaller than the piston area, the retracting speed is less than the forward speed:

$$v_{in} = \frac{q_A}{A_{KR}} \quad \text{and} \quad A_{KR} < A_K \text{ results in: } v_{in} = v_{out}$$

Working pressure

The working pressure p_A is dependent solely on the pump pressure p_P and the area ratio of the cylinder: $\alpha = A_K / A_{KR}$

$$p_A = \frac{p_P}{1 + \alpha^3}$$

To complete the picture, the arithmetic deduction of this formula is to be described:

$$q_B = q_A \cdot \frac{A_{KR}}{A_K} = q_A \cdot \frac{1}{\alpha}$$

$$q_N \cdot \frac{V}{V_{max}} \cdot \sqrt{\frac{p_B}{\Delta p_N}} = q_N \cdot \frac{V}{V_{max}} \cdot \sqrt{\frac{p_P - p_A}{\Delta p_N}} \cdot \frac{1}{\alpha}$$

$$p_B = \frac{p_P - p_A}{\alpha^2}$$

With: $$p_B = p_A \cdot \frac{A_K}{A_{KR}} = p_A \cdot \alpha$$

the following applies: $$p_A \cdot \alpha = \frac{p_P - p_A}{\alpha^2}$$

$$p_A \cdot \alpha^3 = p_P - p_A$$

$$p_A = \frac{p_P}{1 + \alpha^3}$$

The following applies for retracting according to a similar process of calculation:

$$p_B = \frac{\alpha^3}{1+\alpha^3} \cdot p_P$$

Velocity

The velocity can also be calculated from the nominal variables and depends on:

- supply pressure p_P,
- working pressure p_A or area ratio a,
- the actuating signal V_E,
- the piston area A_K.

The following applies for the velocity during advancing:

$$v_{out} = \frac{q_A}{A_K} = \frac{1}{A_K} \cdot q_N \cdot \frac{V_E}{V_{Emax}} \cdot \sqrt{\frac{p_P - p_A}{\Delta p_N}}$$

$$v_{out} = \frac{q_N}{A_K} \cdot \frac{V_E}{V_{Emax}} \cdot \sqrt{\frac{p_P - \frac{p_P}{1+\alpha^3}}{\Delta p_N}}$$

$$v_{out} = \frac{q_N}{A_K} \cdot \frac{V_E}{V_{Emax}} \cdot \sqrt{\frac{p_P}{\Delta p_N} \cdot \frac{\alpha^3}{1+\alpha^3}}$$

The retracting velocity differs only in the case of cylinders of unequal areas:

$$v_{in} = \frac{1}{\sqrt{\alpha}} \cdot v_{out}$$

Controlled-system gain

The following ratio applies for controlled-system gain K_S between

- the velocity v for output variable and
- the actuating signal V_E for input variable.

The following then applies:

$$K_S = \frac{v}{V_E}$$

It is also possible to calculate the controlled-system gain from the characteristics using the above formulae:

Advancing $$K_{Sout} = \frac{q_N}{A_K \cdot V_{max}} \cdot \sqrt{\frac{p_P}{\Delta p_N} \cdot \frac{\alpha^3}{1+\alpha^3}}$$

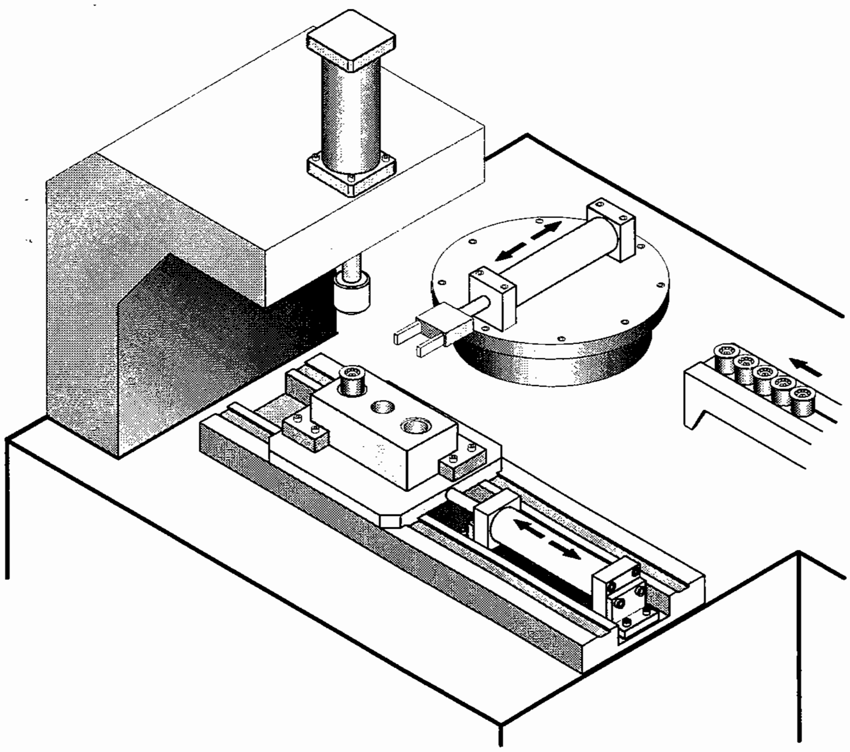
Retracting $$K_{Sin} = \frac{1}{\sqrt{\alpha}} \cdot K_{Sout}$$

Problem description

Several bearings are to be pressed into a housing on an assembly station. The bearings are supplied via a feed unit. The housing is positioned by means of a linear unit, which is operated within a position control loop.

After a number of hours in operation, the designated cycle time is no longer achieved. Therefore, the function of the linear unit is to be checked. To do this, the controlled-system gain is to be determined from the step response. In addition, the hydraulic characteristics of the controlled system are to be checked (pressure and flow rate). The values determined are to be compared with arithmetic results.

Positional sketch



Exercise

Linear unit as controlled system

1. Constructing the hydraulic and electrical measuring circuit
2. Recording the step response of the controlled system
3. Calculating the velocity and controlled-system gain
4. Recording the pressure characteristics and flow rate

Execution

1. Measuring circuit

In order to record a transition function,

- a step function (square-wave signal) is given as the actuating signal for the directional control valve (= input variable) and
- the step response recorded in the form of the change in the slide position x during the time t (= output variable).

In addition, the pressure characteristics in the operating cylinder and the flow are to be measured. This results in the following measured variables:

- pressures p_A and p_B, measured with pressure sensors,
- the supply flow rate q, measured by means of a flow sensor and
- the slide position x, measured with the displacement sensor of the linear unit.

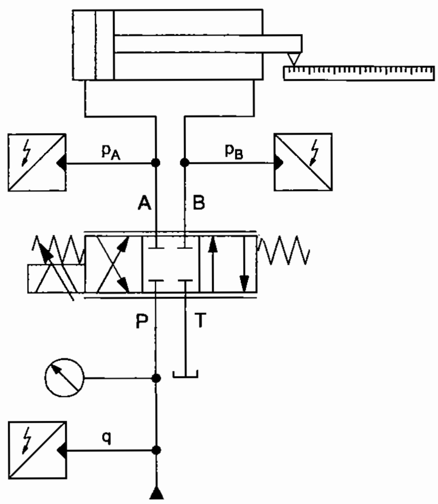
All measured variables are recorded on the oscilloscope over the time.

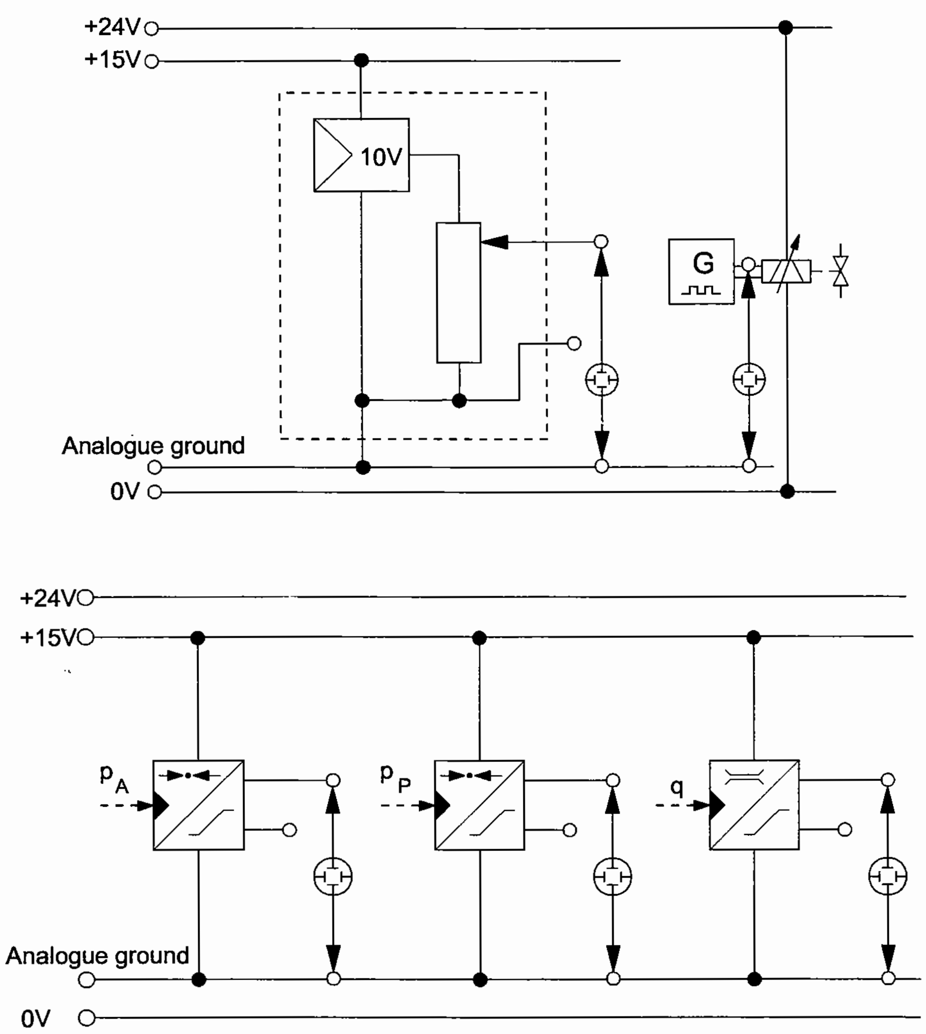
The step function of the actuating signal V_E is specified via the frequency generator.

It is useful to check the supply pressure p_P by means of a pressure gauge.

This results in the following hydraulic and electrical circuit diagrams.

Circuit diagram, hydraulic





Circuit diagram, electrical

2. Step response of the controlled system

The linear range of the circuit used here is limited (see exercise 13). In order to record the characteristics, it is therefore necessary to establish the linear range first.

The step response for $V_E = \pm$ 10V indicates the maximum speed possible with the available equipment set. With $V_E = \pm$ 9V the same characteristics are still achieved. Only when the setpoint step change is smaller than ± 8V is a linear correlation produced between actuating signal V_E and the velocity. It is therefore useful to record step responses, e.g. at $V_E = \pm$ 6V (60%) and $V_E = \pm$ 3V (30%).

3. Velocity and controlled system gain

The following is to be preset

- an actuating signal V_E in the linear range.

The following are to be measured

- Slide position x and
- Time t.

This results in the velocity v:

$$v = \frac{x}{t} \text{ in m/s}$$

The controlled-system gain K_S is then calculated from the velocity v and the actuating signal V_E

$$K_S = \frac{v}{V_E} \text{ in (m/s)/V}$$

Since a cylinder with dissimilar piston areas is used, this results in different speeds during advancing and retracting and therefore also different controlled-system gains.

To give an example, let us calculate the controlled-system gain during advancing from the nominal values:

Cylinder characteristics

Piston diameter:	$D = 16mm$
Rod diameter:	$d = 10mm$
Piston area:	$A_K = \pi/4 \cdot D^2 = 201mm^2$
Piston annular area:	$A_{KR} = \pi/4 \cdot (D^2 - d^2) = 122.6mm^2$
Area ratio:	$\alpha = \frac{A_K}{A_{KR}} = \frac{1.6}{1}$

Valve characteristics

Nominal flow rate:	$q_N = 5$ l/min
Nominal differential pressure:	$p_N = 35bar$
Control voltage:	$V_{Emax} = 10V$

Pump performance

Supply pressure: $p_P = 60bar$

Working pressure

$$p_A = \frac{p_P}{1 + \alpha^3} = \frac{60bar}{1 + 1.6^3} = 11.77bar$$

Forward speed at V_E= 3 V

$$v_{out} = \frac{q_N}{A_K} \cdot \frac{V_E}{V_{Emax}} \cdot \sqrt{\frac{p_P - p_A}{\Delta p_N}}$$

$$v_{out} = \frac{5l/min}{201mm^2} \cdot \frac{3V}{10V} \cdot \sqrt{\frac{60bar - 11.77bar}{35bar}} = 0.15m/sec$$

Controlled-system gain

$$K_{Sout} = \frac{q_N}{A_K \cdot V_{max}} \cdot \sqrt{\frac{p_P - p_A}{\Delta p_N}}$$

$$K_{Sout} = \frac{5l/min}{201mm^2 \cdot 10V} \cdot \sqrt{\frac{60bar - 11.77bar}{35bar}} = 0.55\frac{m/sec}{V}$$

The following applies to retracting according to this:

Working pressure

$$p_B = \frac{\alpha^3}{1+\alpha^3} \cdot p_P = \frac{1.6^3}{1+1.6^3} \cdot 60bar = 48bar$$

Retracting speed at V_E = 3 V

$$v_{in} = \frac{1}{\sqrt{\alpha}} \cdot v_{out} = \frac{1}{\sqrt{1.6}} \cdot 0.15m/sec = 0.12m/sec$$

Controlled-system gain

$$K_{Sin} = \frac{1}{\sqrt{\alpha}} \cdot K_{Sout} = \frac{1}{\sqrt{1.6}} \cdot 0.05\text{m/sec} = 0.04\text{m/sec}$$

4. Pressure and flow rate characteristics

To gain a better understanding of hydraulic parameters during travelling motions, it is useful to record the following characteristics during the step response:

- pressure characteristic of power ports, p_A and p_B, and
- flow rate q.

The established measured values are to be entered in a circuit diagram for the purpose of evaluation. The measured values enable you to calculate the differential pressures of the inlet control edges:

- Advancing: $\Delta p_{out} = p_P - p_{Aout}$
- Retracting: $\Delta p_{in} = p_P - p_{Bin}$

The actuating signal V_E results in two operating points:

- during advancing: Δp_{out}, q_{out}, V_E
- during retracting: Δp_{in}, q_{in}, V_E

These operating points may be entered in the flow characteristic curves (solution for A13).

WORKSHEET

Linear unit as controlled system

1. Measuring circuit

The hydraulic linear unit is to be actuated by means of a dynamic 4/3-way valve.

Preset is

- a step-change actuating signal V_E.

To be measured are:

- Step response: $x(t)$
- Operating pressures: p_A and p_B
- Supply pressure: p_P
- Flow rate: q

- Construct the hydraulic and electrical circuit in accordance with the circuit diagrams.

Make sure that the test set-up and in particular the linear unit are securely attached to a sturdy base!

2. Step response of controlled system

Risk of injury!
Make sure that no one is within the operating space of the slide during the following tests!

- Set the actuating signal V_E = 0V after the hydraulic and electrical power has been switched on.

  What are the measured values shown?

  p_A = ____________________

  p_B = ____________________

  p_P = ____________________

  q = ____________________

  x = ____________________

- Change the actuating signal V_E slightly.

  How does the slide position change ______________________

- Set the circuit in such a way that the slide advances with an increasing, positive actuating signal, i.e.:

  V_E rises ⟶ x rises.

- Move the slide into mid-position.
- Record the step response with the following settings:

  V_E = ± 10V, 0.2Hz, square signal

  x = 2 V/Div

  t = 0.5 s/Div

- What time behaviour can you derive from this transition function?

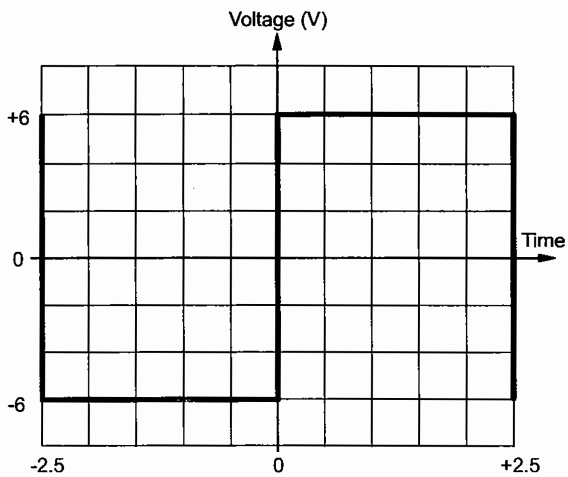
  ____

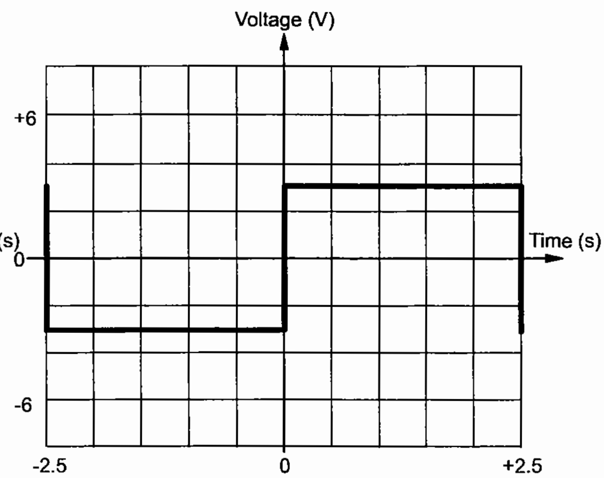
- Reduce the amplitude of the actuating signal V_E and record the transition function for:

  V_E = 6V and

  V_E = 3V.

Diagram





WORKSHEET

3. Velocity and controlled-system gain

- Calculate the velocity v and the controlled-system gain K_S from the measured values during advancing and retracting.

$V_E = \pm 6V$ and x = ______________________________ mm

Value table

Linear unit	*Time t*	*Velocity v*	*Gain K_S*
Advancing			
Retracting			

$V_E = \pm 3V$ and x = ______________________________ mm

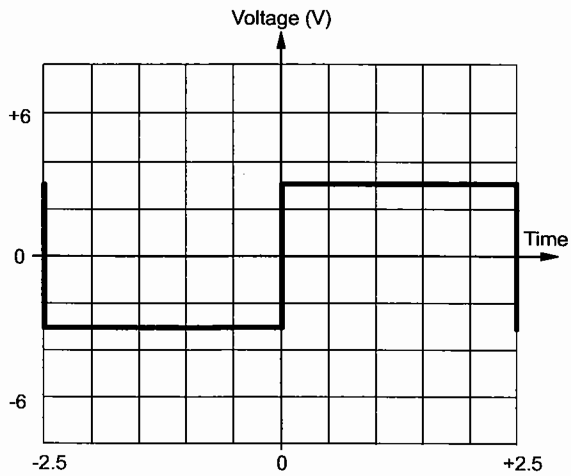
Value table

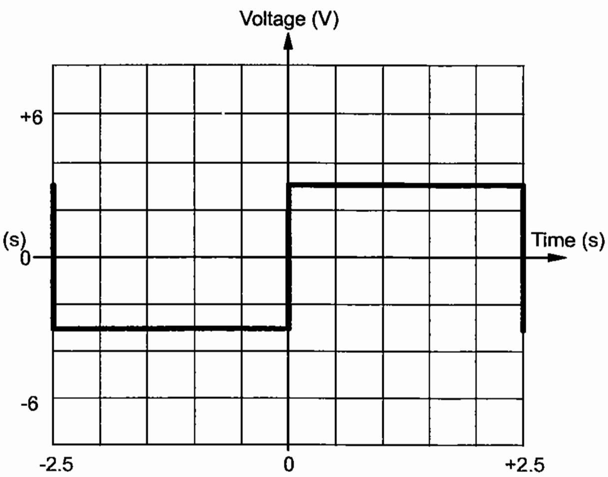
Linear unit	*Time t*	*Velocity v*	*Gain K_S*
Advancing			
Retracting			

4. Pressure and flow rate characteristics

- Set $V_E = \pm 3V$.
- Record the time characteristics of working pressures p_A and p_B.

Diagram





- Create a value table with flow rate q and supply pressure p_P during advancing and retracting.

Value table

Linear unit	*Pressure p_A*	*Pressure p_B*	*Pressure p_P*	*Flow q*
Advancing				
Retracting				

- Calculate the differential pressure at the inlet control edges during advancing and retracting from the value table:

  Advancing: Δp_{out} = ____________________

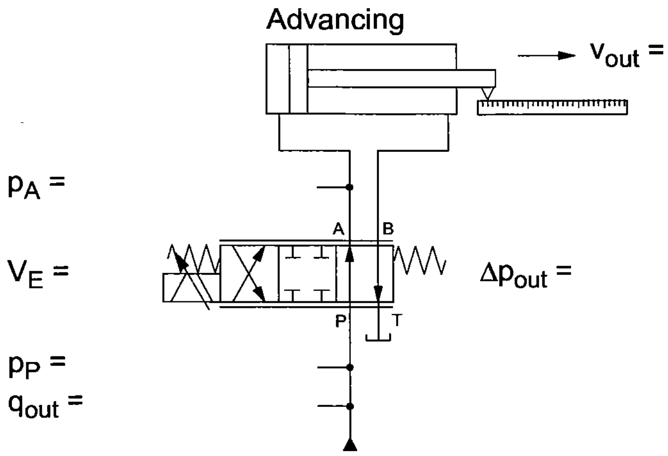
  Retracting: Δp_{in} = ____________________

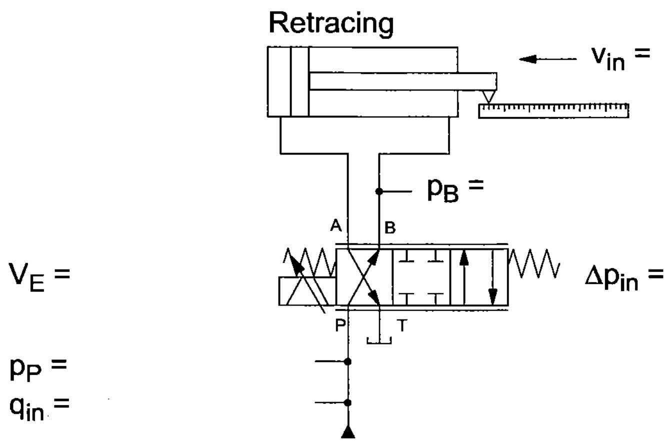
- What correlation can you detect between differential pressure and flow rate?

  ____

WORKSHEET

- Enter the determined measured values in the circuit diagrams, both for advancing and retracting.





- Enter the two operating points in the flow characteristic curves (C13).
- Which operating point has the higher flow rate/signal gain?

____

- Are the operating points within the tolerance range of ± 10% of the flow/pressure characteristic curve with V_E = 30%?

____

Closed-loop hydraulics — *Subject*

Automobile simulator — *Title*

Training aim

- To be able to describe a position control loop using block symbols
- To be able to construct and commission a position control loop
- To be able to measure and calculate fundamental characteristics

Technical knowledge

Position control loop

A position control loop consists of:

- a directional control valve as a final control element,
- a linear drive as a controlled system element,
- a displacement sensor as feedback for the controlled variable,
- and a controller.

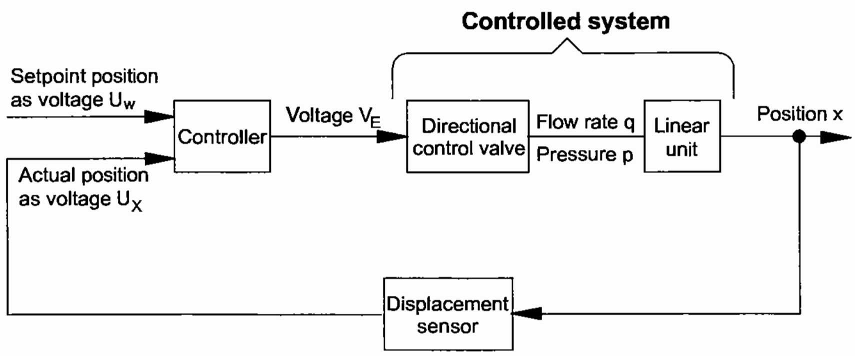


Fig. A15.1:
Elements in a
closed control loop

The representation of the controlled system using block symbols is illustrated in fig. 15.2. The controlled system consists of a final control element and a controlled system element, i.e. a directional control valve and a linear drive. The block symbols represent the time behaviour of the individual elements. Moreover, a description is given of the physical variables at the input and output of the elements and the equations for linking the physical variables.

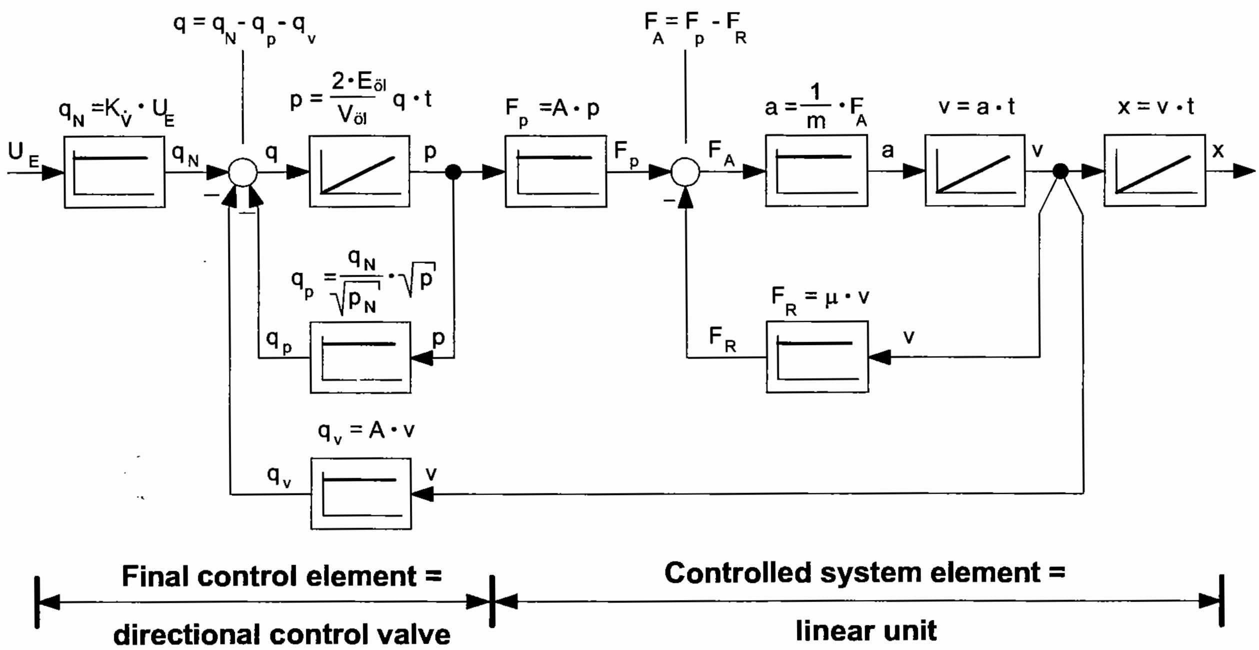


Fig A15.2:
The controlled system in block symbols with physical fundamental equations

Symbols

V_E	Control signal	F	Force
q	Flow (volumetric flow rate)	A	Area
K_V	Flow gain	m	Load
p	Pressure	μ	Friction coefficient
E_{oil}	Elasticity module of hydraulic oil	a	Acceleration
V_{oil}	Volume of hydraulic oil	v	Velocity
t	Time	X	Displacement (position)

Fundamental equations:

Flow/signal characteristic curve: $q_N = K_V \cdot V_E$

Elasticity of oil: $p = \frac{2 \cdot E_{oil}}{V_{oil} \cdot q \cdot t}$

Orifice equation: $q = q_N \cdot \sqrt{\left(\frac{p}{p_N}\right)}$

Flow rate equation: $q = A \cdot v$

Pressure transference: $F = A \cdot p$

Mass acceleration: $F = m \cdot a$

Sliding friction: $F = \mu \cdot v$

Equations of motion: $v = \frac{x}{t}$ and $a = \frac{v}{t}$

The transition function of the controlled system shows that this is a system without compensation. A P controller is suitable for systems of this type. Equally, a PD controller can be used.

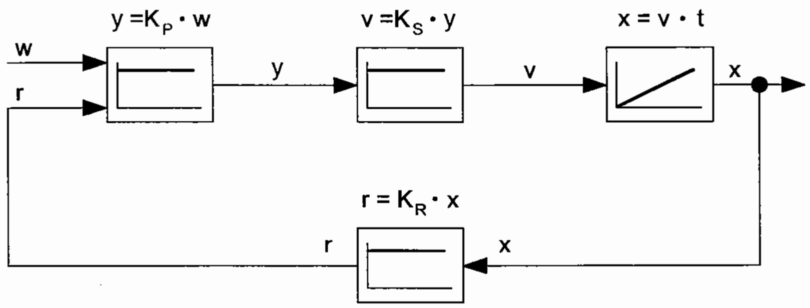


Fig. A15.3: Closed-loop gain V_0 in position control loop

$$V_0 = K_P \cdot K_S \cdot K_R$$

K_P	Gain factor of P controller
K_S	Gain factor of controlled system
K_P	Transfer coefficient of feedback
V_O	Closed-loop gain

Closed-loop gain

Fig. A15.3 represents the time behaviour of the position control loop using a P controller. The closed-loop gain V_0 describes the response to setpoint changes of this closed control loop. This means:

- that with a change in the reference variable w at the output
- a corresponding change occurs in the controlled variable x at the output.
- The correlation is described by the

$$\text{Closed-loop gain } V_0 = \frac{\text{Output variable}}{\text{Input variable}}$$

Strictly speaking, the feedback variable r is present at the end of the closed control loop, hence

$$V_0 = \frac{r}{w}$$

The output variable is formed by the input variable passing through all the elements of the closed control loop. The following therefore applies:

$$r = w \cdot K_P \cdot K_S \cdot t \cdot K_R = w \cdot K_P \cdot K_S \cdot K_R \cdot t$$

resulting in:

$$\frac{r}{w} = K_P \cdot K_S \cdot K_R \cdot t = V_0 \cdot t$$

The closed-loop gain V_0 is therefore:

$$V_0 = K_P \cdot K_S \cdot K_R \qquad \text{in} \qquad 1/s$$

Quality criteria for a position control loop

The purpose of position control is to approach a position x as speedily and accurately as possible. A brief settling time T_a and minimal system deviation e_{stat} is therefore required, whereby stability, i.e. no oscillations, are a prerequisite. A further, and often even more important prerequisite is for the position not to be overtravelled, i.e. no oscillations whatsoever must occur!

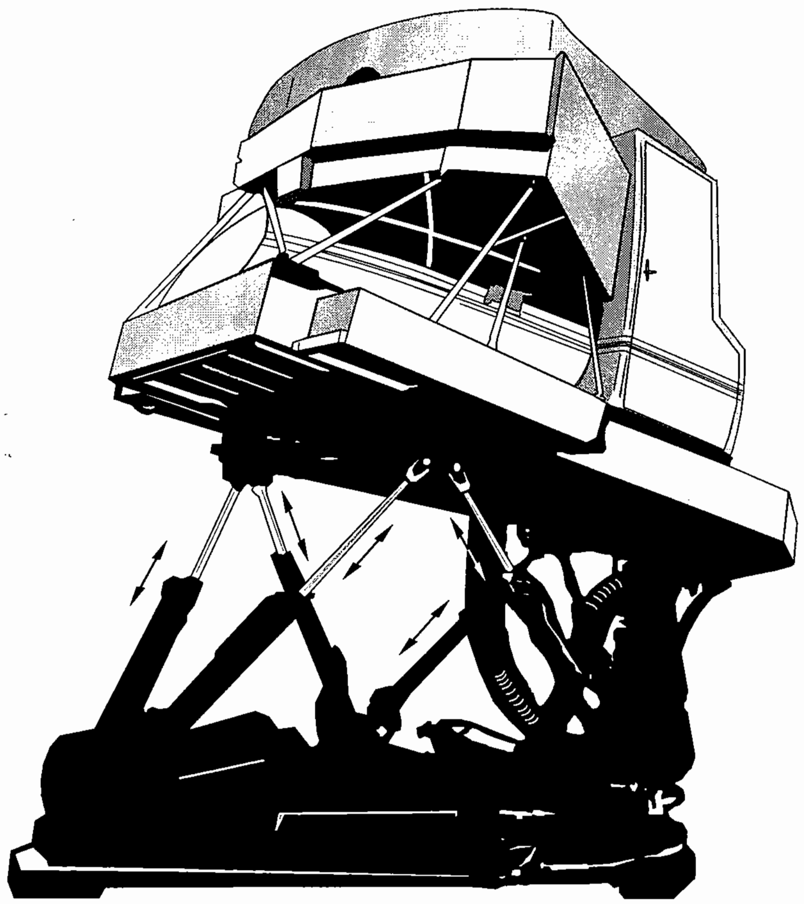
The following resulting quality criteria are listed in order of priority:

1. no oscillation: $x_m = 0$
2. Stability (no steady-state oscillation): $K_P < K_{Pcrit}$
3. minimum system deviation: e_{stat} within tolerance
4. minimum settling time: T_a within cycle time

Problem description

The cabin of an automobile simulator rests on several cylinder supports. In order to be able to change the position of the cabin as required, it must be possible to randomly position the cylinder supports. To achieve this, each cylinder is to be equipped with a position control loop. A position control loop is to be constructed and commissioned.

Positional sketch



Exercise

Position control loop

1. Constructing a position control loop electrically and hydraulically
2. Checking the control direction and setting the offset
3. Recording the transition function and setting parameters using the empirical method
4. Calculating the closed-loop gain
5. Verifying the positional dependence of the limit of stability
6. Testing other closed-loop controllers

Execution

1. Constructing the position control loop

The position control loop consists of:

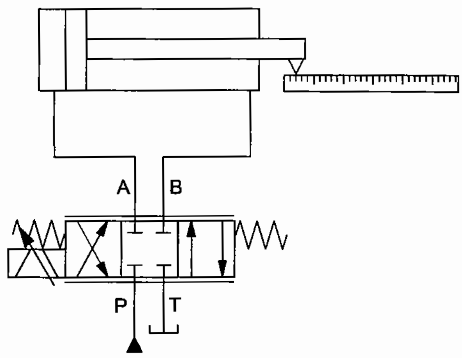
- a dynamic directional control valve — as a final control element,
- a linear drive — as a controlled system,
- a displacement sensor — for feedback,
- a P controller — as a control

In order to record the transition function,

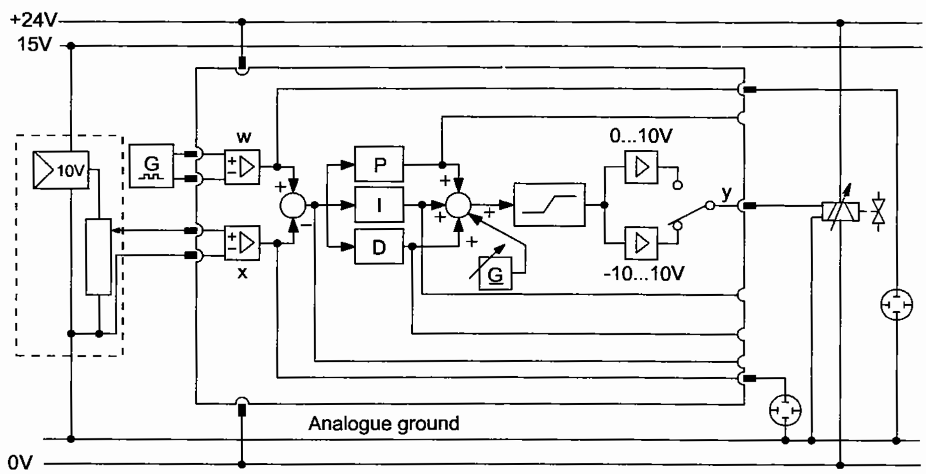
- a step function is specified as setpoint value via the function generator and
- the step response recorded on the oscilloscope.

This results in the following circuit diagrams.

Circuit diagram, hydraulic



Circuit diagram, electrical



2. Control direction and offset

The initial position is to be a position of the slide in the middle of the operating path. Thus,

- the setpoint value is w = 5V = 100mm.
- The control parameters are all set to zero, as is the offset.

The slide moves into the zero position, after the power supply has been switched on. Then, the control direction is checked. To do this,

- K_P = 1 is set and the slide moves into the mid position.

Re-adjustment of the setpoint value ensures that the slide advances with increasing setpoint value. Once these conditions have been met, the control direction is correct. Otherwise, the polarity of these connections must be reversed.

The slide is then moved to the mid position. Should a drift occur, then this is eliminated by means of setting the offset. The slide is to remain stationary with a constant setpoint value.

3. Transition function and empirical parameterisation

The step function of the setpoint value is to be in the middle of the transfer range and at a sufficient distance to the end stops. Also, for instance

- setpoint value w = 5V ± 3V (= 100mm ± 60mm) as square wave signal

In this instance, the parameters must be set empirically, i.e. by

- changing of K_P and
- measuring and comparing the quality criteria.

The Ziegler-Nichols setting rules cannot be used here, as these do not apply to this type of system. Note

4. Closed-loop gain

K_{Pcrit} enables you to calculate the maximum closed-loop gain V_{0max} of the position control loop:

$$V_{0max} = K_{Pcrit} \cdot K_S \cdot K_R \quad \text{in } 1/s$$

K_{Pcrit}	amplification gain of P controller with limit of stability
$K_S = 0.05 \ \frac{m/s}{V}$	Closed-loop gain
$K_R = 50$ V/m	Transfer coefficient of feedback

5. Positional dependence of limit of stability

A setpoint step-change totalling 6V in total produces a large range of constant velocity. The valve is completely open in this range and no adjustments are made via the controller. The effective signal range of the controller is in fact, much smaller:

1. The maximum possible actuating signal is $V_{Emax} = 10V$.
2. At e.g. $K_P = 20$ a setpoint step-change of $w = 0.5V$ is sufficient to create a control signal $y = V_E = 10V$.

As such, a setpoint step-change of ± 0.5V already demonstrates the effectiveness of the controller. The setpoint step-change of ± 0.5V corresponds to a setpoint position value of ± 10mm. If the mean value of this setpoint value is moved beyond the operational path of the slide, then this illustrates that the limit of stability K_{Pcrit} is dependent on the slide position.

6. Other controllers

The following controllers are recommended for uncompensated systems:

- P controller,
- PD controller,
- triple loop status controller.

The combination of closed-loop controller and system can be optimised using the empirical method in this case by endeavouring to improve the quality criteria by means of different controller types. The use of a status controller is described in exercise 20.

WORKSHEET

Position control loop

1. Constructing a position control loop

- Construct the closed control loop in accordance with the circuit diagrams.

Make sure that the test set-up and in particular the linear unit are securely attached to a sturdy base!

2. Control direction and offset

- Set all controller parameters and the offset to zero.

Danger of injury!
Prior to switching on make sure that no one is within the operating range of the slide!

- The slide moves to an end stop after the power supply has been switched on.

  Is this really the zero position? ____________________

- Set a setpoint value w = 5V and the controller gain $K_P = 1$.

  Does the slide move to a mid position? ____________________

- Break the closed control loop by not connecting the measuring system to the controller.

  To which position does the slide move? ____________________

- Slowly alter the reference variable w.

  Does the following condition apply: + w equals + x? ____________

  If "yes", then the control direction is correct.

  If "no", then correct the control direction by setting the correct polarity of reference variable w and correcting variable y.

- Set the reference variable w = 0V and close the closed control loop by connecting the measuring system to the controller card.

  To which position does the slide move?____________________

- Check the effects of the following polarity reversals:

Polarity reversal	*Change of controlled variable x with increasing reference variable w*
Reference variable w	
Correcting variable y	
Feedback r	

- Set the closed control loop correctly.
  Set a reference variable of w = 5 V.

  What effect does the re-adjustment of offset have? ______________

  ____

3. Transition function and empirical parameterisation

- Set a setpoint step-change of w = 5V ± 3V, f= 1Hz.
  Set the following scales in the oscilloscope:

Time t:	0.1 s/Div
Reference variable w:	1 V/Div
Controlled variable x:	1 V/Div

  Frequency and time scales are to be adjusted if the settling time is too long.

- Record the transition function with different controller gains K_P and evaluate the quality criteria relative to
  - Overshoot amplitude x_m
  - Settling time T_a
  - System deviation e_{stat}
  - Stability

WORKSHEET

Value table

K_P	x_m	T_a	e_{stat}	*stable/unstable*	*Evaluation*
1					
5					
10					
20					
30					
40					
50					
55					
63					

- What is the value determined for optimum controller gain?

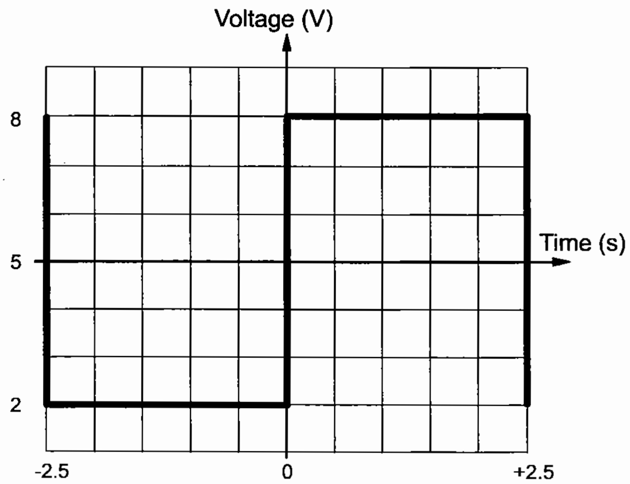
  K_{Popt} = ____________________

- Where does the limit of stability lie?

  K_{Pcrit} = ____________________

- Record the transition function at K_{Popt}.

Diagram



4. Closed-loop gain

- Calculate the maximum closed-loop gain V_{0max} and the closed-loop gain V_{0opt} with optimum parameterisation.

V_{0max} = ______________________________

V_{0opt} = ______________________________

5. Positional dependence of limit of stability

- Set a setpoint step-change of w = 1.5V ± 0.5V at 1Hz.
  Select the following scales on the oscilloscope:

Time t:	0.1 s/Div
Reference variable w:	0.2 V/Div
Controlled variable x:	0.2 V/Div

- Transfer the mean value of the setpoint step-change step gradually across the entire transfer range of the slide. It is not possible to display the step responses on the oscilloscope within the above selected scaling. You should therefore establish K_{Pcrit} by observing the slide.

Value table

w ± 0.5V	*K_{Pcrit}*	*Evaluation*
1.5V		
2.5V		
3.5V		
4.5V		
5.5V		
6.5V		
7.5V		
8.5V		

WORKSHEET

- Mark the maximum and minimum critical gain.
- In which sections of the transfer range is the stability greatest?

____

- In which section of the transfer range is the stability at its lowest?

____

6. Other controllers

- Set a setpoint step-change of w = 1.5V ± 0.5V.
  Select the following scales on the oscilloscope:

  Time t: 0.1 s/Div
  Reference variable w: 0.2 V/Div
  Controlled variable x: 0.2 V/Div

- Set $K_P = K_{Popt}$, and examine whether the quality criteria could be met more effectively by using a different controller combination of the PID controller card.

PI controller

Value table

K_{Popt}	K_I	x_m	T_a	e_{stat}	*stable/unstable*	*Comment*

PD controller

Set K_{Popt}. Now add an increasing D-element.

Value table

K_{Popt}	K_D	x_m	T_a	e_{stat}	stable/unstable	Comment

PID controller

Set K_{Popt}. Now add increasing I and D elements.

Value table

K_{Popt}	K_D	K_I	x_m	T_a	e_{stat}	stable/unstable	Comment

Closed-loop hydraulics — *Subject*

Contour milling — *Title*

Training aim

- To learn about a follower control system
- To be able to calculate a lag error
- To be able to measure a lag error

Technical knowledge

Follower control system

The purpose of a position control system is not just to position a slide. Often, it is even more important to maintain a specific feed speed, in which case a continuously increasing setpoint value is specified. The control task is then to adapt the actual value to the time characteristics of the setpoint value, whereby the actual value follows the setpoint value with a certain time delay, i.e. the actual value lags behind the setpoint value. This is why closed loop controls of this type are known as follower control systems or servo control system.

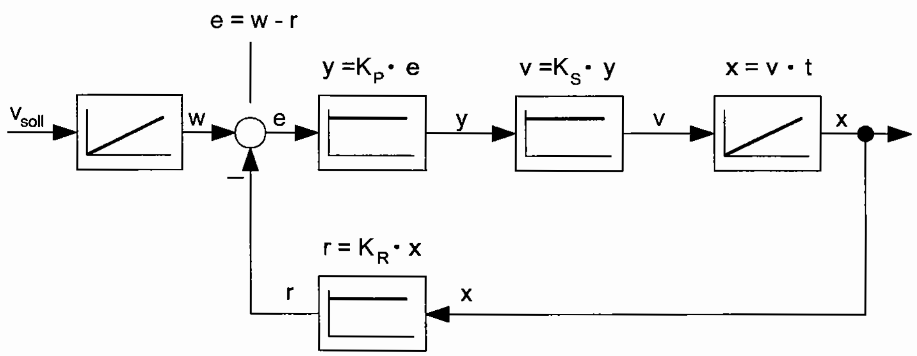


Fig. A16.1: Closed control loop for follower control system

v_{soll}	Setpoint velocity	K_S	System gain
t	Time	v	Velocity
w	Reference variable	x	Controlled variable
e	System deviation	K_R	Transfer coefficient of feedback
K_P	Gain of p controller	r	Feedback variable
y	Correcting variable		

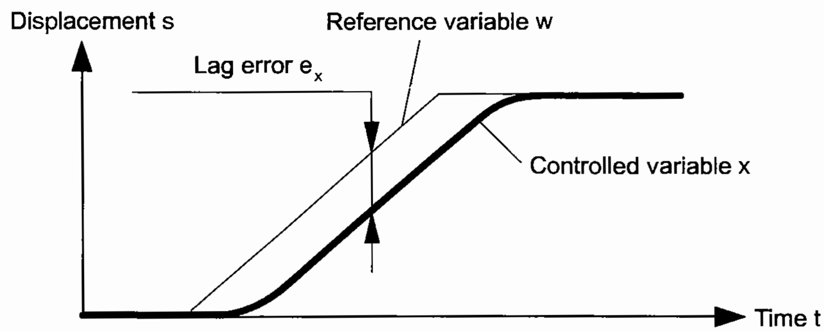
Lag error

If a constant speed is specified as setpoint value

- the actual speed is in fact adapted to the setpoint speed.
- There is, however, still a system deviation. This is equivalent to a position deviation, which is known as lag error or following error.

Fig. A16.2 illustrates the displacement-time diagram of a follower control system with constant setpoint input. The mathematical correlations are given below as an explanation.

Fig. A16.2: Lag error with constant feed velocity



Lag error: $e_x = w - x = \text{const.} > 0$

Setpoint velocity: $v_{soll} = \Delta w / \Delta t = \text{const.}$

Actual velocity: $v_{ist} = \Delta x / \Delta t = v_{soll}$

Calculating the lap error

A lag error can be calculated from the characteristics of the closed control loop (see fig. A16.1). The following applies for a closed control loop:

$$\Delta x = e \cdot K_P \cdot K_S \cdot \Delta t$$

$$e = \frac{1}{K_P \cdot K_S} \cdot \frac{\Delta x}{\Delta t} = \frac{v}{K_P \cdot K_R}$$

The system deviation e (in V) is converted into a lag error e_x (in mm) with the transfer coefficient of the feedback K_R

$$e_x = \frac{e}{K_R} = \frac{v}{K_P \cdot K_S \cdot K_R}$$

The closed-loop gain $V_0 = K_P \cdot K_S \cdot K_R$ produces the fundamental equation for the lag error:

$$e_x = \frac{v}{V_0}$$

Influences acting on the lag error

As shown by the fundamental equation, the lag error ex is dependent on

- the setpoint velocity v_{set} and
- the closed-loop gain V_0.

As the velocity increases, the lag error becomes larger. If the setpoint velocity is to great, closed-loop control can no longer follow. The setpoint velocity is then no longer reached.

The lag error is reduced as a result of high closed-loop gain V_0. Since the closed-loop gain is directly influenced by the controller gain K_P, a high closed-loop gain also reduces the lag error. The maximum increase of the controller gain is however only possible up to the limit of stability at K_{Pcrit}.

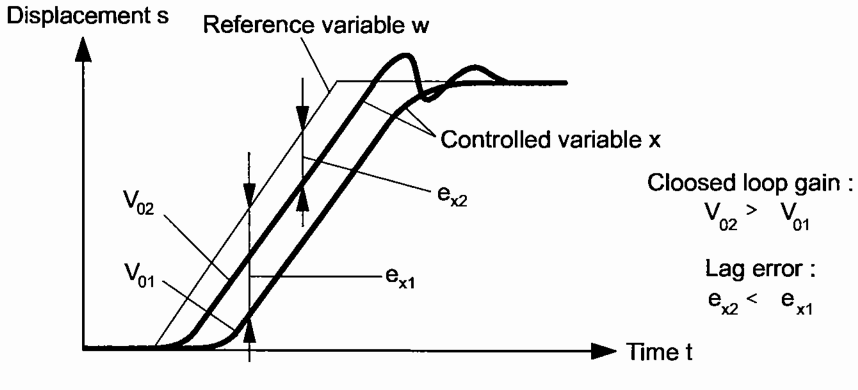
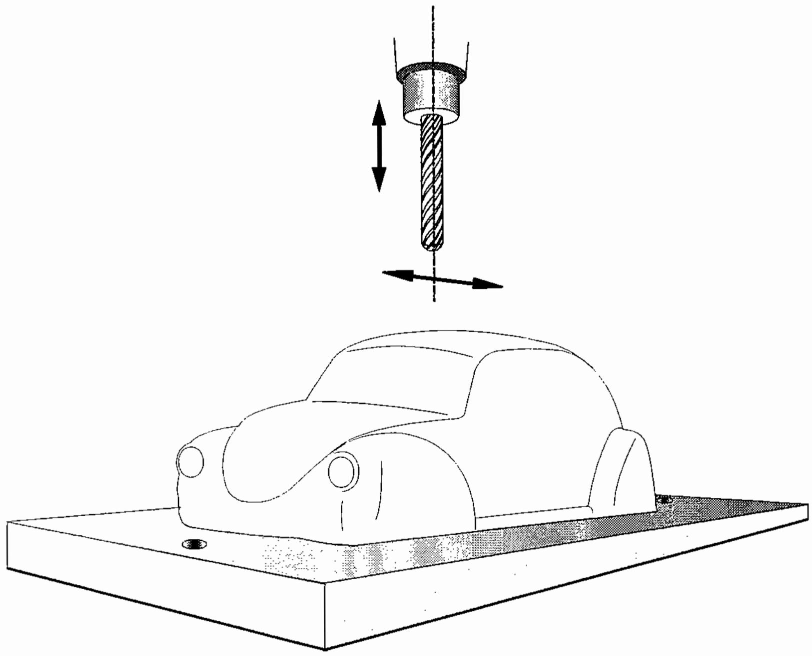


Fig. A16.3: Effect of closed-loop gain on lag error

Problem description

Models for casting moulds are to be produced on a milling machine. The models are to be machined via an end mill cutter. The contour tolerances concern both dimensional and form deviations. The machining process is to proceed at a constant feed speed. The lag error created as a result of this is to be determined.

Positional sketch



Exercise **Lag error**

1. Constructing and commissioning a position control loop
2. Specifying a constant feed speed as reference variable
3. Calculating and measuring the lag error
4. Determining the positional dependence of the lag error

1. Constructing and commissioning a position control loop

Execution

The same position control loop is used here as in exercise 15.
Circuit diagram and commissioning are described in this exercise.

2. Constant feed speed as reference variable

A reference variable w with constant time change is set to determine the lag error (ramp function).
The following applies:

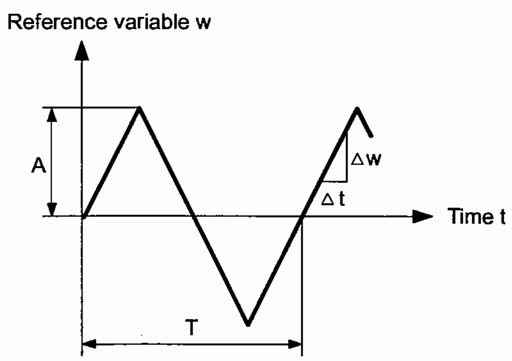
$$\frac{\Delta w}{\Delta t} = K_R \cdot v = \text{constant} \qquad (1)$$

The reference variable w is set by means of the frequency generator via the characteristics amplitude A and frequency f (see fig. A16.4). Within a period T, the amplitude A is passed through a total of four times, thereby resulting in a signal change of

$$\frac{\Delta w}{\Delta t} = \frac{4 \cdot A}{T} = 4 \cdot A \cdot f$$

The equation (1) results in:

$$v = \frac{4 \cdot A \cdot f}{K_R}$$



A = Amplitude
T = Duration
f = Frequency

$$f = \frac{1}{T}$$

$$\frac{\Delta w}{\Delta t} = \frac{4 \cdot A}{T} = 4 \cdot A \cdot f$$

Fig. A16.4:
Reference variable with constant gradient

Example:

The travel velocity is to be v = 0.2 m/s.

The transfer coefficient of the feedback K_R = 50 V/m produces:

$$\frac{\Delta w}{\Delta t} = K_R \cdot v = 50\frac{V}{m} \cdot 0{,}2\frac{m}{s} = 10\frac{V}{s}$$

For a travel path of ± 60 mm around the centre of the travel range, amplitude A is = 3V. The resulting frequency is:

$$f = \frac{\frac{\Delta w}{\Delta t}}{4 \cdot A} = \frac{10\frac{V}{s}}{4 \cdot 3V} = \frac{10}{12} \cdot \frac{1}{s} = 0.83Hz$$

The reference variable w for v = 0.2 m/s is therefore:

w = 5V ± 3V as ramp function with 0.83Hz

3. Lag error

The lag error e_x is calculated from the velocity v and the closed-loop gain V_0:

$$e_x = \frac{v}{V_0}$$

The close-loop gain V_0 is calculated from the gains of the elements in the closed control loop:

$$V_0 = K_P \cdot K_S \cdot K_R$$

With:

K_P	Gain of P controller
K_S = 0.05 s/V	System gain
K_R = 50 V/m	Transfer coefficient of feedback

4. Positional dependence of lag error

To be able to establish the positional dependence, a smaller reference variable must be selected. An amplitude of A = 0.5V is recommended. The setpoint velocity v = 0.2 m/s requires a reference variable of $\Delta w/\Delta t$ = 10 V/s.

The signal frequency for this is

$$f = \frac{\frac{\Delta w}{\Delta t}}{4 \cdot A} = \frac{10\frac{V}{s}}{4 \cdot 0.5V} = \frac{10}{2} \cdot \frac{1}{s} = 5Hz$$

The reference variable is therefore:

w = 1.5V ± 0.5V as ramp function with 5Hz

WORKSHEET

Lag error

1. Constructing and commissioning a position control loop

- Construct the same position control loop as in exercise 15.
- Set the control direction and offset correctly (exercise 15, point 2.).

2. Constant feed speed as reference variable

- Set the controller gain KP = 0.
  Select the following scales on the oscilloscope:

Time t:	0,1 s/Div.
Reference variable w:	1 V/Div.
Controlled variable x:	1 V/Div.

- Specify a reference variable of $w = 5V \pm 3V$.
- Set a frequency of $f = 0.83$ Hz.
- Now change to ramp function.

- Check the characteristics of the reference variable for

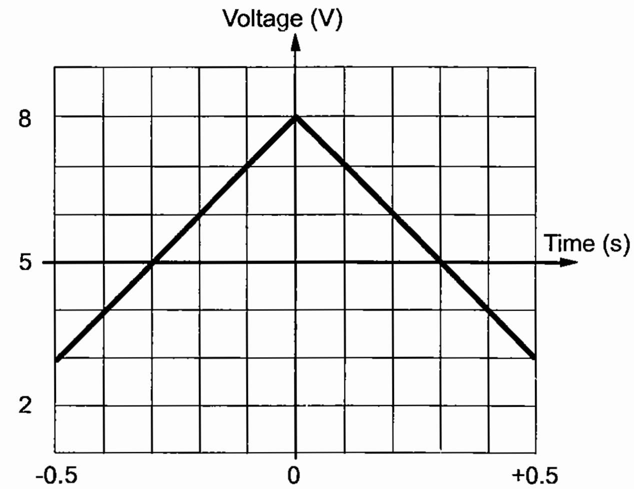
$$\frac{\Delta w}{\Delta t} = 10\frac{V}{s} = \frac{1V}{0{,}1s} \qquad \text{for } v = 0{,}2 \text{ m/s}$$

- Set a controller gain of $K_P = K_{Popt}$, e.g. $K_P = 40$, (see exercise 15).
- Record the characteristics of the following on the oscilloscope
  - reference variable w and
  - controlled variable x.

- Reduce the controller gain K_P to roughly half of the optimum value, e.g. to $K_P = 20$.

- Enter the characteristics of the reference variable and ramp response in the diagram (with v = 0.2 m/s and K_P = 20).

Diagram



- Examine the dependence of the lag error on
  - the velocity v and
  - the controller gain K_P.

Value table

Velocity v	*Controller gain K_P*	*Lag error e_x*
constant	greater	
constant	smaller	
greater	constant	
smaller	constant	

- How does the lag error change with the velocity v?

____

- How does the lag error change with the controller gain K_P?

____

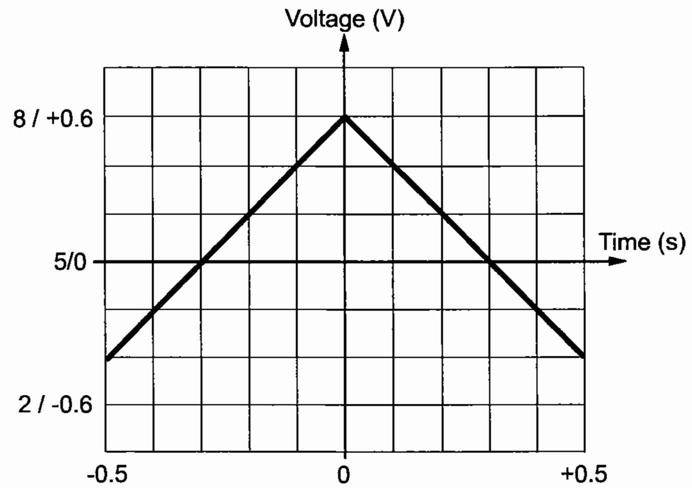
WORKSHEET

- Set the setpoint velocity v = 0.2 m/s and K_{Popt} again.
- Record the following characteristics on the oscilloscope
  - reference variable w and
  - system deviation e.

Scaling for e: 0.2 V/Div.

- Enter the characteristics of reference variable and system deviation in the diagram.

Diagram



- Change the following consecutively
  - the setpoint velocity v and
  - the closed-loop gain K_P.
- Are the above established tendencies confirmed? ________________

3. Lag error

- Calculate the theoretical lag error e_{xth} for
  - velocity $v = 0.2$ m/s and
  - closed-loop gain $K_P = 40$.

  All other gain factors are to be assumed:
  - Controlled-system gain: $K_S = 0.05$ m/s
  - Transfer coefficient of feedback: $K_R = 50$ V/m

- First of all calculate the closed-loop gain V_0

  V_0 = ______________________________

- Now calculate the lag error e_{xth}:

  e_{xth} = ______________________________

- Then, also calculate the system deviation e_{th}:

  e_{th} = ______________________________

- Measure the lag error for $v = 0.2$ m/s in relation to the controller gain.

Value table

K_P	e	e_{xmess}	e_{xth}	*Measuring error* $= e_{xth} - e_{xmess}$
20				
40				

- Why is the lag error directly dependent on the controller gain in this instance?

  ____

  ____

  ____

WORKSHEET

- Is the lag error the same for forward and return stroke? ___________

  If not, why? ____

4. Positional dependence of the lag error

- Record the characteristics of the following on the oscilloscope
  - reference variable w and
  - system deviation e.

Scales as follows:

Time t:	20 ms/Div.
Reference variable w:	0.2 V/Div.
System deviation e:	0.1 V/Div.

- Set the following reference variable:

  w = 1.5V ± 0.5V, f = 5Hz, Ramp function

- Check the setpoint velocity of v = 0,2 m/s

$$\frac{\Delta w}{\Delta t} = 10\frac{V}{s} = \frac{0{,}2V}{20ms}$$

- Set $K_P = K_{Popt}$ (e. g. $K_P = 40$).

  What is the system deviation measure? e = ____________________

  Which lag error does this correspond t? e_{xmeas} = ________________

- Measure the lag error at different points of the travel distance, where $v = 0.2$ m/s and $K_P = K_{Popt}$.

Value table

Range of operating path	*Reference variable* w	*System deviation* e	*Lag error* e_x
Edge	1.5V ± 0.5V		
Centre	5V ± 0.5V		
Edge	8V ± 0.5V		

How does the lag error change? ______________________

____

Subject: *Closed-loop hydraulics*

Title: ***Machining centre***

Training aim

- To learn about the features of a modified control system
- To be able to establish the influence of load
- To learn about the influence of volume

Technical knowledge

Changes in the controlled system

In industrial practice, very often the characteristics of a controlled system are inconsistent. Two frequently varying influencing variables of the controlled system are to be examined here:

- variable mass loads on the slide and
- different oil volumes caused as a result of the lines between valve and cylinder.

Spring/mass vibrator

The hydraulic linear unit is a system capable of oscillation. It can be compared with a spring/mass vibrator. The columns of oil can be regarded as springs and the mass of the slide is clamped between these springs (see fig. A17.1). The natural angular frequency of such a system is:

$$\omega = \sqrt{\frac{c}{m}}$$

c = Spring stiffness
ω = Natural angular frequency
m = Mass

The general rule is:

$$\omega = 2 \cdot \mu \cdot f$$

f = Natural frequency

and

$$T = 1/f$$

T = Time constant of system

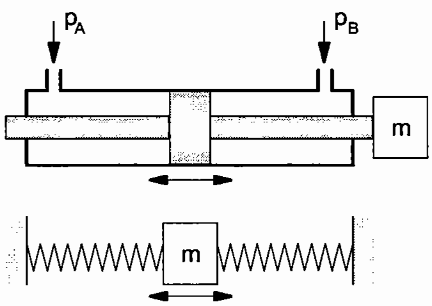


Fig. A17.1:
Spring/mass oscillator

Influence of mass load

A higher mass load reduces the natural angular frequency of the controlled system. This slows down the controlled system.

Influence of the oil volume

The spring stiffness of the oil columns is very high, as the oil is only slightly compressible. The volume change increases

- with the pressure raised and
- the initial volume.

A greater initial volume is more compressible: the spring represented by the oil column becomes effectively more flexible, which reduces spring rigidity. This also results in a reduced natural angular frequency.

Influences acting on the closed control loop

The controlled system becomes slower both as a result of increasing load and also increasing oil volume. The controller parameters must be adapted to this system. The following changes in the characteristic data of the closed control loop can be seen:

- The limit of stability K_{Pcrit} becomes smaller. The slower system already becomes unstable with a minimal controller gain.
- Accordingly, the optimum controller gain also becomes smaller.
- Overall, this results in a higher settling time T_a.
- The lag error remains unchanged, but it takes longer for the setpoint velocity to be attained. However, the controlled variable then follows at the same distance as the reference variable in an unmodified controlled system.

In practice, mass load is rarely avoidable, since the hydraulic drive unit is particularly suitable for transporting large loads thanks to its high driving power. A different controller may therefore be more advantageous in this case.

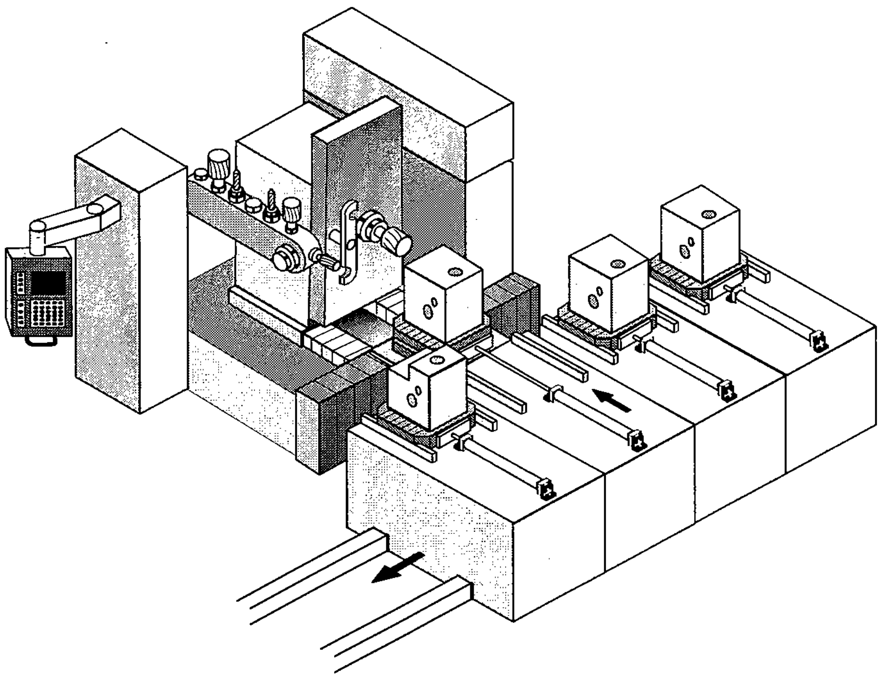
Large oil volumes can be easily avoided, by making sure that the line distances between valve and drive unit are short. For this reason, units where the valve is directly mounted onto the operating cylinder are often used.

Problem description

Engine blocks are to be conveyed towards a machining centre. The engine blocks are mounted on a slide, which conveys them to an exact position in the operational space of the machining centre. After this, the slide is to return empty to fetch the next engine block. The loading position must be accurately approached for this.

The feed slide is to operate free from vibration with and without load and to position accurately. Added to this is the fact that the central hydraulics including the directional control valve are constructed next to the system and that the slide is connected via long hose lines.

Positional sketch



Exercise

Modified controlled system

1. Constructing and commissioning the closed control loop
2. Changing the controlled system by means of load and reservoir
3. Lag error with modified system

Execution

1. Constructing and commissioning the position control loop

The same position control loop is used here as in exercise 15, where the circuit diagram and commissioning have already been described.

2. Modifying the controlled system

The controlled system is modified by

- attaching a load of 10 kg to the slide,
- creating additional oil volume by replacing the lines between the valve and cylinder with 3m long hose sections.
  (Volume per hose line approx. 0.1l)

The influences of these changes is investigated with the help of the transition function. The setpoint step-change is

$w = 1.5V \pm 0.5V$ as square-wave signal

The characteristics of the unchanged controlled system are to be determined from the step response:

- Limit of stability K_{Pcrit0} and
- optimum controller gain K_{Popt0} with
- settling time T_a

The controlled system is then modified by adding individually the load, then the hose and then both together.

3. Lag error with modified system

In this instance, a ramp is specified as a reference variable:

$w = 1.5V \pm 0.5V$ as ramp with frequency f = 5Hz.

This corresponds to a setpoint speed of 0.2 m/s or a setpoint change of $\Delta w/\Delta t = 10$ V/s.

The same controller gain $K_P = 20$, as that used in exercise 16, also produces the same lag error of

$e_x = 4mm$

a system deviation of

$e = 0.2V.$

Theoretically the lag error remains the same, even if the controlled system is subsequently changed.

WORKSHEET

Modified controlled system

1. Constructing and commissioning the closed control loop

- Construct the same closed control loop as in exercise 15.
- Carry out the commissioning according to point 2 of the worksheet in that exercise.

2. Modifying the controlled system

- Set a setpoint step-change of w = 1.5V ± 0.5V.
- Select the oscilloscope scales so as to enable you to completely represent a step response.
- Determine the following by setting the P controller:

K_{Pcrit0} = ____________________

K_{Popt0} = ____________________

T_{a0} = ____________________

- Modify the controlled system via load m and hose volume V and determine the characteristics:

Value table

$\frac{m}{V}$ =	$\frac{0kg}{0l}$	$\frac{10kg}{0l}$	$\frac{0kg}{0,1l}$	$\frac{10kg}{0,1l}$	Tendency
K_{Pcrit}					
K_{Popt}					
T_a at K_{Popt}					

- What tendency do you detect from the measured values? Enter these in the value table for each characteristic.

3. Lag error with modified controlled system

- Set the reference variable w:

  w = 1.5V ± 0.5V with   f = 5Hz   as ramp function

- Check the gradient to $\frac{\Delta w}{\Delta t} = 10\frac{V}{s} = \frac{2V}{0.2ms}$
- Record the lag error e_x with $K_P = 20$.

  Is e_x = 4mm or. e = 0.2V? ____________________

- Change the controlled system via load and hose volume.
  Leave $K_P = 20$.

Wertetabelle

$\frac{m}{V} =$	$\frac{0kg}{0l}$	$\frac{10kg}{0l}$	$\frac{0kg}{0,1l}$	$\frac{10kg}{0,1l}$	Tendency
e					
e_x					

- Why do you measure the same lag error every time?

  ____

- What lag error would you measure with an optimum controller setting?

  ____

- With which system can you travel at the maximum velocity?

  ____

Subject: *Closed-loop hydraulics*

Title: ***Drilling of bearing surfaces***

Training aim

- To be able to undertake the commissioning of a closed control loop
- To be able carry out an optimum setting of the position control loop
- To be able to eliminate interferences

Technical knowledge

Fault finding in a closed control loop

To be able to eliminate interferences in a system, it is necessary to isolate the fault and to establish the cause. Since a fault is often the result of several causes, it is essential to be aware of the effects of all potential individual faults. In this way, the individual causes can be investigated specifically and eliminated, whereby it is best to adopt a systematic procedure.

Types of fault

During the operation of an automatic installation, faults may occur due to a number of very different causes:

- faults due to human error, e.g. when reading measured values or the setting of devices,
- mechanical faults, e.g. due to faulty components or loose connections during assembly
- faults in the hydraulics, e.g. in the interconnection, in the valve, in the cylinder or the power pack,
- electrical faults, e.g. in the wiring, in the measuring system or in the control device,
- faults in the closed-loop controller, e.g. due to wrong setting,
- other faults, e.g. a different operating temperature, wear or pollution.

Since the testing of all likely faults would exceed the scope of this exercise, we shall deal purely with interferences in hydraulics for the purpose of this exercise. This mainly deals with major faults developing gradually after long periods of operation. Due to the wear of an individual device, measurable changes such as:

- power pack: drop in performance, i.e. pressure drop,
- valve: internal leakage,
- cylinder: internal leakage.

The effects of these faults are to be established and measures tried out to eliminate these.

Drop in supply pressure

If the pump no longer produces the required output, then a reduced actuating pressure is available for the closed control loop. This results in the following action chain:

1. reduced supply pressure p_P,
2. reduced differential pressure Δp at the control gap of the valve,
3. reduced flow rate q,
4. reduced velocity v of the cylinder.

In order to eliminate the fault, the valve needs to be further opened. As a result of a larger control gap, the required flow rate can also flow with a reduced pressure differential. A wider opening of the valve is achieved by means of an increased controller gain K_P.

Leakage in the valve

Internal leakage is created as a result of wear of the control edges of the directional control valve, which are normally very sharp edged for zero overlap.

1. Oil escapes towards the tank and is no longer available for the operating cylinder.
2. The pattern of the pressure/signal characteristic curves is flatter.
3. The characteristics of the valve are similar to that of a negative overlap.

A different pressure prevails in the chamber of the operating cylinder due to the force equilibrium on the piston (depending on the area ratio, see exercise 14). The pressure ratio is set via the offset on the valve or on the controller. If the pattern of the pressure/signal characteristic curve is flatter, then a higher input signal is required and the offset needs to be re-adjusted. A second possibility is to set a higher controller gain, thereby also creating a higher input signal.

Leakage in the cylinder

A leakage is created on the piston seal of the cylinder due to wear. This results in the following chain of events:

1. The pressure on the rod side is greater than that on the piston side due to the force equilibrium.
2. A leakage q_L occurs from the rod side to the piston side proportional to the pressure drop. If the leakage is sufficiently large, this results in the piston drifting in the direction of a forward end position.
3. Since a lesser flow rate is required for the return stroke, the leakage is more apparent here: the retracting velocity vin is reduced.

The flow rate reduced by the leakage q_L can be compensated by further opening the control gap on the valve. This can be achieved by means of a higher controller gain K_P. The drifting of the piston can be limited by re-adjusting the offset. In practice, it is however only possible to compensate small leakage. Long-term, it is more sensible to replace the seal.

Measures for the elimination of interferences

The following table is to provide some advice regarding faults, possible causes and measures for elimination. Additional advice can be found in part B.

Measures for the elimination of interferences

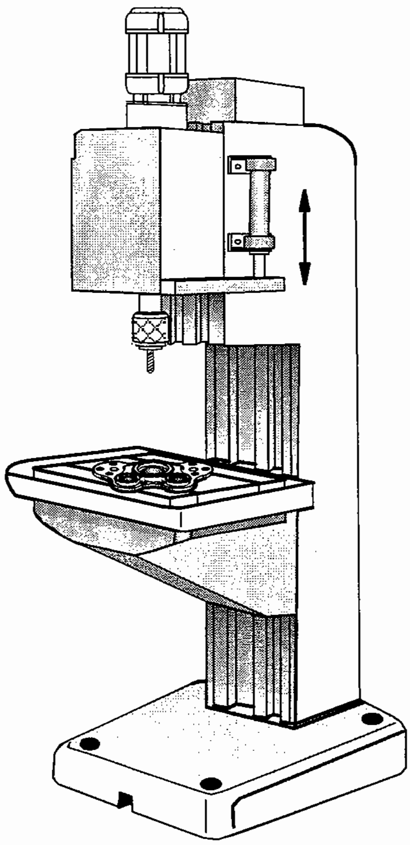
Error	*Cause*	*Remedy*
Position error	Offset	Re-adjustment on the controller
	Leakage	Replace component
Drift	Offset	Re-adjustment, on the controller or on the valve
	Leakage	Replace component
Approaching of end stops	Control direction	check all signals and correct polarity
Approaching of one end stops	Leakage too high	Replace piston seal
Reduced velocity	Pressure drop	Increase controller gain, Check supply pressure, Exchange power pack
Greater lag error	Pressure drop	Increase controller gain or Check power pack
	Leakage	Compensation through offset, Replace piston seal, check valve characteristic curve

Problem description

Bearing surfaces are to be drilled by means of a position controlled feed drive. The drive unit was constructed first of all and then the electrical controller connected. The controller was then parameterised and an optimum quality criteria set. In addition, the required safety precautions have been put in place for the continuous operation of the installation.

Interferences occur in the course of the system operation. These manifest themselves in the form of insufficient accuracy, exceeding of cycle times, chatter marks, tool breakage. These interferences are to be eliminated by identifying and rectifying the causes.

Positional sketch



Exercise

Interferences in the hydraulic position control loop

1. Constructing a hydraulic position control loop
2. Commissioning a closed control loop
3. Investigating interferences in the closed control loop

Execution

1. Constructing a position control loop

The position control loop consists of:

- a dynamic directional control valve as final control element,
- a linear drive as closed control loop,
- a displacement sensor as feedback,
- a P controller as control

Interferences are simulated by means of:

- a pressure relief valve in the by-pass and
- a flow control valve between the working lines.

The following measuring points are to be designated for the pressure:

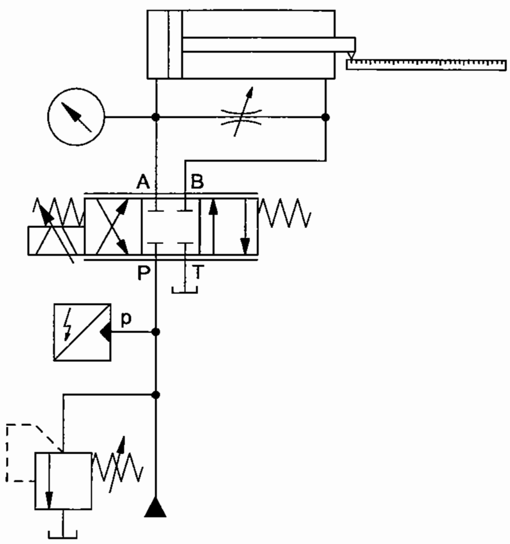
- supply port p_P and
- working port p_A.

The following are required for commissioning:

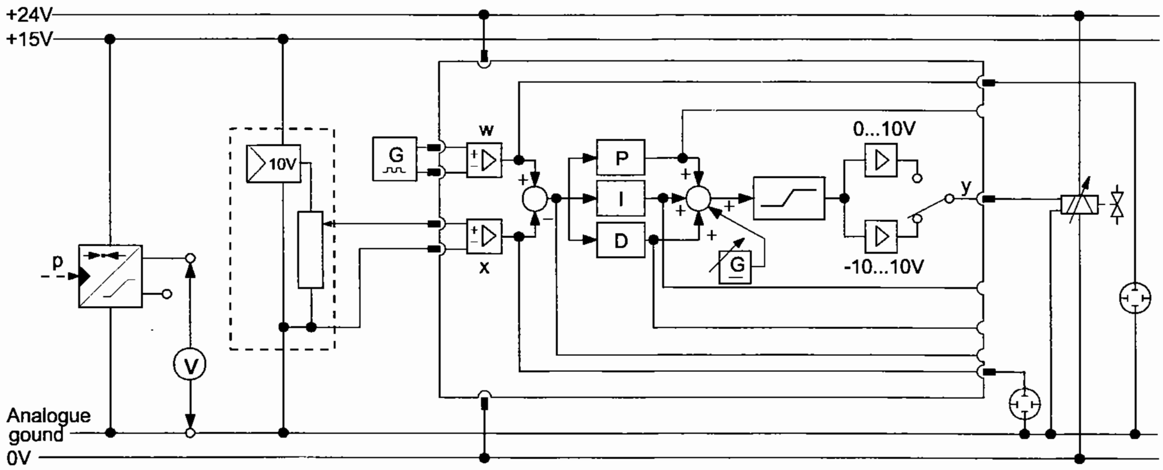
- a multimeter,
- a frequency generator,
- an oscilloscope.

This leads to a hydraulic and electrical circuit diagram.

Circuit diagram, hydraulic



Circuit diagram, electrical



2. Commissioning

The commissioning of a position control loop is to be carried out as a prime example in this exercise. Hence all the steps described in detail in exercises 15 and 16 are to be collated and commissioning is to be effected with the help of a check list. When all the points of this check list have been processed, you will have an optimum set closed control loop and a table with the most important characteristics.

3. Interferences in the closed control loop

3.1 Pressure drop

A step function is set for a reference variable:

w = 1.5V ± 0.5V as square-wave signal

First of all, the initial status is recorded:

- K_{Pcrit0},
- K_{Popt0} and T_{a0}.

The interferences are simulated by opening the pressure relief valve. The supply pressure can be read on the pressure gauge. The following are to be measured to enable you to make comparisons with the initial status:

- K_{Pcrit}
- T_a with K_{Popt0}
- Working pressure p_A
- depending on p_P.

A second series of measurements is carried out to investigate to what extent the interference can be compensated. The controller is set at an optimum setting with different supply pressures p_P. The result is

- K_{Popt} and
- T_a
- depending on p_P.

3.2 Leakage

The same reference as that under point 3.1 is used here.

First of all the interference is determined by means of measuring

- the limit of stability K_{Pkrit} and
- the system deviation e
- with increasing leakage.

Then, various measures of elimination are to be investigated. The position deviation is reduced by re-adjusting

- K_{Popt} and
- offset

WORKSHEET

Interferences in the hydraulic position control loop

1. Constructing the position control loop

- Construct the closed control loop in accordance with the circuit diagrams.
- Close the pressure relief valve and flow control valve completely.

Make sure that the trial set-up and in particular the linear unit are attached securely to a sturdy base!

2. Commissioning

Risk of injury!
Prior to switching on make sure that no one is within the operating space of the slide!

Work your way through the check list points in the sequence given.

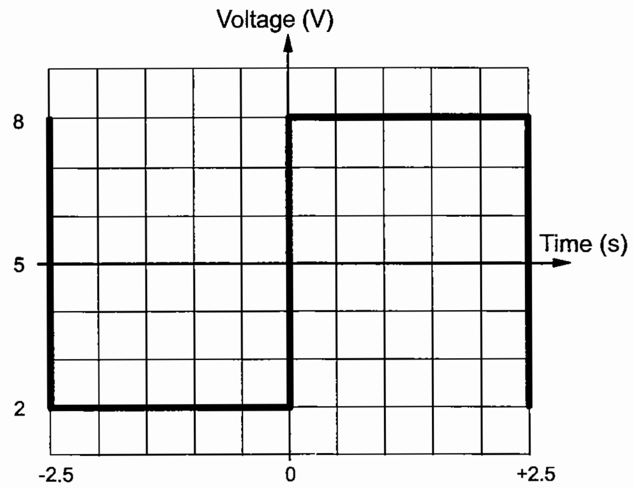
- Safety-related presettings

Reference variable	*Controller gain*	*Other parameters*			
w	K_P	K_I	K_D	Offset	Limiter

- Switch on power supply
- Check the control direction ______________________
- Set the offset ______________________

■ Transition function

Diagram



■ Limit of stability

Reference variable w	*Crit. controller gain K_{Pcrit}*
1.5V ± 0.5V Square-wave	

■ Quality criteria

Priority	*1*	*2*	*3*	*4*
Characteristic				
Tolerance				

■ Optimise controller parameters

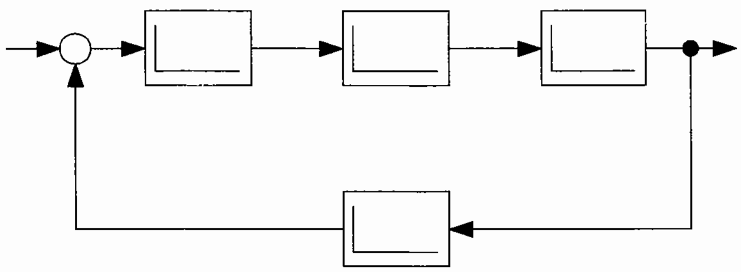
Reference variable w	*Controller gain K_{Popt}*	*Overshoot amplitude x_m*	*Steady-state system deviation e_{stat}*	*Settling time T_a*
1.5V ± 0.5V Square-wave				

WORKSHEET

- Lag error and closed-loop gain (with K_{Popt})

Setpoint velocity v_{soll}	*Reference variable* w	*System deviation* e	*Lag error* e_x	*Closed-loop gain* V_0
0.2m/s = 0.2V / 20ms	1.5V ± 0.5V 5Hz, Ramp			

- Block diagram with amplification gain



Block diagram

3. Interferences in the closed control loop

- Set a setpoint value of w = 1.5V ± 0.5V with f = 5Hz square wave form.
- Record setpoint value w and actual value x on the oscilloscope.
- Check whether the pressure relief valve and flow control valve are closed.

- Note the characteristics for the interference-free closed control loop:

K_{Pcrit0} = ______________________

K_{Popt0} = ______________________

T_{off0} = ______________________

T_{on0} = ______________________

3.1 Pressure drop

- Simulate the drop in supply pressure p_P by gradually opening the pressure relief valve. Determine the following characteristics and evaluate the change:

Value table

Characteristic	*Values*					*Tendency*
p_P	50	40	30	20	10 bar	decreasing
p_A					bar	
K_{Pcrit}						
T_{out} with K_{Popt0}					s	

- Try to compensate the interference by optimising K_P. Enter your evaluation in the value table.

Value table

Characteristic	*Values*					*Tendency*
p_P	50	40	30	20	10 bar	decreasing
K_{Popt0}						
T_{out} with K_{Popt}					s	

- Is it possible to compensate the interference completely?
- Up to what supply pressure p_P is compensation possible?

WORKSHEET

3.2 Leakage

- Simulate a leakage q_L in the cylinder by gradually opening the flow control valve. Determine the following characteristics and evaluate the change:

Wertetabelle

Characteristic	*Values*					*Tendency*
q_L	1/8	1/4	1/8	1/2	Rot.	increasing
K_{Pcrit}						
T_{out} with K_{Popt0}					s	
T_{in} with K_{Popt0}					s	
e_{stat}					V	

- Try to compensate the interference by re-adjusting the K_P and the offset. Enter your evaluation in the value table.

Wertetabelle

Characteristic	*Values*					*Tendency*
q_L	1/8	1/4	1/8	1/2	Rot.	increasing
K_{Popt}						
T_{out} with K_{Popt}					s	
T_{in} with K_{Popt}					s	
e_{stat}					V	

- Is it possible to compensate the interference? ____________________

- How is a large leakage detected?

____

____

- State your reasons for this:

____

____

____

____

____

Closed-loop hydraulics — *Subject*

Feed on a shaping machine — *Title*

Training aim

- To learn about the purpose and construction of a status controller
- To be able to record the transition and ramp functions of a status controller

Technical knowledge

Status controller

A status controller is to be used to influence the status variables of a controlled system. The status variables in the hydraulic position control loop are e.g. the position x, the velocity v, the acceleration a, the working pressure p, the control voltage V_E (see also fig. A15.2).

The status controller used in this instance influences three status variables:

- the position x,
- the velocity v and
- the acceleration a.

The computational algorithm between these variables is very simple: they are formed through integration. Hence, it is possible to calculate back from the position x

- to the velocity $v = \dot{x}$ by single differentiation and
- to the acceleration $a = \ddot{x}$ by

double differentiation. Only one status variable must therefore be measured: the position x.

This results in a triple loop controller structure. Each loop contains an amplifier and the required differentiator.

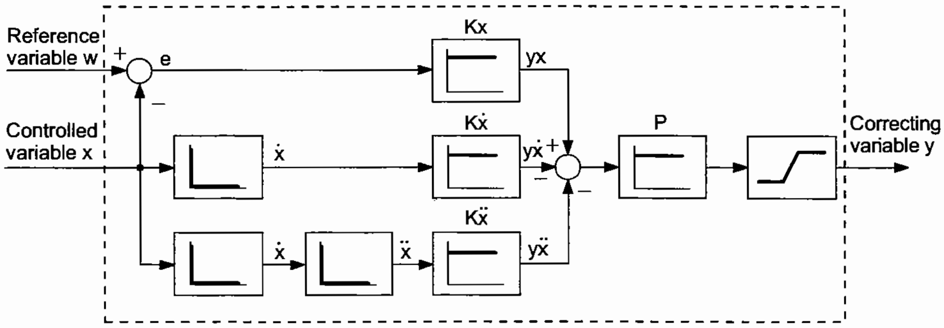


Fig. A19.1: Block diagram of status controller

e = Position variation	Kx = Position coefficient	yx = Position correcting variable
ẋ = Velocity	Kẋ = Velocity coefficient	yẋ = Velocity correcting variable
ẍ = Acceleration	Kẍ = Acceleration coefficient	yẍ = Acceleration correcting variable
	P = Total gain	

The equations for the three loops of the status controller are:

$y_x = Kx \cdot e = Kx \cdot (w - x)$ for the position

$y_{\dot{x}} = K\dot{x} \cdot \dot{x}$ for the velocity

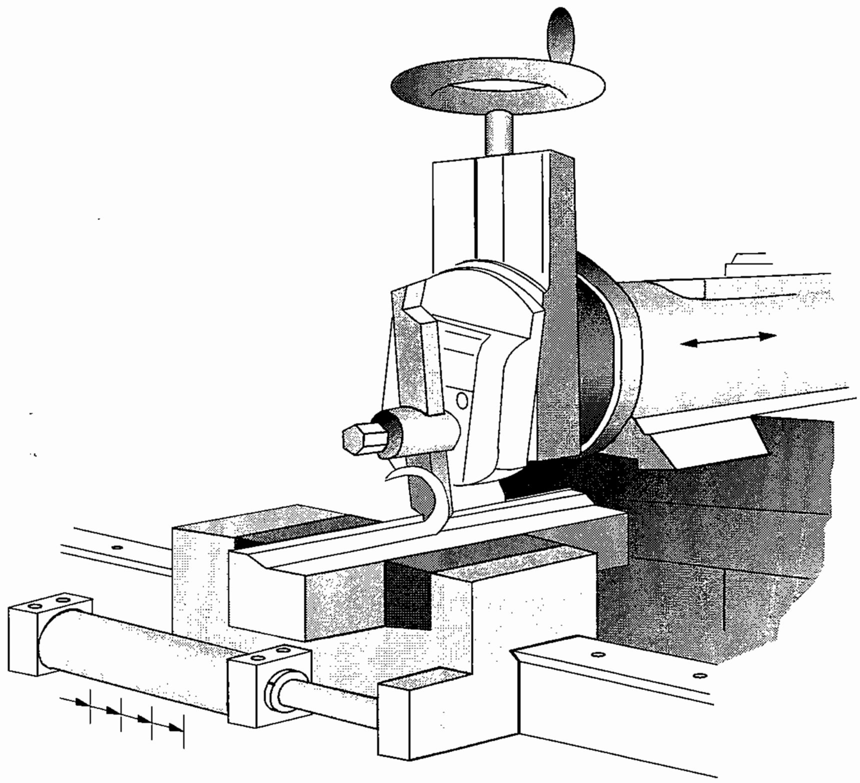
$y_{\ddot{x}} = K\ddot{x} \cdot \ddot{x}$ for the acceleration

The results of the three loops are added together at a summation point, whereby the proportions from speed and acceleration are deducted from the proportion from the position. The result is the total gain P. The signal then passes through a limiter before being transmitted to the valve in the form of a correcting variable y.

Problem description

The feed axis of a shaping machine is to be equipped with a hydraulic position control loop. A status controller is to be used as a control device. To begin with, the function and characteristics of the status controller are to be checked.

Positional sketch



Exercise **Status controller**

1. Constructing the measuring circuit
2. Determining the characteristics of the status controller
3. Recording the transition and ramp function

Execution **1. Measuring circuit**

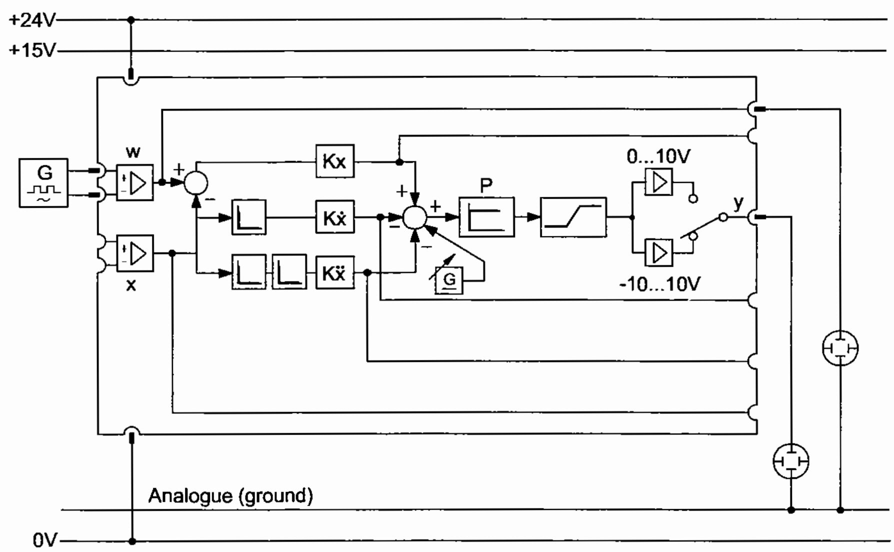
The following characteristics must be recorded to establish the transition and ramp function:

- the reference variable w for input variable
- the correcting variable y for output variable

The following equipment is required for the measurements:

- a frequency generator to set the step and ramp function as a reference variable, with an adjusting range of ± 10V,
- an oscilloscope to record the response functions,
- a multimeter to commission the circuit,
- a voltage supply of 24V for the status controller.

Circuit diagram, electrical



2. Characteristics of a status controller

All setting parameters are set to zero for the commissioning.

Then, the characteristics are checked with the multimeter. Any exceeding of signal ranges is indicated via LEDs.

The most important characteristics of a status controller are:

Input variables

Reference variable w:	0V - 10V
Controlled variable x:	0V - 10V

Output variable

Correcting variable y:	0V - 10V or ± 10V

Controller coefficients

Position coefficient Kx:	0 - 10
Velocity coefficient $K\dot{x}$:	0ms - 100ms
Acceleration coefficient $K\ddot{x}$:	$0ms^2$ - $10ms^2$
Total gain P:	0 - 100

Further characteristics

Supply voltage:	24V
Voltage connections for sensors:	15V and 24V
Offset:	5V ± 3.5V or 7V
Limiter:	0V - 10V or ± 10V

3. Transition and ramp function

Since a controller with differentiating elements is used here, it is appropriate to use a ramp function as a test signal.

The following applies for a reference variable w = 0V ± 5V and f = 2Hz:

$$\frac{\Delta w}{\Delta t} = 4 \cdot A \cdot f = 4 \cdot 5V \cdot 2\frac{1}{s} = 40\frac{V}{s}$$

The position correcting variable y_x is the result of $K_x = 0.5$ and $P = 1$, whereby $x = 0$:

$$y_x = Kx \cdot w = 0.5 \cdot 5V = 2.5V$$

The correcting variable for the velocity loop is calculated with $K\dot{x} = 7ms$:

$$y_{\dot{x}} = K\dot{x} \cdot \dot{x} = 0.007 \cdot 40\frac{V}{s} = 2.28V$$

The following applies for the correcting variable of the acceleration loop:

$$y_{\ddot{x}} = K\ddot{x} \cdot \ddot{x} = K\ddot{x} \cdot 0 = 0$$

The test signal is applied at different points to measure the transition and ramp function of the individual loops:

- *at connection w for the position element,*
- *at connection x for the velocity and acceleration elements.*

WORKSHEET

Status controller

1. Measuring circuit

- Construct the measuring circuit in accordance with the circuit diagram.
- Set
  - all potentiometers to zero,
  - the offset to centre,
  - the limiter to ± 10V.
- Connect the supply voltage 24V.

2. Characteristics of a status controller

- Specify different voltages with the generator.
- Measure the range of values of the following characteristics with the multimeter:

  Max./min. Reference variable w: ______________________

  Max./min. Controlled variable x: ______________________

  Max./min. Correcting variable y: ______________________

  Max./min. Offset: ______________________

  Max./min. Limiter: ______________________

  Do the measurements agree with the setpoint value? __________

3. Transition and ramp function

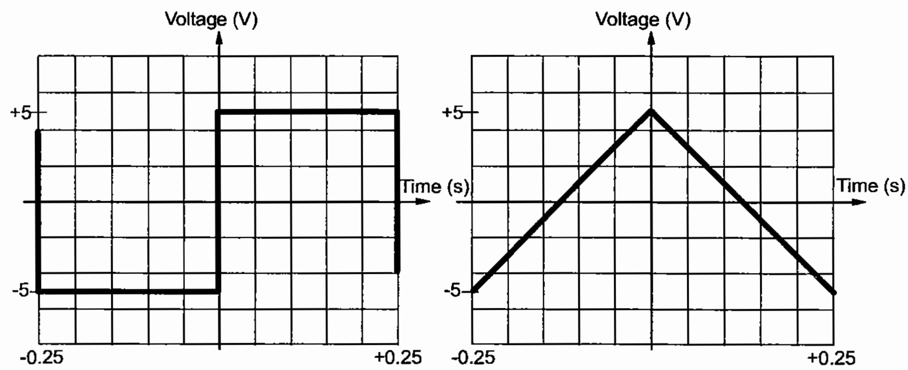
- Set:
  - all controller parameters to zero,
  - the total gain P = 1,
  - the offset to zero,
  - the limiter to ± 10V.

- Set the following reference variable:
  - $w = 0V \pm 5V$, f = 2Hz, square wave or ramp
- Select the following scales on the oscilloscope:
  - Time t: 50 ms/Div.
  - Reference variable w: 2 V/Div.
  - Correcting variable y: 2 V/Div.

3.1 Position controller

- Set Kx = 0.5, and record the transition and ramp function.

Diagram

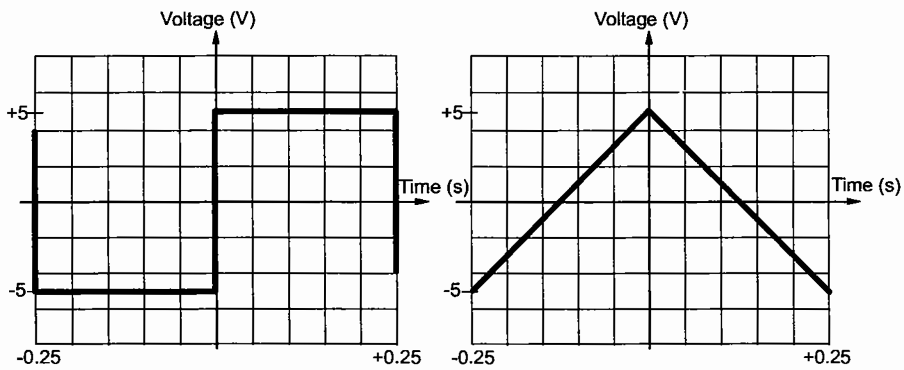


Which controller type does the transition correspond t?

3.2 Velocity controller

- Set the parameter Kx to zero.
- Specify the desired function at input x.
- Set $K\dot{x}$=7ms (potentiometer setting 0.7), and record the transition and ramp function.

WORKSHEET

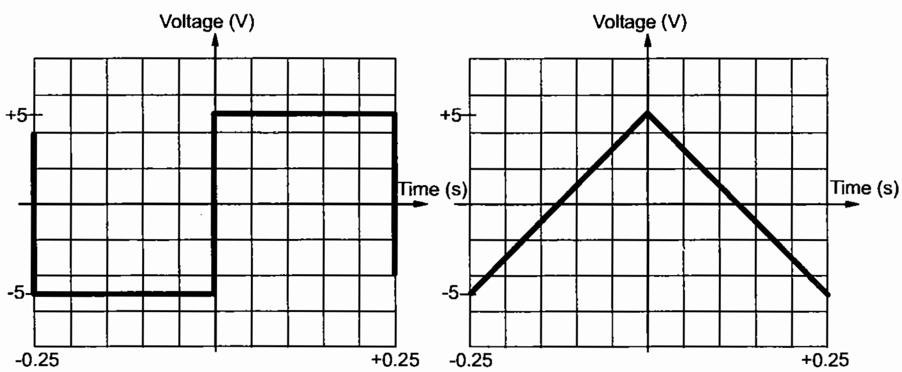


Diagram

Which controller type does the transition function correspond t?

3.3 Acceleration controller

- Set the parameter $K\dot{x}$ to zero.
- Specify the desired function at input x.
- Set $K\ddot{x} = 1 ms^2$ (potentiometer setting 1.0), and record the transition and ramp function.



Diagram

By what do you recognise the double differentiator?

Closed-loop hydraulics — *Subject*

Paper feed of a printing machine — *Title*

Training aim

- To be able to commission a position control loop with status controller
- To be able to set optimum parameters of a status controller
- To be able to measure lag errors of a position control loop with a status controller

Technical knowledge

Position control loop with status controller

A status controller contains three loops:

one P element with $Kx \cdot (w - x)$

one D element with $K\dot{x} \cdot \frac{x}{t} = K\dot{x} \cdot v$

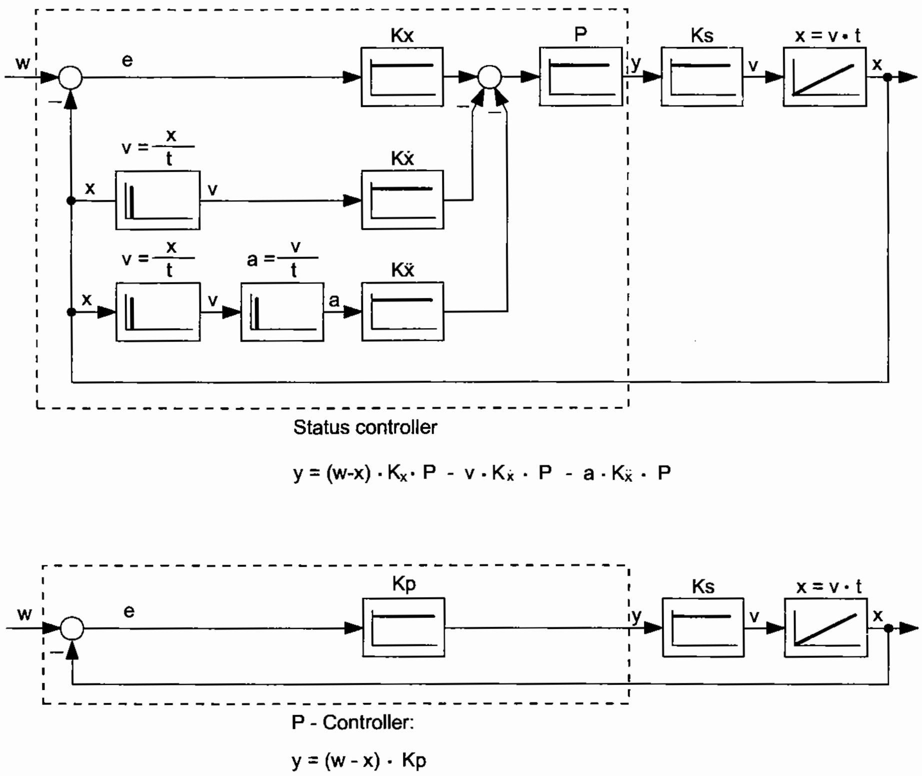
one D2 element with $K\ddot{x} \cdot \frac{\left(\frac{x}{t}\right)}{t} = K\ddot{x} \cdot a$

As illustrated both by the equations and fig. A20.1, with a status controller, it is not just the setpoint and actual value, w and x, (as in the case of a P controller) which are influenced, but in addition the velocity v and acceleration a.

Status controller:	$y = (w - x) \cdot Kx \cdot P - v \cdot K\dot{x} \cdot P - a \cdot K\ddot{x} \cdot P$
P controller:	$y = (w - x) \cdot K_P$

To provide a clearer representation, the feedback has not been taken into account in this instance (or set $K_R = 1$).

Fig. A20.1:
Status controller and
P controller in
position control loop



Parameterisation of a status controller

1. Initially, all parameters are set to zero.
2. Then, the limit of stability is established with the P controller.
3. By connecting the acceleration gain $K\ddot{x}$, the oscillations are reduced to a large overshoot.
4. This overshoot is attenuated by connecting the velocity gain $K\ddot{x}$

In this way, a stable setting of the closed control loop can be achieved, even though the proportional gain Kx (corresponds to K_P with P controller) is near the critical stability. The extremely high closed-loop gain resulting from this is the main advantage of a status controller compared to a P controller.

Lag error with status controller

The signal equation of a position control loop with a status controller is (including feedback K_R):

$$y = e \cdot Kx \cdot P - v \cdot K_R \cdot K\dot{x} \cdot P - a \cdot K_R \cdot K\ddot{x} \cdot P$$

With a constant speed, the acceleration is equal to zero:

$$v = \text{constant} \quad \rightarrow \quad a = 0$$

Thus, the following applies with system gain $K_S = \frac{v}{y}$:

$$y = \frac{v}{K_S} = e \cdot Kx \cdot P - v \cdot K_R \cdot K\dot{x} \cdot P$$

Conversion results in:

$$e = \frac{1}{Kx \cdot P} \cdot \left(\frac{v}{K_S} + v \cdot K_R \cdot K\dot{x} \cdot P \right)$$

The system deviation e with a status controller is:

$$e = v \cdot \left(\frac{1}{Kx \cdot P \cdot K_S} + \frac{K_R \cdot K\dot{x}}{Kx} \right)$$

The lag error ex can be calculated from the system deviation:

$$e_x = \frac{e}{K_R} = v \cdot \left(\frac{1}{K_R \cdot Kx \cdot P \cdot K_S} + \frac{K\dot{x}}{Kx} \right)$$

By using closed-loop gain $V_0 = K_R \cdot Kx \cdot P \cdot K_S$ the calculation is simplified to:

$$e_x = \frac{e}{K_R} = v \cdot \left(\frac{1}{V_0} + \frac{K\dot{x}}{Kx} \right)$$

The first addend of this equation corresponds to the lag error of a P controller:

$$e_x = \frac{v}{V_0}$$

At first glance, in comparison with a P controller, the lag error with a status controller appears to be greater by a component coupled with the velocity gain. This is confirmed during parameterisation: as soon as the gain $K\dot{x}$ is increased, the lag error also increases.

The proportional gain Kx can, however, be set very high so that the lag error is already significantly less than with the P controller. Even if the lag error is now increased by the velocity gain $K\dot{x}$, it will still not be as great as with the P controller.

Status controller with modified controlled system

The characteristics of a controlled system change as a result of

- load or
- hose volume.

The spring/mass model described in exercise 17 results in:

- a lower spring rigidity c and
- a lower natural angular frequency $\omega = \sqrt{\frac{c}{m}}$

With a status controller it is possible, by optimal parameterisation, to adapt the controller to the modified controlled system to such an extent that the controlled system almost attains the quality criteria of the unmodified controlled system.

- The load is compensated by increasing $K\ddot{x}$.
- The hose volume is partially compensated by means of high closed-loop gain V_0.

Please refer to fig. A15.2 for explanation. The acceleration gain $K\ddot{x}$ has a direct effect on the acceleration a, which is dependent on the mass load. None of the three loops of the status controller directly influences the controlled system element where the change in oil volume enters. Hence, only the very high gain of the P element in the status controller is of any advantage.

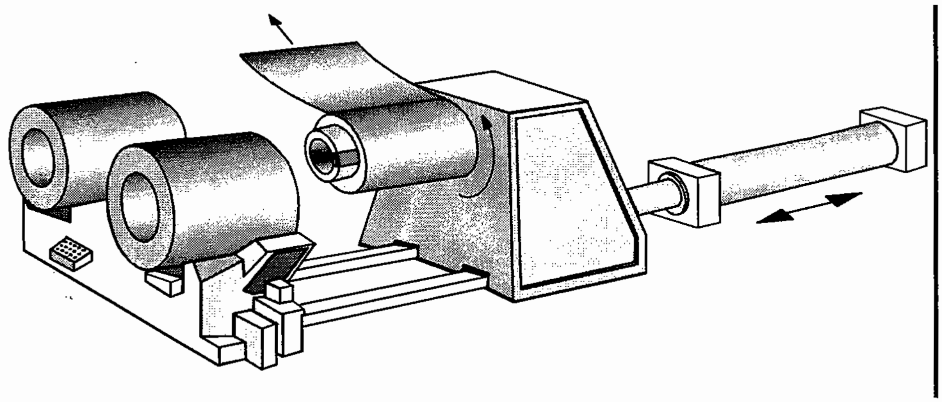
Problem description

The exchange of paper rolls on a printing machine is to take place automatically. One large, heavy paper roll is to be transported at a time from a storing place to the printing machine and attached in a fixture.

The paper roll is to be transported on a slide with a hydraulic drive unit. The paper roll must be precisely positioned so that it can be secured in the paper guide. The slide then returns empty.

The position control loop for this task is to be constructed and commissioned.

Positional sketch



Exercise

Position control loop with status controller

1. Constructing a position control loop with status controller
2. Establishing the stability range
3. Setting the parameters of a status controller
4. Measuring and calculating lag errors
5. Adapting the status controller to a modified controlled system

Execution

1. Position control loop with status controller

The position control loop consists of:

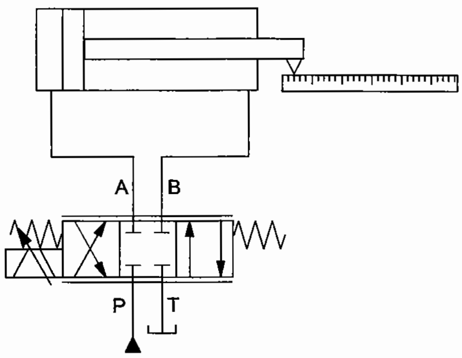
- the dynamic directional control valve for final control element,
- the linear drive for controlled system,
- the displacement sensor for feedback,
- the status controller for control

To be able to record the transition function,

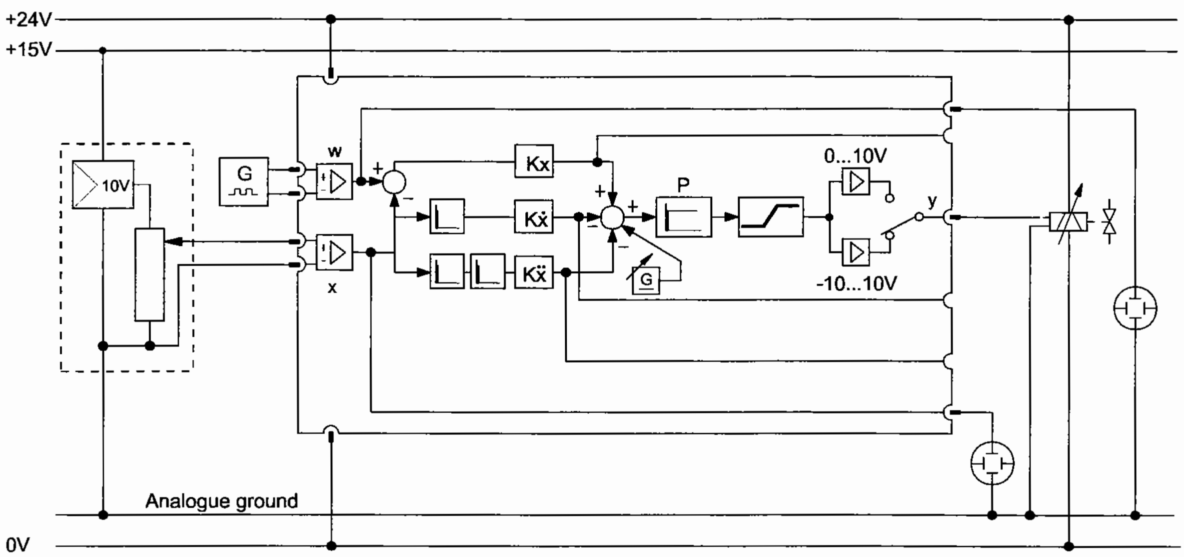
- a step function is specified as a setpoint value via the function generator and
- the step response recorded via the oscilloscope.

This results in the hydraulic and electrical circuit diagrams.

Circuit diagram, hydraulic



Circuit diagram, electrical



2. Stability range

Commissioning follows the same steps as those used for the position control loop of a P controller (exercises 15 and 18):

1. Specifying setpoint value for mid-position
2. Checking control direction
3. Setting offset

The status controller is used purely as a P controller to begin with in that the parameters of the two other loops are set at zero. The P controller gain is set to 10:

$$P = 10 \text{ and } K_x = 1 \text{ produces: } K_P = K_x \cdot P = 10$$

Setpoint and actual value are set on the oscilloscope. Then Kx is increased until steady-state oscillations occur, whereby the limit of stability is reached.

3. Parameterisation of status controller

1. The proportional gain $K_P = K_x \cdot P$ remains set as high as possible.
2. The oscillations are converted to a large overshoot by increasing the acceleration gain $K_{\ddot{x}}$.
3. This overshoot is attenuated by increasing the velocity gain $K_{\dot{x}}$.

The quality criteria to apply is:

1. No overshoot
2. No oscillations during the positioning process
3. Minimal position deviation
4. Short setting time

4. Measuring and calculating lag errors

If a ramp function has been specified as setpoint velocity, then it is also possible to measure a lag error in this instance.

The pure P branch produces the same lag error as that in exercise 16.

The lag error is significantly reduced by setting the optimised parameters of the status controller (see point 3.).

The lag error is to be calculated as a means of comparison.

To do so, the closed-loop gain V_0 is to be calculated first:

$$V_0 = K_R \cdot Kx \cdot P \cdot K_S$$

The values determined in exercises 12 and 14 apply for the feedback K_R and the controlled-system gain:

$$K_R = 50\frac{V}{m} \text{ and } K_S = 0.05\frac{\frac{m}{s}}{V}$$

5. Status controller with modified controlled system

As in exercise 17, the controlled system is modified by means of

- a load of 10kg
- two hose volumes of 0.1l each.

The same effects as those in exercise 17 can be seen for the P controller:

- smaller stability range and
- longer settling time.

The status controller is adapted to the modified controlled system by re-adjusting the parameters. The quality criteria is met to a much higher degree than with a P controller.

WORKSHEET

Position control loop with status controller

1. Constructing the position control loop

- Construct the closed control loop in accordance with the circuit diagrams.

Make sure that the test set-up and in particular the linear unit are securely attached to a sturdy base!

2. Establishing the stability range

Risk of injury!
Prior to switching on, make sure that no one is within the operating range of the slide

- Commission the closed control loop step by step:
- Safety-related presettings

Value table

Reference variable	*Controller parameter*				*Other*	
w	P	Kx	$K\dot{x}$	$K\ddot{x}$	Offset	Limiter

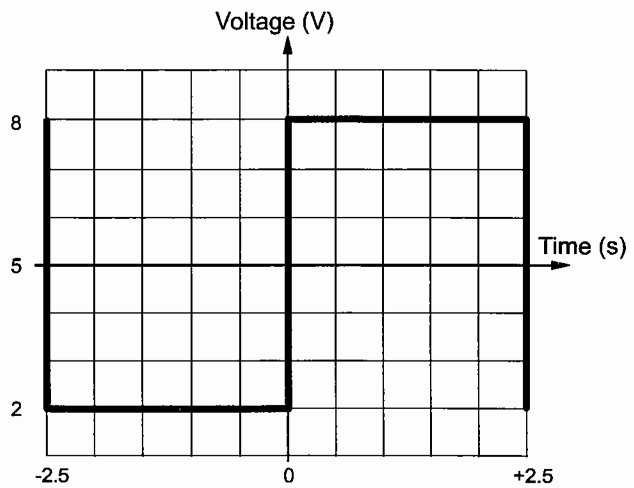
- Switch on the power supply

  Check the control direction ______________________

  Set the offset ______________________

- Transition function
- Setpoint value w = 5V ± 3V, f = approx. 1Hz square-wave

Diagram



Limit of stability

$$K_{Pcrit} = Kx \cdot P$$

3. Setting the parameters of the status controller

Set the parameters of the status controller in order that the quality criteria are met.

- Leave the K_P at the critical value K_{Pcrit}.
  Evaluate the transition function:

  ____

- Increase $K\ddot{x}$. How does the transition function change?

  ____

- Increase $K\dot{x}$. How does the transition function change?

  ____

- Do you obtain an optimal setting? yes / no

  If the quality criteria cannot be obtained in this way, then start again with a slightly reduced K_P.

- Also examine the limits with high values for $K\dot{x}$ and $K\ddot{x}$.

WORKSHEET

- Note the optimised parameters of the status controller and the settling time:

  P = ______________________________

  Kx = ______________________________

  $K\dot{x}$ = ______________________________ ms

  $K\ddot{x}$ = ______________________________ ms^2

  T_a = ______________________________ ms

Value table

Reference variable	*optimum controller parameters*				*Settling time*
	P	Kx	$K\dot{x}$	$K\ddot{x}$	T_a
5V ± 3V Square-wave			ms	ms^2	ms

4. Calculating and measuring lag errors

- Set the following setpoint value:

  w = 5V ± 3V, with 0.83Hz for ramp function

- Check the characteristics of the setpoint value at

  $$\frac{\Delta w}{\Delta t} = 10\frac{V}{s} = \frac{0{,}2V}{20ms}, \quad v = 0.2\ m/s$$

- Set the parameters of the status controller established above.
- Measure the system deviation e:

  e = ______________________________ (V)

- Convert the lag error e_x:

  e_x = ______________________________ (mm)

- Check the arithmetics of the lag error. To do so, first calculate the closed-loop gain V_0:

V_0 = ______________________ (1/s)

The lag error is then: $e_x = v \cdot \left(\frac{1}{V_0} + \frac{K\dot{x}}{Kx} \right)$

e_x = ______________________ (m)

- Compare the lag error with that for the P controller.
  For which controller is the lag error greater and why?

____

____

5. Status controller with modified controlled system

- Modify the controlled system by means of a load m and a hose volume V.
- Optimise the controller parameter for the modified system.
- Measure the settling time with optimum parameterisation.

Wertetabelle

$\frac{m}{V}$	$\frac{0kg}{0l}$	$\frac{10kg}{0l}$	$\frac{0kg}{0{,}1l}$	$\frac{10kg}{0{,}1l}$	*Tendency*
P					
Kx_{crit}					
Kx_{opt}					
$K\dot{x}_{opt}$					
$K\ddot{x}_{opt}$					
T_a					

- What difference do you notice in comparison with a pure P controller? (comparison with solution for exercise 17)

____

____

Closed-loop hydraulics — *Subject*

Horizontal grinding machine — *Title*

Training aim

- To be able to eliminate interferences in the hydraulic position control loop
- To be able to construct a position control loop with braking load
- To be able to detect interferences due to braking load

Technical knowledge

Controlled system with braking load

Forces occur on a machine during the machining process, which act against the feed. These are known as the “braking load”. The characteristics of the controlled system are considerably changed as a result of this braking load.

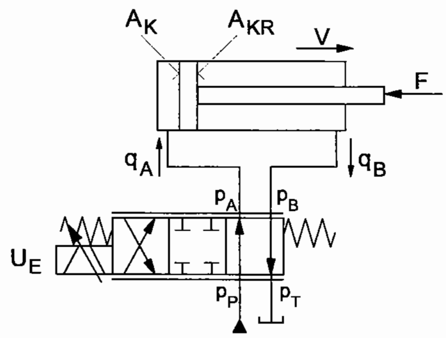


Fig. A21.1:
Hydraulic controlled system with braking load

Table A21.1: Changes in system variables as a result of braking load

Variable	*Formula*	*Change as a result of braking load*
Pump supply pressure p_P	-	constant
Valve activating signal V_E	-	constant
Braking load F	-	constant
Load pressure p_L	$\frac{F}{A_K}$	constant
Working pressure inside cylinder p_A	$p_A + p_L$	greater
Flow valve, inlet control edge q_A	$q_N \cdot \sqrt{\frac{(p_P - p_A)}{\Delta p_N}}$	smaller, since p_A greater
Forward velocity of piston v_{aus}	$q_A \cdot A_K$	smaller, since q_A smaller
System gain K_S	$\frac{v_{out}}{V_E}$	smaller, since v_{out} smaller
Closed-loop gain V_0	$K_P \cdot K_S \cdot K_R$	smaller, since K_S smaller
Lag error e	$\frac{v_{set}}{V_0}$	smaller, since v_0 smaller

Characteristics in the closed control loop with braking load

The description of the hydraulic characteristics in the closed control loop is set out in detail in exercise 14. The following describes the changes in the main characteristics. To simplify matters, only the advancing piston will be examined. The results are summarised in fig. A21.1 and table A21.1.

- The braking load F is converted into a load pressure p_L via the piston area A_K:

$$p_L = \frac{F}{A_K}$$

- The working pressure p_{AL} is greater with braking load than without:

$$p_{AL} > p_{A0}$$

- The differential pressure at the inlet control edge of the valve,

$$\Delta p = p_P - p_A,$$

  becomes smaller with increasing working pressure p_A:

$$\Delta p_L < \Delta p_0$$

- Since the flow rate is dependent on the differential pressure, this is also reduced under load (see flow characteristic curve of the valve):

  $q_L < q_0$.

- The forward velocity is reduced proportional to the flow rate:

  $v_L < v_0$

- $K_S = v / V_E$ results in a smaller system gain under load:

  $K_{SL} < K_{S0}$

- $V_0 = K_P \cdot K_S \cdot K_R$ results in a smaller closed-loop gain under load:

  $V_{0L} < V_{00}$

- $e = v / V_0$ results in a larger lag error:

  $e_L > e_0$

As a further explanation, the mathematical procedure for the working pressure with braking load is set out below (analogous to exercise 14):

Force equilibrium exists at the piston:

$$p_{AL} \cdot A_K = p_B \cdot A_{KR} + F$$

Area ratio

$$\alpha = \frac{A_K}{A_{KR}}$$

produces the working pressure

$$p_{AL} = p_B \cdot \frac{1}{\alpha} \cdot \frac{F}{A_K}$$

or

$$p_{AL} = p_B \cdot \frac{1}{\alpha} \cdot p_L$$

and the back pressure

$$p_{BL} = \alpha \cdot (p_{AL} - p_L)$$

The flow rate equilibrium in the cylinder is

$$q_{AL} = \alpha \cdot q_{BL}$$

The flow rate in the valve results in

$$q_N \cdot \frac{V_E}{V_{Emax}} \cdot \sqrt{\frac{p_P - p_{AL}}{\Delta p_N}} = \alpha \cdot q_N \cdot \frac{V_E}{V_{Emax}} \cdot \sqrt{\frac{p_{BL}}{\Delta p_N}}$$

$$p_P - p_{AL} = \alpha^2 \cdot p_{BL}$$

$$p_P - p_{AL} = \alpha^2 \cdot \alpha \cdot (p_{AL} - p_L)$$

$$p_P - p_{AL} = \alpha^3 \cdot p_{AL} - \alpha^3 \cdot p_L$$

$$p_{AL} \cdot (1 + \alpha^3) = p_P + \alpha^3 \cdot p_L$$

$$p_{AL} = \frac{p_P}{1+\alpha^3} + \frac{\alpha^3}{1+\alpha^3} \cdot p_L$$

$$p_{AL} = p_{A0} + \frac{\alpha^3}{1+\alpha^3} \cdot p_L$$

The working pressure p_{AL} under load is thus dependent on the load pressure pL and the area ratio in the cylinder.

Measures in the event of a braking load

The closed-loop gain, which has been reduced as a result of a load, can be adapted theoretically by means of a higher controller gain. In practice, however, a limit has been set by the stability.

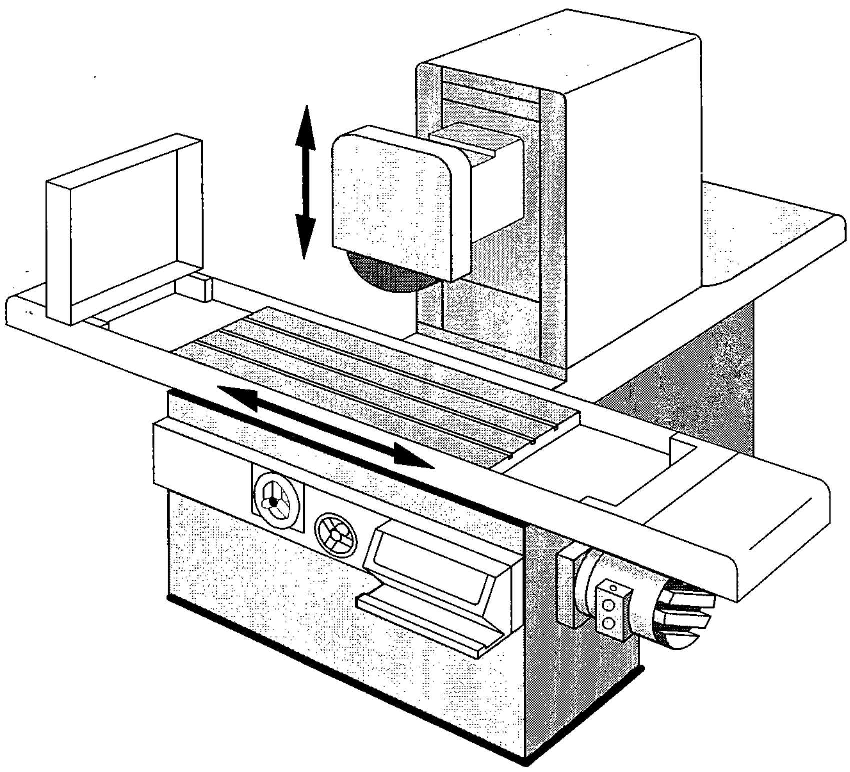
The lag error, which has been increased as a result of a load, can either be compensated by means of a higher closed-loop gain or a reduced velocity.

Problem description

Guide rails are to be machined on a horizontal grinding machine. The feed of the grinding wheel is to be set by means of a position control loop. Due to the machining forces, the load of the feed slide acts against the force. Despite this, the feed slide is to remain accurately positioned.

The installation has been constructed and commissioned. After a number of hours in operation, faults are occurring, which are to be rectified. The areas concerned are the hydraulics and faults as result of braking load.

Positional sketch



Exercise

Interferences in the closed control loop

1. Constructing and commissioning the closed control loop
2. Investigating interferences in the hydraulic circuit
3. Constructing a position control loop with braking load
4. Examining the interference behaviour with braking load

Execution

1. Position control loop

Exercise 18 provides a detailed description of fault finding in a hydraulic position control loop with P controller. The faults addressed in the hydraulics in that exercise are to be examined as a comparison using a status controller relating to:

- drop in supply pressure
- leakage in the cylinder.

The closed control loop thus consists of:

- a dynamic directional control valve for final control element,
- a linear drive for controlled system,
- a displacement sensor for feedback,
- a status controller for control d

Interferences are to be simulated by means of:

- a pressure relief valve in the by-pass to the hydraulic power pack and
- a flow control valve between the working lines.

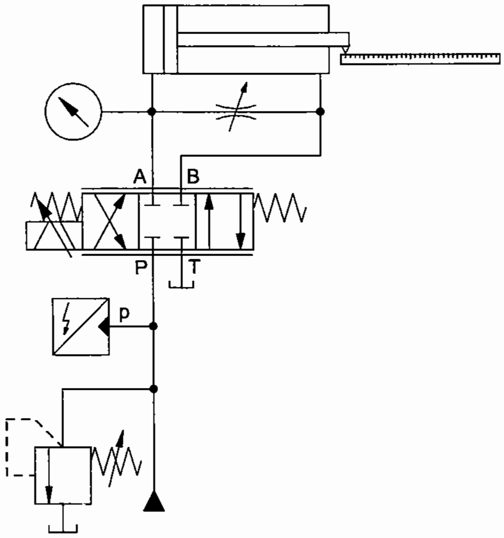
Measuring points for the pressure are to be provided at:

- Supply port p_P and
- Power port p_A.

The following are required for commissioning:

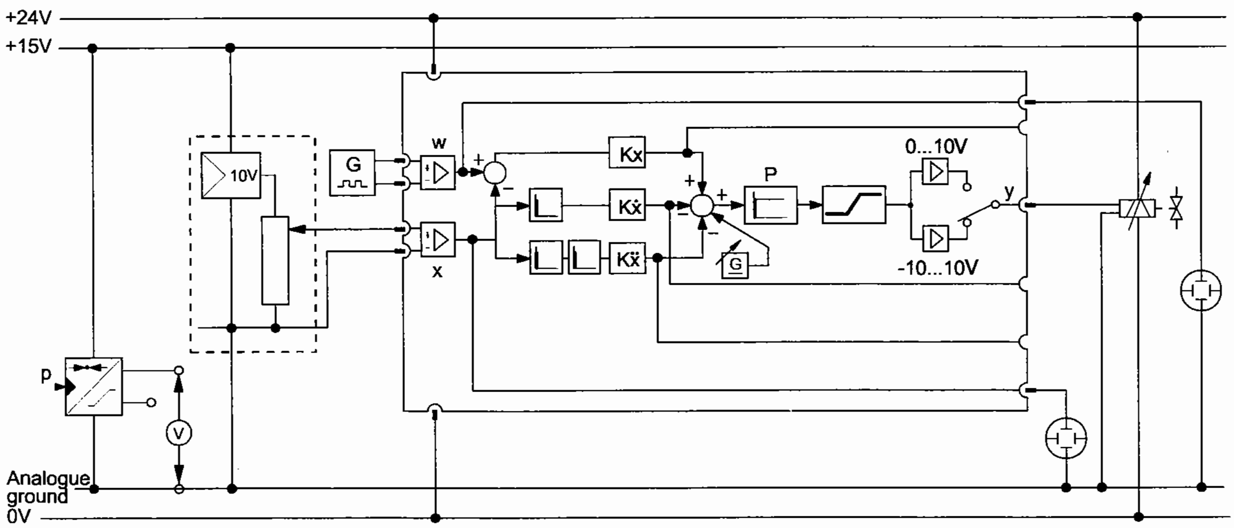
- a multimeter,
- a frequency generator,
- an oscilloscope.

This results in the hydraulic and electrical circuit diagrams.



Circuit diagram, hydraulic

Circuit diagram, electrical



It is assumed that the procedure for the commissioning of the position control loop is known. However, to make sure, the most important points in the check list are covered in exercise 18).

2. Interferences in the hydraulic circuit

A step function is set as reference variable:

- $w = 1.5V \pm 0.5V$ as square wave signal

The interference-free initial status is described by:

- $K_{Pcrit0} = Kx_{crit0} \cdot P$
- K_{Popt0} and T_{a0}

2.1 Pressure drop

The interference is to be simulated by gradually adjusting the pressure relief valve. The supply pressure p_P can be read on the pressure gauge.

To be able to make a comparison with the initial status, the characteristics are measured first of all without interference:

- $K_{Pcrit} = Kx_{crit} \cdot P$
- T_a at K_{Popt0}
- working pressure p_A
- dependent on supply pressure p_P

A second series of measurements is to investigate how far the interference can be compensated by means of the status controller. The status controller is to be set at an optimum setting with different supply pressures p_P. The result is:

- Kx_{opt}, $K\dot{x}_{opt}$, $K\ddot{x}_{opt}$,
- T_{aopt}
- dependent on supply pressure p_P

2.2 Leakage

The following characteristics are measured with the help of the step response:

- limit of stability K_{Pcrit} and
- system deviation e
- dependent on leakage..

The deviations as a result of the interference are to be compensated by re-adjusting the controller parameters. The result is to be compared with the P controller (exercise 18).

3. Position control loop with braking load

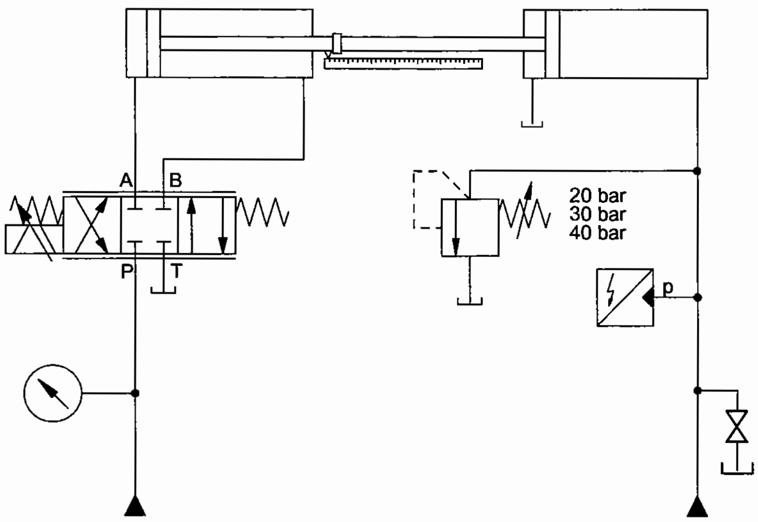
The breaking load is generated by means of a double-acting cylinder, which acts against the operating cylinder. This results in a second control sequence with following devices:

- hydraulic power pack for the load cylinder,
- pressure relief valve in the by-pass to set the pressure in the load cylinder,
- stop cock to relieve the pressure in the load cylinder to the tank.

The following are to be measured

- supply pressure p_P and
- load pressure p_L

This results in a new hydraulic circuit. The electrical circuit remains the same as that under point 1.



Circuit diagram, hydraulic

4. Response to interference with braking load

Since the load cylinder and operating cylinder are of the same dimensions, the set pressure on the piston side of the load cylinder corresponds to the load pressure p_L on the piston side of the operating cylinder. The force F_L, exerted by the load cylinder can be calculated from:

$$F_L = p_L \cdot A_K \qquad A_K = 2.01\,cm^2$$

p_L in bar	5	10	20	40
F_L in kp	10	20	40	80

4.1 Transition function

In order to record the transition function of an interference,

- a constant reference variable is specified and
- a step-change interference connected.

The transition function changes with

- the connection and disconnection of the load,
- the size of the load and
- the controller gain set.

4.2 Lag error

A ramp is specified as a reference variable:

- $v_{soll} = \frac{w}{t} = \text{constant}$

The following are to be investigated:

- different loads,
- different controller settings and
- different setpoint velocities.

The comparison with the result from exercise 17 demonstrates that the lag error changes as a result of the interference (braking load), whilst no changes occur as a result of the modified controlled system (mass and volume).

Computational verification for larger lag error — *Note*

The following characteristics are to be assumed for the purpose of an example (in accordance with exercise 14 and exercise 16):

Piston area:	A_K	=	$201cm^2$
Piston annular area:	A_{KR}	=	$122.6cm^2$
Area ratio:	α	=	1.6
Supply pressure:	p_P	=	60bar
Load pressure:	p_L	=	30bar
Nominal differential pressure:	Δp_N	=	35bar
Nominal flow rate:	q_N	=	5 l/min
Control voltage:	V_{Emax}	=	10V
Controller gain:	K_P	=	40
Transfer coefficient of feedback:	K_R	=	50 V/m
Setpoint velocity:	v_{set}	=	0.2 m/s

The following is the product of the formulas given in exercise 14:

Working pressure

$$p_{AL} = \frac{p_P}{1+\alpha^3} + \frac{\alpha^3}{1+\alpha^3} \cdot p_L$$

$$p_{AL} = \frac{1}{1+\alpha^3} \cdot (p_P + \alpha^3 \cdot p_L)$$

$$p_{AL} = \frac{1}{1+1.6^3} \cdot (60bar + 1.6^3 \cdot 30bar)$$

$$p_{AL} = 36bar$$

Controlled-system gain

$$K_{SL} = \frac{q_N}{A_K \cdot V_{Emax}} \cdot \sqrt{\frac{\alpha^3}{1+\alpha^3} \cdot \frac{p_P - p_L}{\Delta p_N}}$$

$$K_{SL} = \frac{5\,\mathrm{l/min}}{2.01\,\mathrm{cm}^2 \cdot 10\,\mathrm{V}} \cdot \sqrt{\frac{1.6^3}{1+1.6^3} \cdot \frac{60\,\mathrm{bar} - 30\,\mathrm{bar}}{35\,\mathrm{bar}}}$$

$$K_{SL} = 3.45\frac{\mathrm{cm/s}}{\mathrm{V}} = 0.0345\frac{\mathrm{m/s}}{\mathrm{V}}$$

Closed-loop gain

$$V_{0L} = K_P \cdot K_{SL} \cdot K_R = 40 \cdot 0.0345\frac{\mathrm{m/s}}{\mathrm{V}} \cdot 50\frac{\mathrm{V}}{\mathrm{m}}$$

$$V_{0L} = 69\frac{1}{\mathrm{s}}$$

Lag error

$$e_{xL} = \frac{v_{set}}{V_{0L}} = \frac{0.2\frac{\mathrm{m}}{\mathrm{s}}}{69\frac{1}{\mathrm{s}}} = 2.9\,\mathrm{mm}$$

System deviation

$$e_L = e_{xL} \cdot K_R = 0.0029\mathrm{m} \cdot 50\,\mathrm{V/m} = 0.145\mathrm{V}$$

The comparison produces:

Value table

	without interference	with interference
Load pressure p_L	0bar	30bar
Working pressure p_A	12bar	36bar
System gain K_S	$0.05\frac{\mathrm{m/s}}{\mathrm{V}}$	$0.03\frac{\mathrm{m/s}}{\mathrm{V}}$
Closed-loop gain V_0	$100\frac{1}{\mathrm{s}}$	$69\frac{1}{\mathrm{s}}$
Lag error e_x	2mm	2.9mm

WORKSHEET

Interferences in the position control loop

1. Position control loop

- Construct the closed control loop in accordance with the circuit diagrams.
- Completely close the pressure relief valve and the flow control valve.

Make sure that the test set-up and in particular the linear unit are securely attached to a sturdy base!

- Carry out the commissioning of the closed control loop.

Risk of injury!
Prior to switching on, make sure that no one is within the operating range of the slide!

- Safety-related presettings

Value table

Reference variable	*Controller parameters*				*Other parameters*	
w	P	Kx	$K\dot{x}$	$K\ddot{x}$	Offset	Limiter

- Switch on power supply
- Check control direction
- Set offset
- Set the controller

Value table

Reference variable	*Controller parameters*				
w	K_{Pcrit}	K_{Popt}	P	$K\dot{x}$	$K\ddot{x}$
1.5V ± 0.5V Square-wave					

2. Interferences in the hydraulic circuit

- Set a setpoint value of w = 1.5V ± 0.5V as a square wave.
- Record the reference variable w and the controlled variable x on the oscilloscope.
- Check whether the pressure relief valve and the flow control valve are closed.
- Note the characteristics for the interference-free closed control loop:

K_{Pcrit0} = ______________________________

K_{Popt0} = ______________________________

$K\dot{x}$ = ______________________________

$K\ddot{x}$ = ______________________________

T_{off0} = ______________________________

T_{on0} = ______________________________

2.1 Pressure drop

Simulate the drop in supply pressure p_P by gradually opening the pressure relief valve. Determine the following characteristics and evaluate the changes:

Value table

Characteristic	*Values*					*Tendency*
p_P	50	40	30	20	10bar	decreases
K_{Pcrit}						
T_{out} at K_{Popt0}						

WORKSHEET

- Try to compensate the interference by optimising the controller parameters. Enter the parameters and your evaluation in the value table.

Value table

Characteristic	*Values*					*Tendency*
p_P	50	40	30	20	10bar	decreases
K_{Popt}						
$K\dot{x}_{opt}$						
$K\ddot{x}_{opt}$						
T_{outopt}						

- How far can you compensate the interference? Compare the result with the P controller in exercise 18.

____

____

2.2 Leakage

Simulate a leakage qL in the cylinder by gradually opening the flow control valve. Determine the following characteristics and evaluate the change:

Value table

Characteristic	*Values*				*Tendency*
q_L	1/8	1/4	3/8	1/2 Rot.	increasing
K_{Pcrit}					
T_{out} at K_{Popt0}					
T_{in} at K_{Popt0}					
e_{stat}					

- Try to compensate the interference by re-adjusting the controller parameters and the offset. Enter your evaluation in the table.

Value table

Characteristic	*Values*				*Tendency*
q_L	1/8	1/4	3/8	1/2 Rot.	increasing
K_{Pcrit}					
$K\dot{x}_{opt}$					
$K\ddot{x}_{opt}$					
T_{outopt}					
T_{inopt}					
e_{stat}					

- Can you compensate the interference? Compare the result with the P controller in exercise 18.

____

____

3. Position control loop with braking load

- Construct a circuit with breaking load. Mount the load cylinder so that it covers the stroke range of the operating cylinder: If the load cylinder is advanced, then the operating cylinder is retracted.
- Carry out the commissioning as described under 1, whereby the pressure relief valve and the flow valve are to be completely opened so that the load cylinder is relieved of pressure.
- Test the load cylinder by closing the flow valve and setting different load pressures.

WORKSHEET

4. Response to interference with braking load

4.1 Transition function

- Set a constant reference variable, e.g. w = 2V.
- Set $K_P = K_{Popt}$ for controller gain, e.g. $K_P = 40$.
- Compare the transition functions with different loads with the help of the characteristic data.

Value table

Characteristic	*Values*							*Tendency*
Connecting load	on	off	on	off	on	off		
p_L	20	20	30	30	40	40	bar	increasing
x							mV	
x_m							mm	
T_a							sec	

- Set a constant load pressure, e. g. p_L = 30bar. Compare the transition functions connecting the load with different controller parameters.

Value table

Characteristic	*Values*					*Tendency*
K_P	20	40	60	80		increasing
x					mV	
x_m					mm	
T_a					sec	
e_{stat}						

- As what point of controller gain does the steady-state system deviation e_{stat} become zero?

____

____

4.2 Lag error

- Set the following reference variable:

  $w = 5V \pm 3V$ with 0.83Hz as ramp function

- Check the pattern of the setpoint value for

$$\frac{\Delta w}{\Delta t} = 10\frac{V}{s} = \frac{0.2V}{20ms}, \qquad v_{set} = 0.2\frac{m}{s}$$

- Set a P controller with $K_P = K_{Popt}$, e.g. $K_P = 40$.
- Compare the lag error using different loads.

Value table

Characteristic	*Values*					*Tendency*
p_L	0	10	20	30	bar	increasing
e					V	
e_x					mm	

- Set a constant load, e.g. p_L = 30bar. Minimise the lag error by optimising the controller parameters.

Value table

Characteristic	*Values*					*Tendency*
K_P	20	40	60	80		increasing
e					V	
e_x					mm	

- Set a constant load, e.g. p_L = 30bar.
- Set a constant controller gain, e. g. K_P = 40.
- Compare the lag error using different velocities.

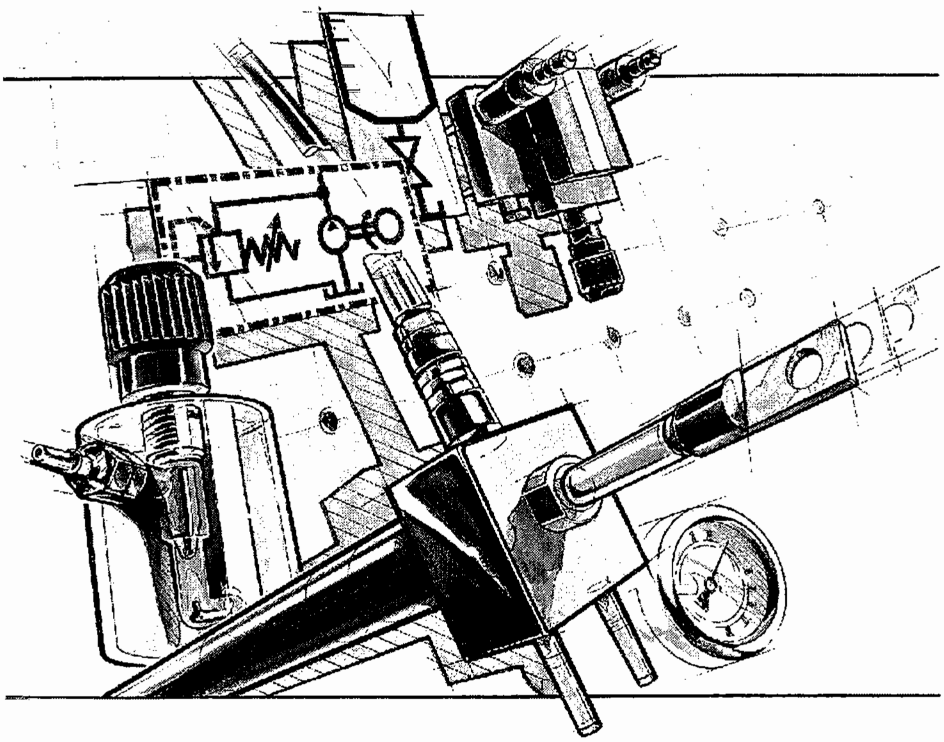
Value table

Characteristic	*Values*			*Tendency*
v_{soll}	0.1	0.2	m/s	increasing
w	0.1/20	0.2/20	V/ms	increasing
e			V	
e_x			mm	

Fundamentals

Closed-loop hydraulics

Textbook



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Part B – Fundamentals

Fundamentals

In order to understand closed-loop control technology, it is necessary to be familiar with certain technical terms.

These terms will be presented and explained in this chapter.

1.1 Signals

A signal is used to transmit information in a technical system. A signal is represented by a physical variable, for example an electrical voltage or a pressure.

Binary signal

The pressure in a compressed-air reservoir is monitored by a pressure sensor (Fig. B1.1). The associated signal may assume two values:

- Permissible pressure exceeded, circuit closed, indicating light illuminated
- Permissible pressure not exceeded, circuit open, indicating light not illuminated.

A signal which can assume only two values is known as a binary signal.

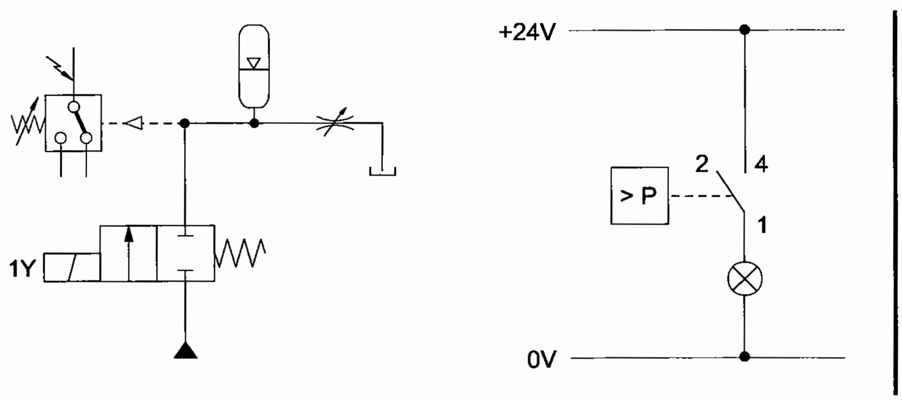


Fig. B1.1: Reservoir with pressure monitoring

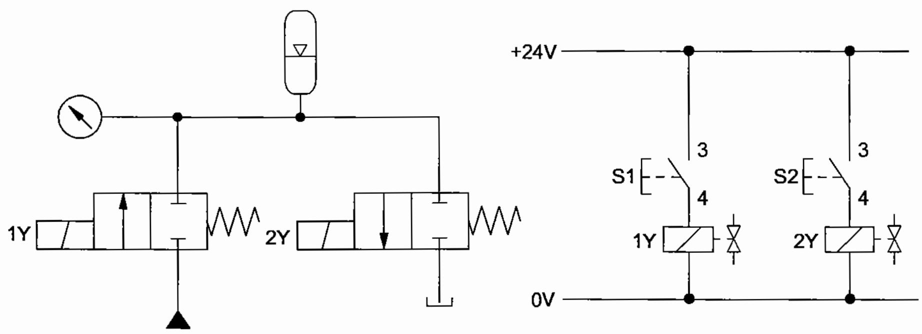
When the reservoir is filled or emptied, the value of the signal changes. The binary signal is shown in graphic form in Fig. B1.2 as a function of time. The value changes in steps. Since the signal has precisely one value at any point in time, its value is a function of time.

Fig. B1.2: Binary signal as a function of time

Analogue signal

In the case of the hydraulic circuit in Fig. B1.3, the pressure is measured and displayed using a pressure gauge. The pressure signal can assume any number of intermediate values between its minimum and maximum values. This is referred to as an analogue signal.

Fig. B1.3: Reservoir with pressure gauge



The pressure in the reservoir can be controlled by the two switching valves (Fig. B1.3). The signal curve is shown in Fig. B1.4.

- In phase 1, valve 1 is open. Air flows into the reservoir. The pressure in the reservoir rises.
- In phase 2, both valves are closed. The pressure remains constant.
- In phase 3, valve 1 is once again open. The pressure rises further.
- At the start of phase 4, valve 1 is closed and valve 2 is open. Compressed air flows out of the reservoir. The pressure in the reservoir falls to the level of the ambient pressure.

A comparison of Figs. B1.2 and B1.4 shows:

- The binary signal exhibits a step-change.
- The analogue signal changes continuously.

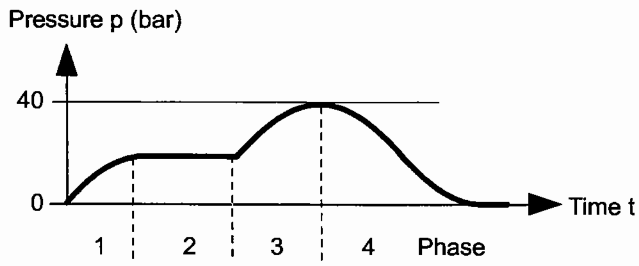


Fig. B1.4: Analogue signal as a function of time

Signals for valve actuation

A binary signal is used to actuate a switching valve (Fig. B1.5a). The signal and thus the opening of the valve can assume only two values:

- Signal 0V, valve closed
- Signal 24V, valve open.

An analogue signal is used to actuate a dynamic valve. The signal and thus the opening of the valve can vary continuously between a minimum and a maximum value (Fig. 1.5b).

- A signal of 0V means: Valve closed.
- A signal of 5V means: Valve half open.
- With a signal of 10V the maximum valve opening is achieved.

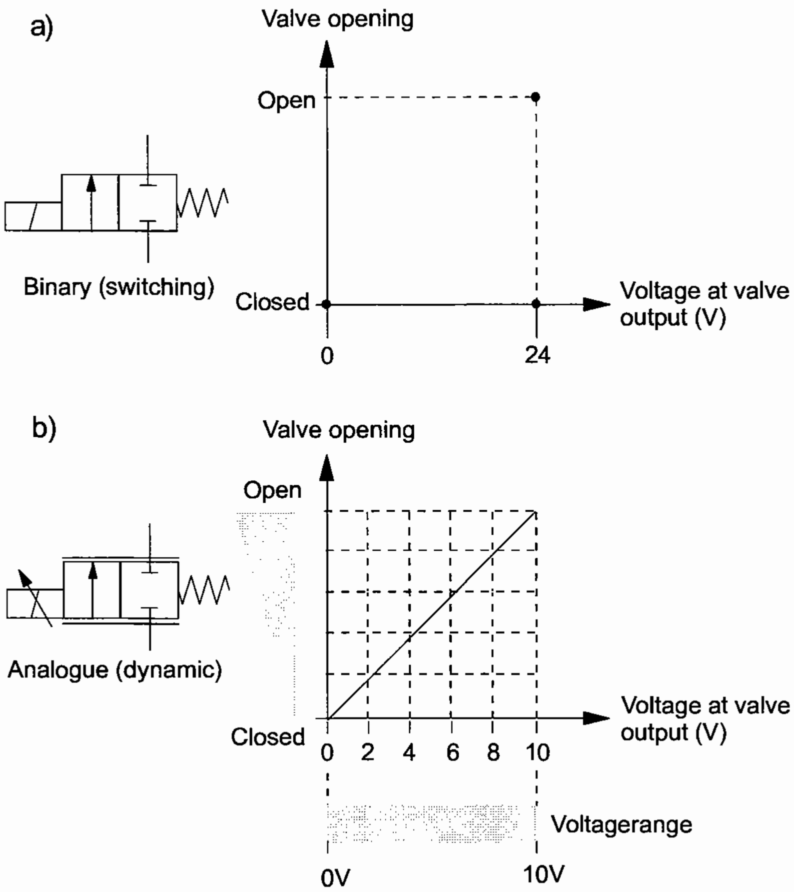


Fig. B1.5:
Actuation of a switching valve and a dynamic valve

1.2 Block diagram

Block diagrams are a graphic means of displaying

- the signals present and
- the effects these signals have.

We distinguish between the input signal and the output signal.

- The input signal acts on an electrical or hydraulic device.
- The output signal is generated by the device.

The block diagram shows the input signal, the transmission box and the output signal.

Fig. B1.6a shows the example of the block diagram for an electrically-actuated switching valve.

- The voltage V acts on the valve. The voltage represents the input signal.
- The valve influences the flow rate q. The flow rate represents the output signal.
- The valve itself represents the transmission component or the transmission box.

Fig. B1.6b shows a block diagram for a hydraulic cylinder.

- The volumetric flow rate q represents the input signal.
- The velocity v of the piston represents the output signal.
- The cylinder represents the transmission component or transmission box.

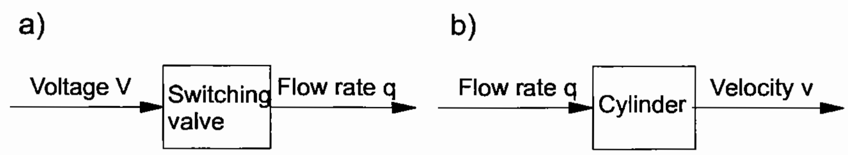


Fig. B1.6a + b: Block diagrams for a switching valve and a hydraulic cylinder

Step response, transition function

If a step-change input signal acts on a transmission component, we describe the output signal as a step response or a transition function.

Fig. 1.7 shows circuit diagrams, signals and a block diagram for a hydraulic proportional valve. The following allocations apply:

- The input signal forms the electrical signal for valve actuation
- The output signal represents the flow through the valve.

Phase 1: The input signal is zero. The valve is closed.

Phase 2: The input signal has changed. The spool does not as yet move. The flow rate remains at zero for the time being.

Phase 3: The valve spool moves. The flow rate increases. This phase is relatively short (between 5 and 50 ms, depending on the valve).

Phase 4: The spool is in its end position. The flow rate is constant.

Block diagrams generally feature a graphic representation of the step response (Fig. B1.7e). This provides a clearer representation than a description in words (Fig. B1.6).

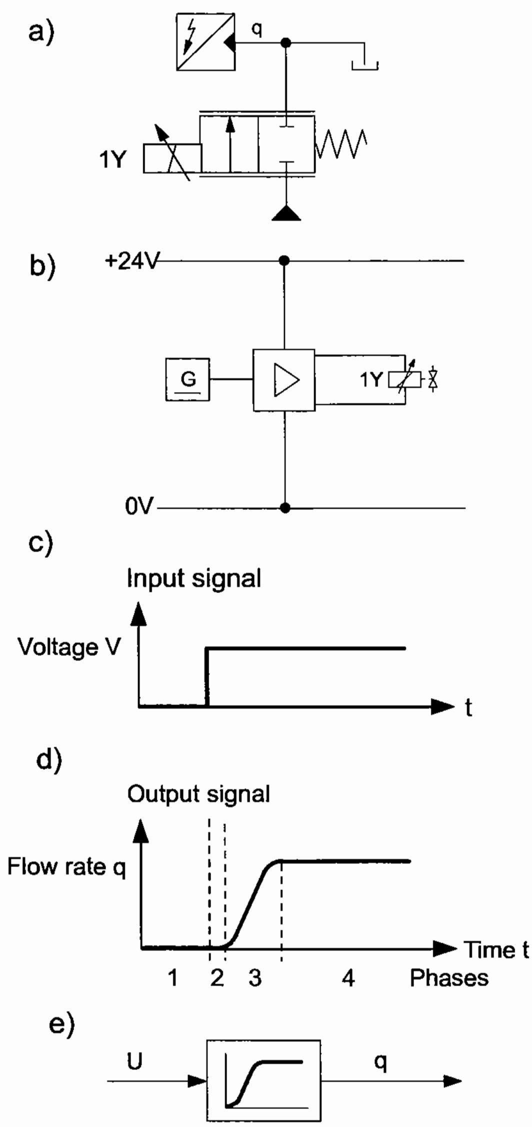


Fig. B1.7:
Step response and block diagram for a proportional valve

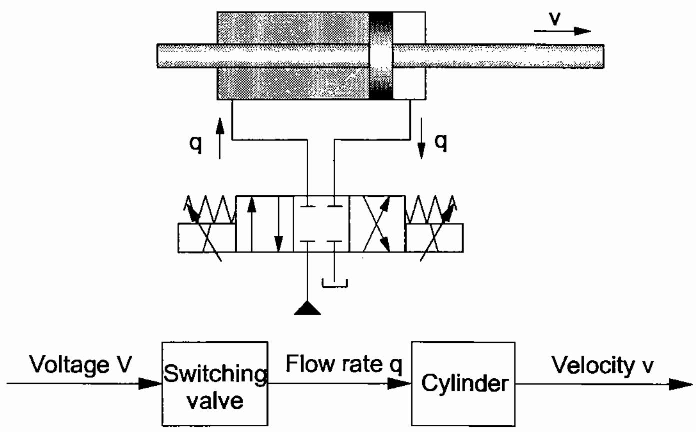
1.3 Signal flow diagram

In the signal flow diagram, the individual transmission blocks of a circuit are linked together.

Series circuit

Fig. B1.8 shows a hydraulic circuit consisting of a switching valve and hydraulic cylinder. The output signal of the switching valve forms the input signal for the hydraulic cylinder. We describe the two blocks as being in a series circuit.

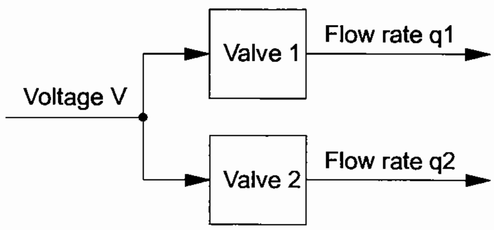
Fig. B1.8: Signal flow diagram: Series circuit



Branch

If the valve energisation signal acts on two switching valves, this means a branch in the signal flow diagram (Fig. B1.9). A branch is indicated by a dot. This is the same as the representation of a branch in an electrical circuit diagram.

Fig. B1.9: Signal flow diagram: Branch



Junction

If a cylinder can be pressurised by two switching valves, this involves a junction in the signal flow diagram. A junction is shown by a circle and two "plus" signs (Fig. B1.10). If one of the two switching valves is connected not to the supply port but to the exhaust, this means that the piston will move in the opposite direction. This is shown in the signal flow diagram by a "minus" sign.

The "plus" signs are generally omitted from signal flow diagrams. "Minus" signs, on the other hand, must always be shown.

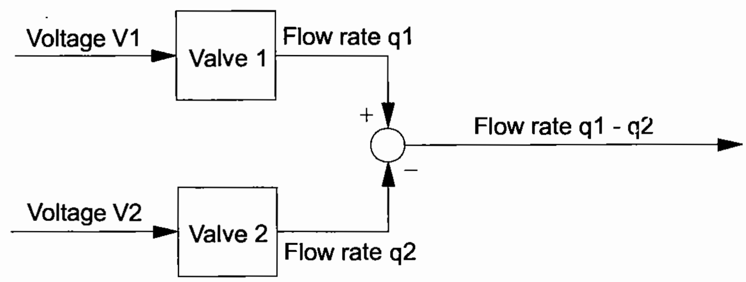


Fig. B1.10:
Signal flow diagram:
Junction

Parallel circuit

Fig. B1.11 shows a system in which the input signal acts on two switching valves (signal branch). The two switching valves supply the same cylinder with compressed air (junction). This combination of a branch and junction is known as a parallel circuit.

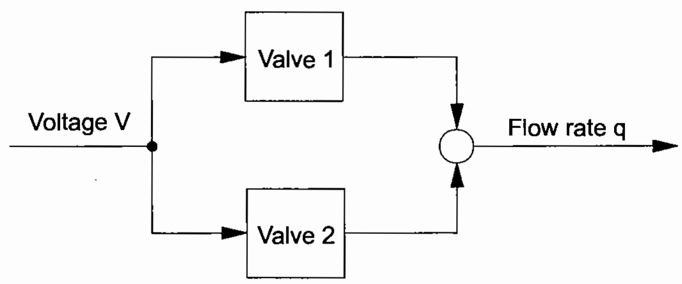


Fig. B1.11:
Signal flow diagram:
Parallel circuit

1.4 Test signals

A test signal is applied to the input of a transmission component. This may be a step-change or ramp-shaped signal. The transmission component reacts to the change in the input signal with a change in the output signal. The output signal of the transmission component is displayed.

Transition function

Fig. B1.12b shows the transition function of a hydraulic valve.

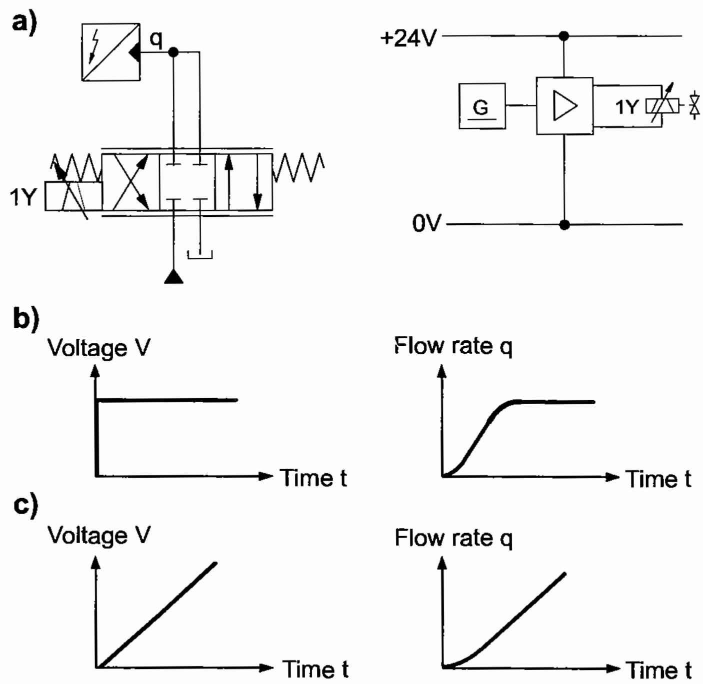
- The voltage V forms the input signal. This is subjected to a step-change.
- The flow rate q forms the output signal. This changes continuously. The change in the flow rate occurs with a delay relative to the change in the voltage.

Ramp function

Fig. B1.12c shows a ramp function of a valve.

- The voltage V is subject to a ramp change.
- The flow rate q rises with a delay relative to the voltage.

Fig. B1.12: Transition and ramp functions



In practice, test signals are produced with an electrical function generator. The three most common types of test signals are:

- Square-wave signal (result of step changes)
- Triangular-wave signal (result of ramps)
- Sine-wave signal.

Fig. B1.13 shows a test signal acting on a valve. The output signal is the flow rate measured through the valve. The valve exhibits the following reaction:

- The output signal follows square-wave changes in the test signal with a slight delay. The edges of the output signal are inclined and the transition points are rounded. The output signal corresponds to a series of several transition functions.
- With the triangular-wave signal, too, a delay in the output signal can be observed. The input signal exhibits peaks. In the output signal, the transition points are rounded. The output signal corresponds to a series of several ramp functions.
- In the case of the sine-wave input signal, the output signal also follows with a slight delay. The output signal is approximately sinusoidal.

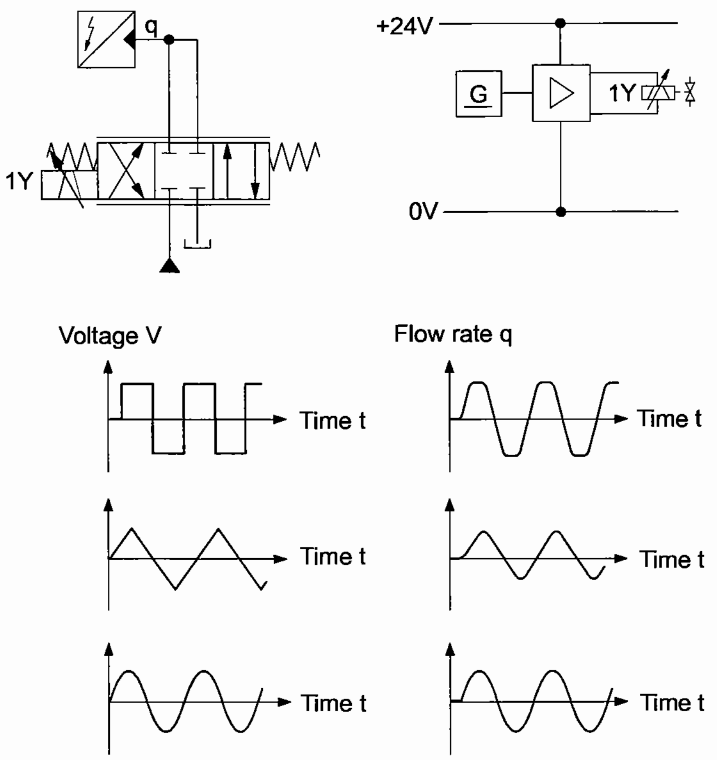


Fig. B1.13:
Test signals

1.5 Open-loop and closed-loop control

Fig. B1.14a shows a hydraulic circuit for the open-loop control of velocity. The velocity of the piston rod is measured with a speed sensor.

The piston of the hydraulic cylinder is to advance at a constant velocity of 30 cm/s. Tests have been carried out to determine the signal required for valve actuation. Measurements have indicated that the required velocity is achieved with a voltage of 4V.

Fig. B1.14b shows the associated signal flow diagram:

- The required voltage, i.e. 4V, is generated by an electrical circuit.
- The voltage acts on the valve.
- The valve controls the flow rate.
- The flow rate determines the velocity of the piston.

Open control loop

All the transmission blocks in the signal flow diagram are connected in series. A series connection of several devices is known as an open control loop.

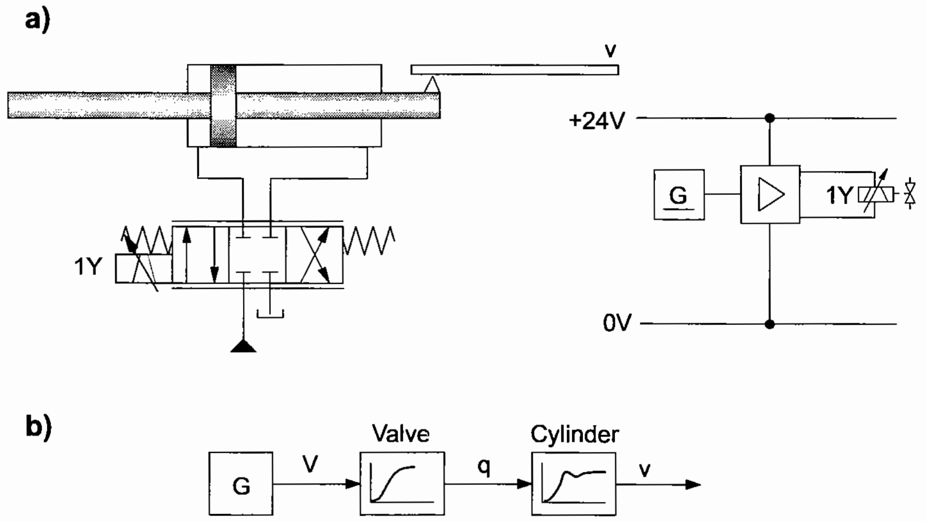


Fig. B1.14: Open control loop

The piston velocity shown in Fig. B1.14 depends not only on the valve opening but is influenced by further variables such as the following:

- Frictional forces acting on the seals of the hydraulic cylinder
- Fluctuations in the supply pressure
- Leakage through loose connectors
- Reduced flow rate due to the use of tubing with a small cross-section.

All these influential factors mean that a velocity of 30 cm/s is not reached precisely using the above circuit.

Closed control loop

In order to improve accuracy, the actual velocity must also be evaluated. The velocity is continuously measured with a speed sensor. The measured value is continuously compared with the velocity setpoint value.

- If the velocity is too low, the valve is opened further.
- If the velocity is higher than desired, the opening of the valve is reduced.

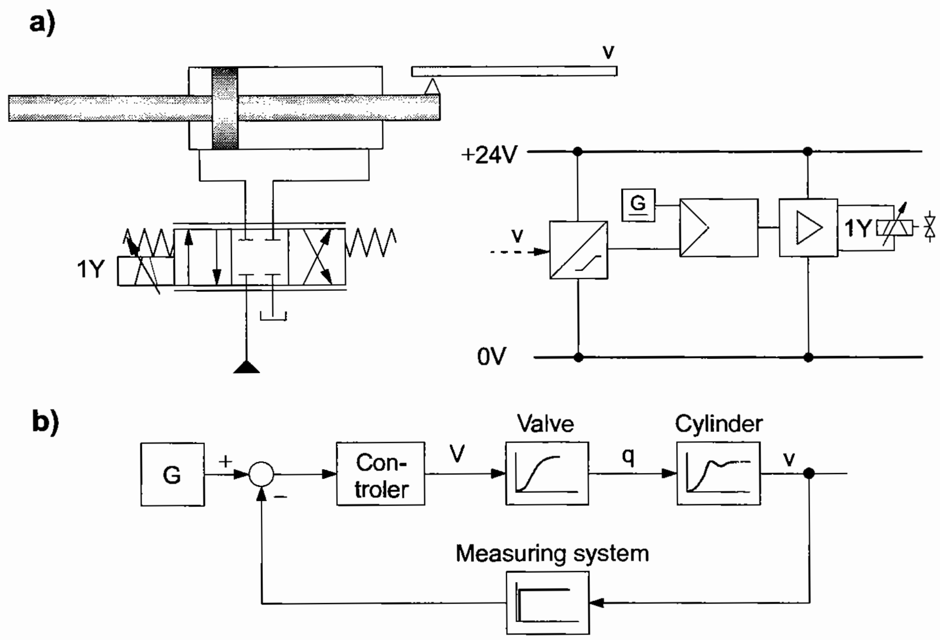
By adjusting the valve it is endeavoured to keep the difference between the setpoint velocity value and the actual velocity value as small as possible.

This circuit is a closed-loop control, Fig. B1.15 shows the signal flow diagram for this. Because of its closed structure the signal flow diagram is known as a closed control loop.

Feedback

In a closed-loop control circuit, the measured value is fed back in the signal flow diagram to the controller input. This is known as feedback.

Fig. B1.15:
Closed control loop
for speed control



Comparison of open-loop and closed-loop control circuits

A distinction can be made between open-loop control circuits and closed-loop circuits as follows:

- Circuits which operate with continuous feedback of the output variable are known as closed-loop control circuits.
- Circuits which operate without continuous feedback of the output variable are known as open-loop control circuits.

Table B1.1 shows the properties of the signal flow diagrams.

Table B1.1:
Signal flow diagrams for open-loop and closed-loop controls

Criteria	*Open-loop control*	*Closed-loop control*
Form of signal flow diagram	Open (series circuit)	Closed
Designation of signal flow diagram	Open-loop control circuit	Closed-loop control circuit
Measurement of output signal	Not necessary	Continuous measurement
Feedback of output signal	No	Yes

1.6 Closed control loop terminology

Fig. B1.16 shows a closed-loop control circuit with the standard designations for the various signals and components. These terms are defined in DIN 19226 “Closed-Loop and Open-Loop Control Technology”.

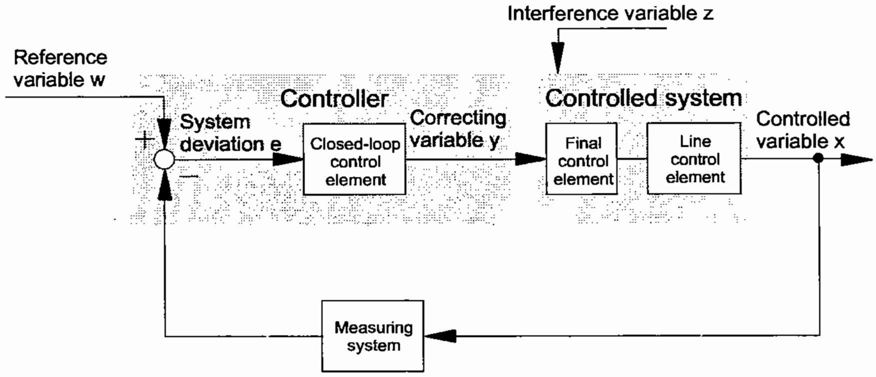


Fig. B1.16: Closed control loop: Terminology

Controlled variable x

The controlled variable x is the output variable of the closed-loop control circuit. The controlled variable is also known as the actual value.

In Fig. B1.15, the velocity forms the controlled variable.

Reference variable w

The reference variable w represents the value which the controlled variable is to assume. With an ideal closed-loop control system, the reference variable and controlled variable will have the same value. The reference variable is also known as the setpoint value.

The velocity setpoint represents the reference variable for the closed-loop velocity control system (Fig. B1.15).

Feedback variable r

DIN 19226 makes a distinction between the controlled variable x and the feedback variable r. The feedback variable is defined as the measured value of the controlled variable.

In the closed-loop velocity control system (Fig. B1.15), the velocity forms the controlled variable. The velocity is measured with a speed sensor. The output variable of this speed sensor is a voltage. The voltage forms the feedback variable r.

The term "feedback variable" has not yet become widely accepted. People often speak of the controlled variable x when they actually mean the feedback variable r.

System deviation e

The system deviation e is the difference between the reference variable w and the feedback variable r. It is calculated as follows:

$$e = w - r$$

If, for the sake of simplicity, we use the controlled variable instead of the feedback variable, the following formula results:

$$e = w - x$$

In the closed-loop control circuit in Fig. B1.15, the system deviation is represented by the difference between the velocity setpoint value and the measured value for the actual piston velocity.

Correcting variable y

The controller compares the controlled variable with the reference variable. It generates a controller output variable, which is known as the correcting variable. The correcting variable y applies the controlling action of the controller to the final control element. It forms the input signal for the controlled system.

In Fig. B1.15, the controller energises the valve with a voltage. This voltage is the correcting variable.

Final control element

The final control element is part of the controlled system. It is energised with the correcting variable and acts on the flow of energy in the closed-loop control circuit.

A dynamic 5/3-way valve is used as a final control element in the closed-loop velocity control system in Fig. B1.15.

Controlled-system component

The controlled-system component is the part of the closed-loop control circuit in which the controlled variable is generated. In the case of the closed-loop velocity control system (Fig. B1.15), the controlled-system component is formed by the tubing and the hydraulic cylinder.

Controlled system

The controlled system consists of the final control element and the controlled-system component. The controlled system in Fig. B1.15 is made up of the following components:

- Valve
- Tubing
- Cylinder.

Interference variable z

Interference variables act from the outside on the closed-loop control circuit and produce an undesired change in the controlled variable. Interference variables act in the main on the controlled system.

Examples of interference variables in the closed-loop velocity control system shown in Fig. B1.15 are leaks. friction and forces acting on the piston rod.

Measuring system

A measuring system is used to measure the controlled variable. A measuring system is often also referred to as a sensor or encoder.

In the closed-loop velocity control system (Fig. B1.15), a speed sensor is used as a measuring system.

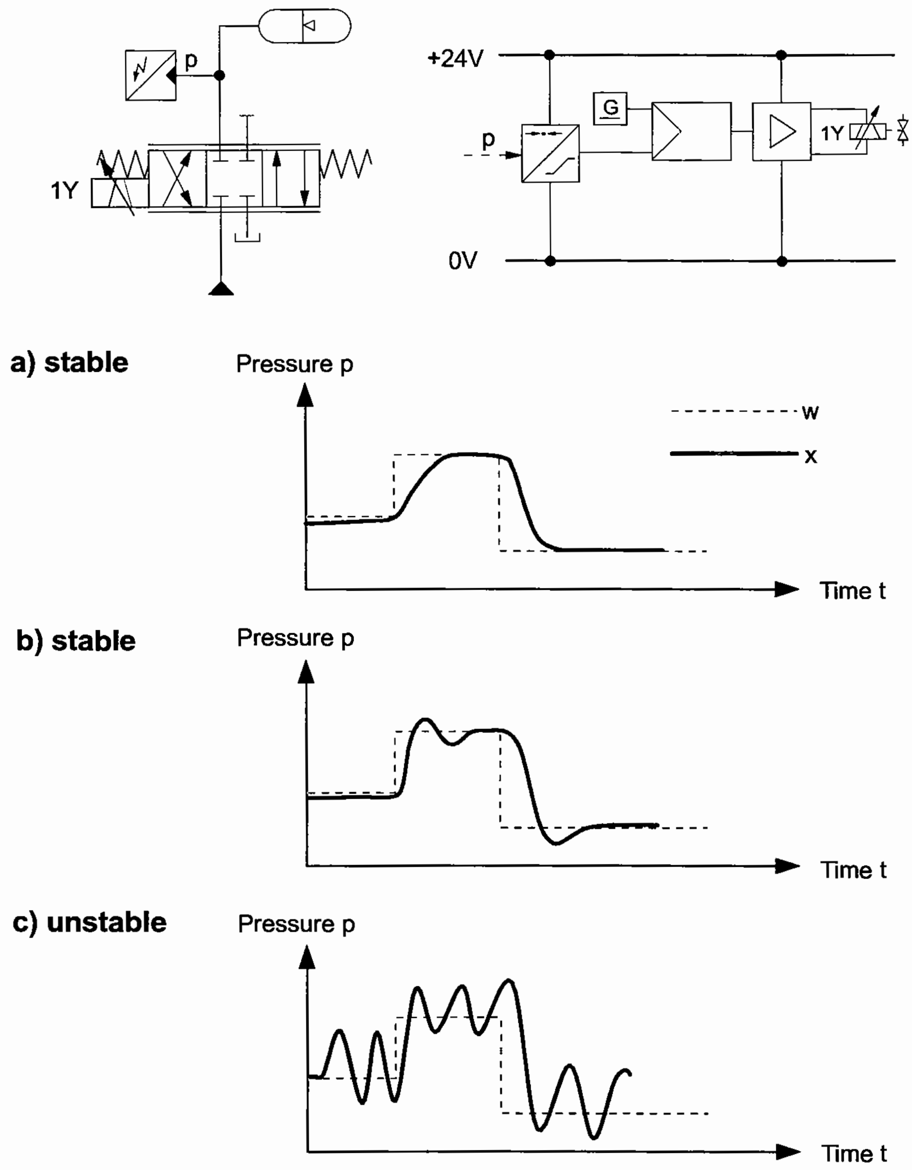
1.7 Stability and instability

Fig. B1.17 shows a closed-loop hydraulic pressure control system.

- With a correctly-selected controller and correct controller parameters, the controlled variable will follow the reference variable with only a slight delay and a slight deviation (Fig. B1.17a).
- If the controller is set incorrectly, the controlled variable may oscillate (Fig. B1.17b).
- If the controller settings are seriously incorrect, steady-state oscillations may result (Fig. B1.17c).

If no or decaying oscillations occur, the controlled settings can be regarded as stable (Figs. B1.17a and B17b). If, on the other hand, the controlled variable exhibits steady-state oscillations, the controller settings are described as unstable (Fig. B1.17c).

Fig. B1.17: Stable and unstable behaviour of a closed-loop control circuit



Effects of unstable controller settings

With unstable controller settings, the closed-loop control circuit no longer fulfils the function of keeping the system deviation as small as possible. Unstable behaviour leads to increased wear of valves and cylinders. These may under certain circumstances lead to damage to or the destruction of components.

In practice, a controller must always be set in such a way that the operation of the associated closed-loop control circuit is stable.

1.8 Steady-state and dynamic behaviour

Steady-state behaviour

The steady-state behaviour of a closed-loop control circuit is its behaviour in a state in which the controlled variable does not change.

Fig. B1.18 shows two step responses of a closed-loop control circuit. These step responses have been recorded with different controller settings. As can been seen from the signal curves, the steady-state behaviour is different for the two controller settings:

- With controller setting a, there is no system deviation in a steady state.
- With controller setting b, a system deviation e is present in a steady state.

Steady-state system deviation

The steady-state system deviation is calculated as follows:

$e_{stat} = w - x$ where w: constant
x: constant

Good steady-state behaviour is achieved when the steady-state system deviation is small or even zero.

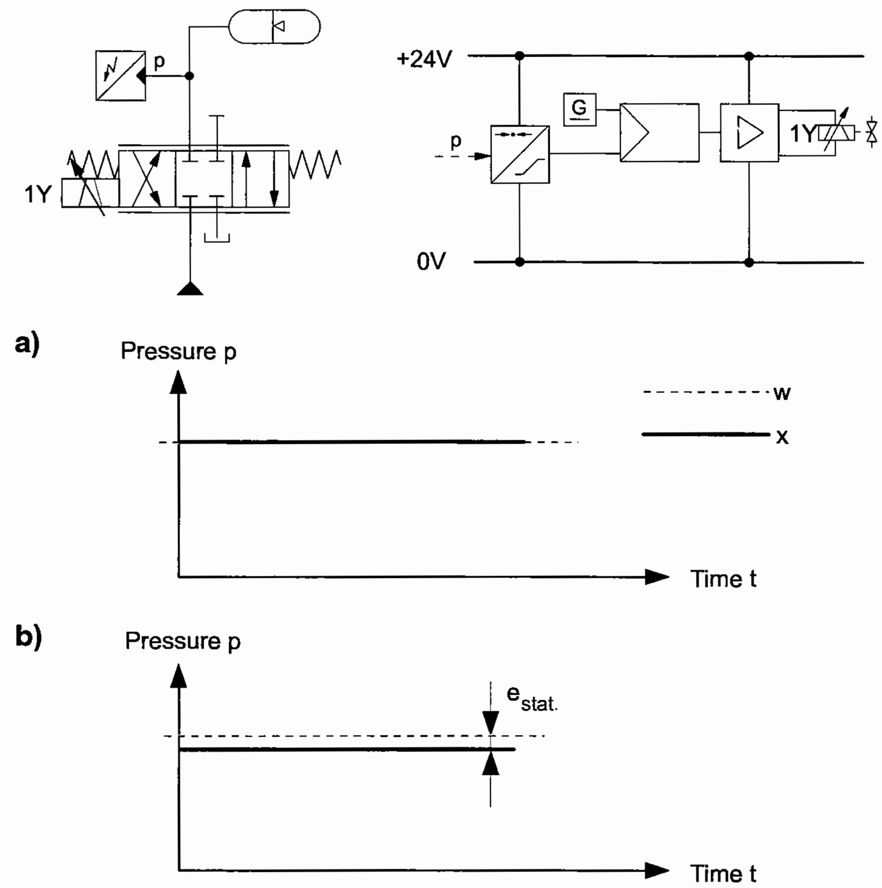


Fig. B1.18: Steady state behaviour of a closed-loop pressure control circuit with two different controller settings

Dynamic behaviour

The dynamic behaviour of a closed-loop control circuit describes a state in which both the controlled variable and the correcting variable change.

Fig. B1.19 shows two closed-loop pressure control circuits with different dynamic behaviour:

- Closed-loop control circuit (a) reacts very slowly to a change in the reference variable
- Closed-loop control circuit (b) reacts significantly faster. On the other hand, the controlled variable initially goes past the reference variable. This is referred to as overshooting.

In order to offer good dynamic behaviour, a closed-loop control circuit must fulfil the following requirements:

- Overshoots should occur either not at all or only to a slight extent.
- When the reference variable changes, the controlled variable should follow this rapidly

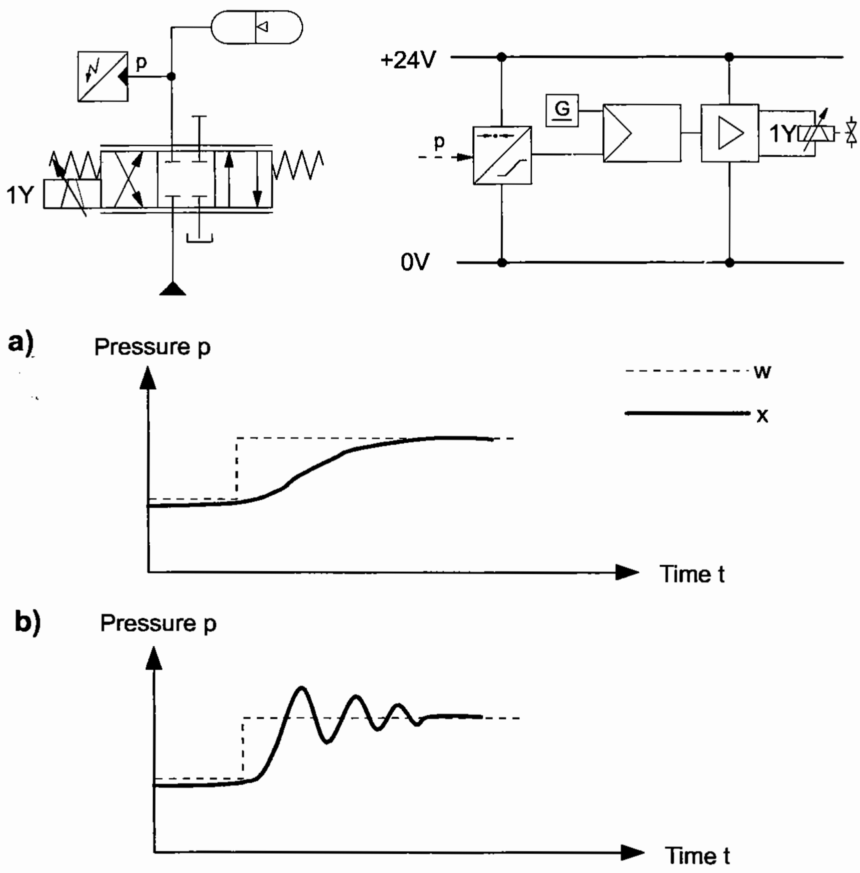


Fig. B1.19: Dynamic behaviour of two closed-loop pressure control circuits

Control quality

The quality provided by a closed-loop control system is known as the control quality. Important criteria for high control quality are:

- Small steady-state system deviation
- Minimal overshoots
- Short settling time
- Stability.

1.9 Response to setpoint changes and interference

Response to setpoint changes

Fig. B1.20 shows a closed-loop pressure control circuit. The pressure setpoint forms the reference variable for the closed-loop control circuit. At the point in time t0, the pressure setpoint exhibits a step change. The reaction of the closed-loop control circuit to the change in the reference variable is known as the response to setpoint changes.

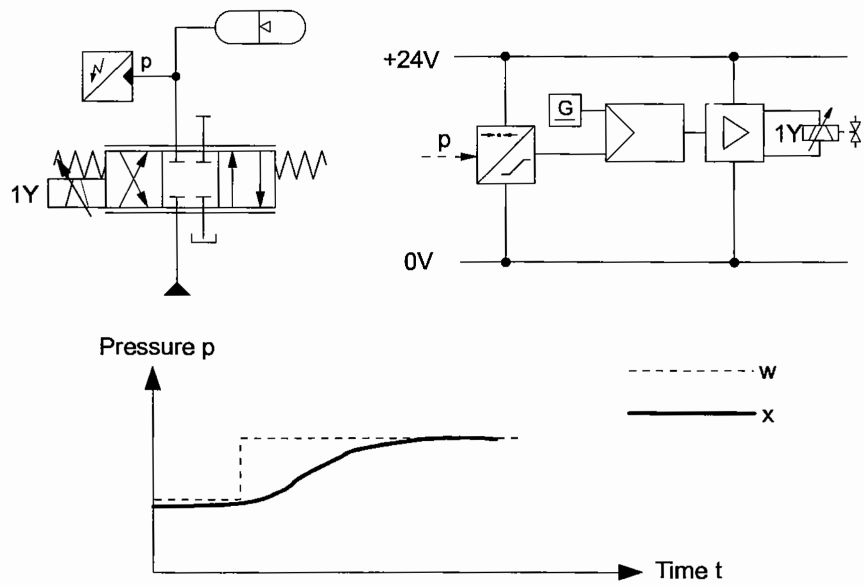


Fig. B1.20: Hydraulic pressure control: Response to setpoint changes

Response to interference

In Fig. B1.21, the reference variable remains constant. At the point in time t_0, a switching valve is opened. Compressed air flows from the reservoir. The pressure first falls noticeably and then rises again as the result of the intervention of the closed-loop control system.

The opening of the switching valve represents interference to the closed-loop control circuit in its attempt to compensate for the system deviation. The opening of the switching valve thus represents an interference variable for this closed-loop control circuit. The reaction of the closed-loop control circuit to the effect of the interference variable is known as its response to interference.

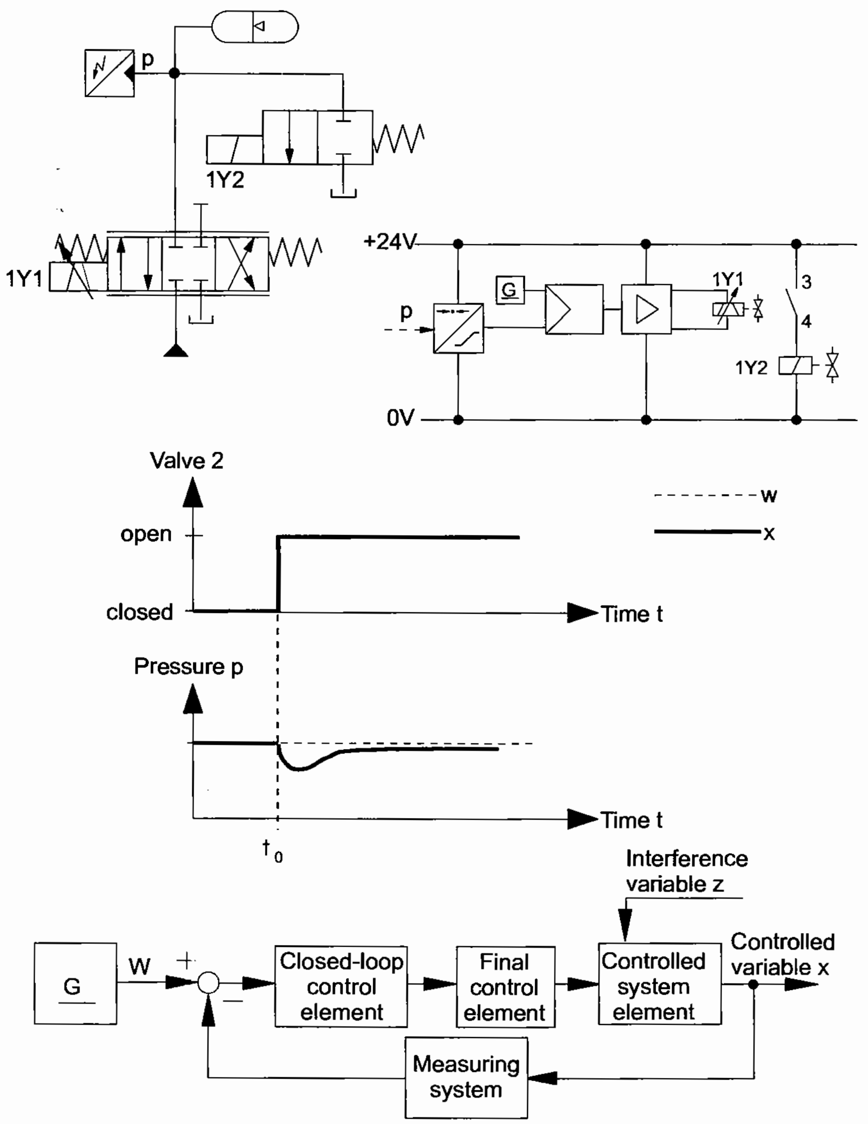


Fig. B1.21:
Hydraulic pressure control:
Response to interference

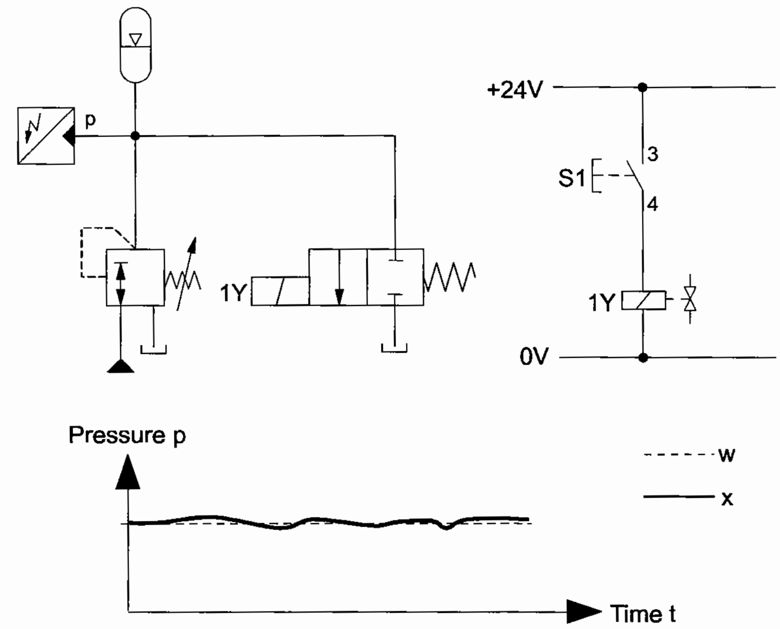
1.10 Fixed-value, follow-up and timing control systems

Fixed-value control system

Fig. B1.22 shows a hydraulic circuit for pressure control. The pressure regulator is used to achieve a constant supply pressure of 6bar. Since the reference variable does not change, we speak of a fixed-value control system.

In a fixed-value control system, the controlled variable changes as the result of the influence of interference variables. In the case of the closed-loop control circuit in Fig. B1.22, the opening of the switching valve leads to a temporary fall in the controlled variable.

Fig B1.22: Fixed-value control system



Follow-up control system

Fig. B1.23 shows a hydraulic positioning actuator. The position (s) of the piston follows the changes in the position setpoint. This form of closed-loop control is known as a follow-up control system.

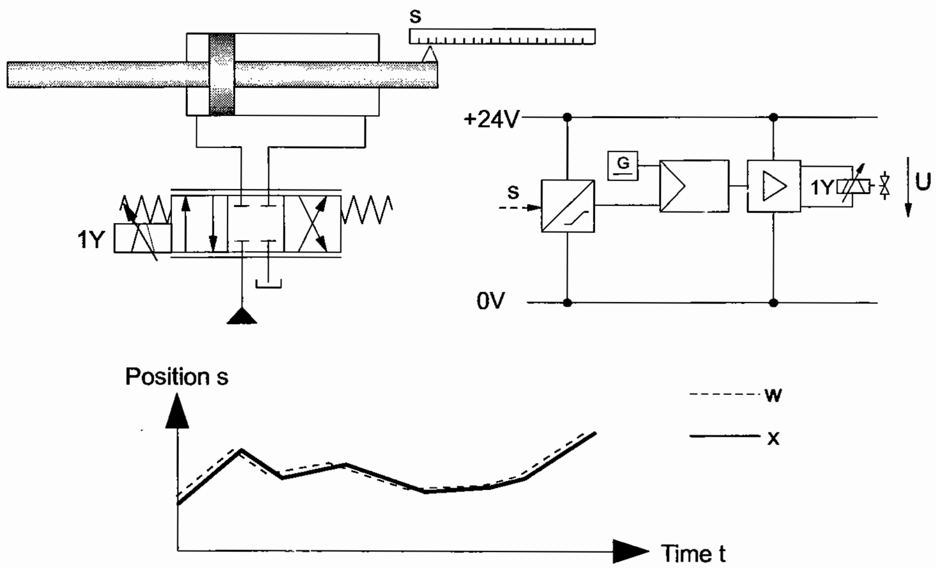


Fig. B1.23:
Follow-up control system

Timing control system

On a plastic moulding machine, the pressure must be varied in accordance with a specified timing schedule. We speak in this case of a timing control system. A timing control system is a special form of a follow-up control system (Fig. B1.24).

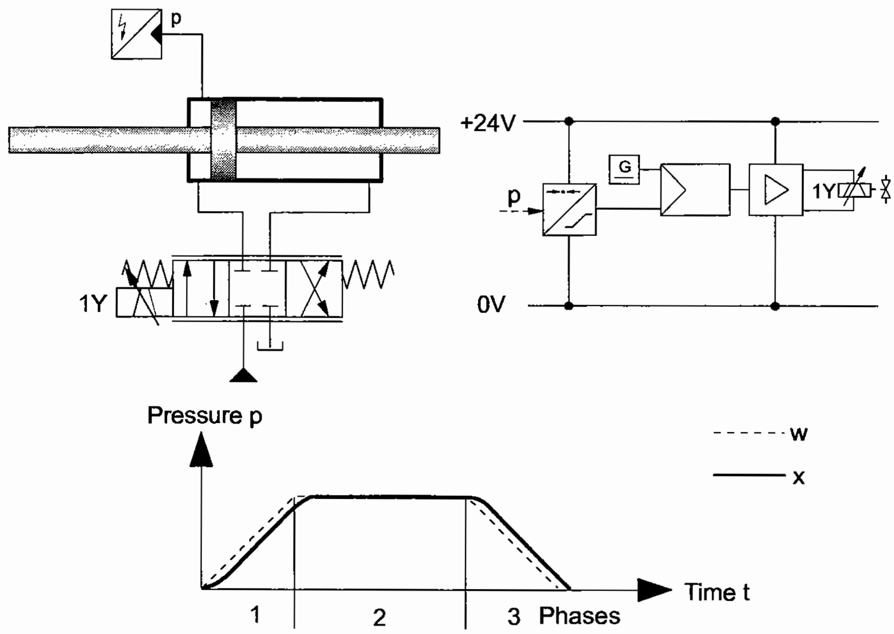


Fig. B1.24:
Timing control system

1.11 Differentiation of a signal

Fig. B1.25 shows an example of an application of a differentiator.

- The position of the piston of a hydraulic actuator is measured with a positional transducer. The position represents the input signal for the differentiator.
- The velocity is determined by differentiation of the position. This indicates how fast the position of the piston is changing.

When signal differentiation is used, the change in the input signal directly affects the output signal.

- In phase 1, the piston moves in the positive direction. The input signal of the differentiator increases. The output signal, i.e. the velocity of the piston, has a positive value.
- In phase 2, the piston moves in the negative direction. The input signal of the differentiator falls. The output signal has a negative value.
- In phase 3, the piston of the hydraulic cylinder is at a standstill. The input signal of the differentiator is constant. The output signal is zero.
- In phase 4, the piston moves in the positive direction. The signal gradient is less steep than in phase 1. The output signal is greater than zero but lower than the output signal in phase 1.
- In phase 5, the piston moves in the negative direction. Since the downward gradient of the input signal is less steep than in phase 2, the output signal is less negative.

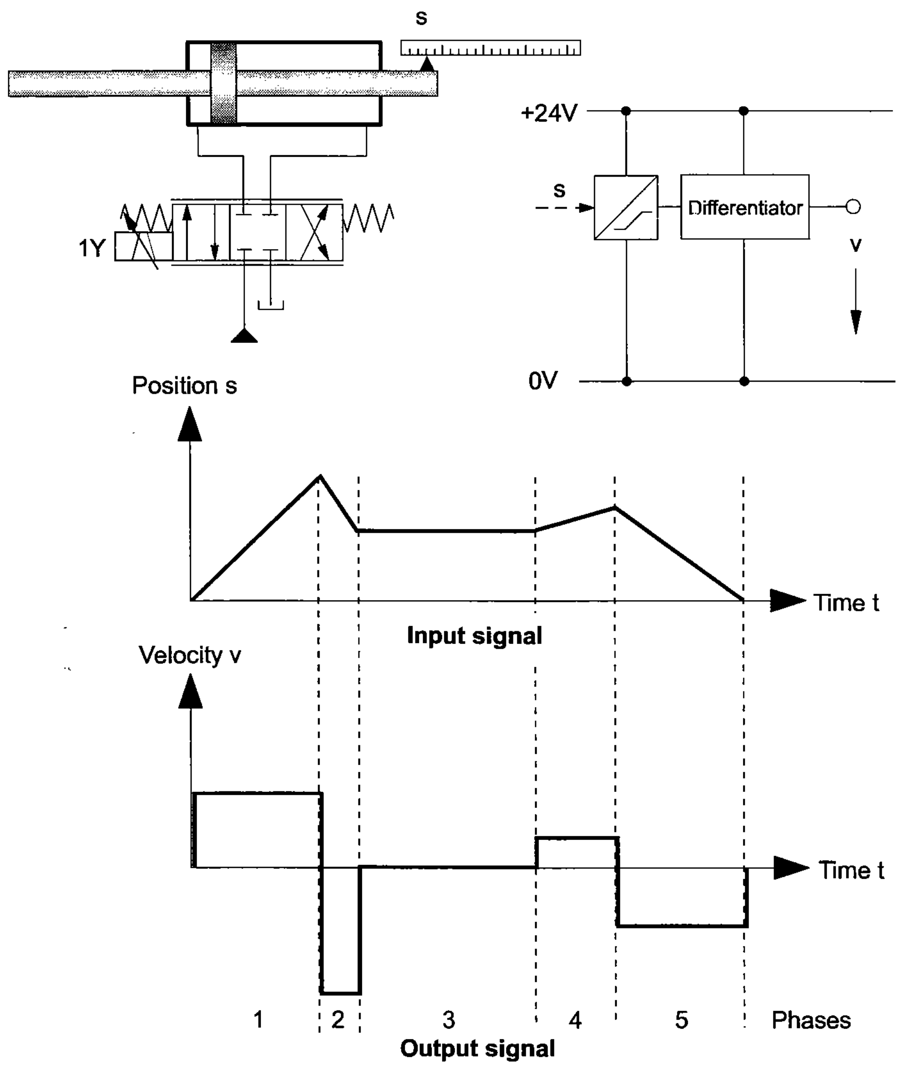
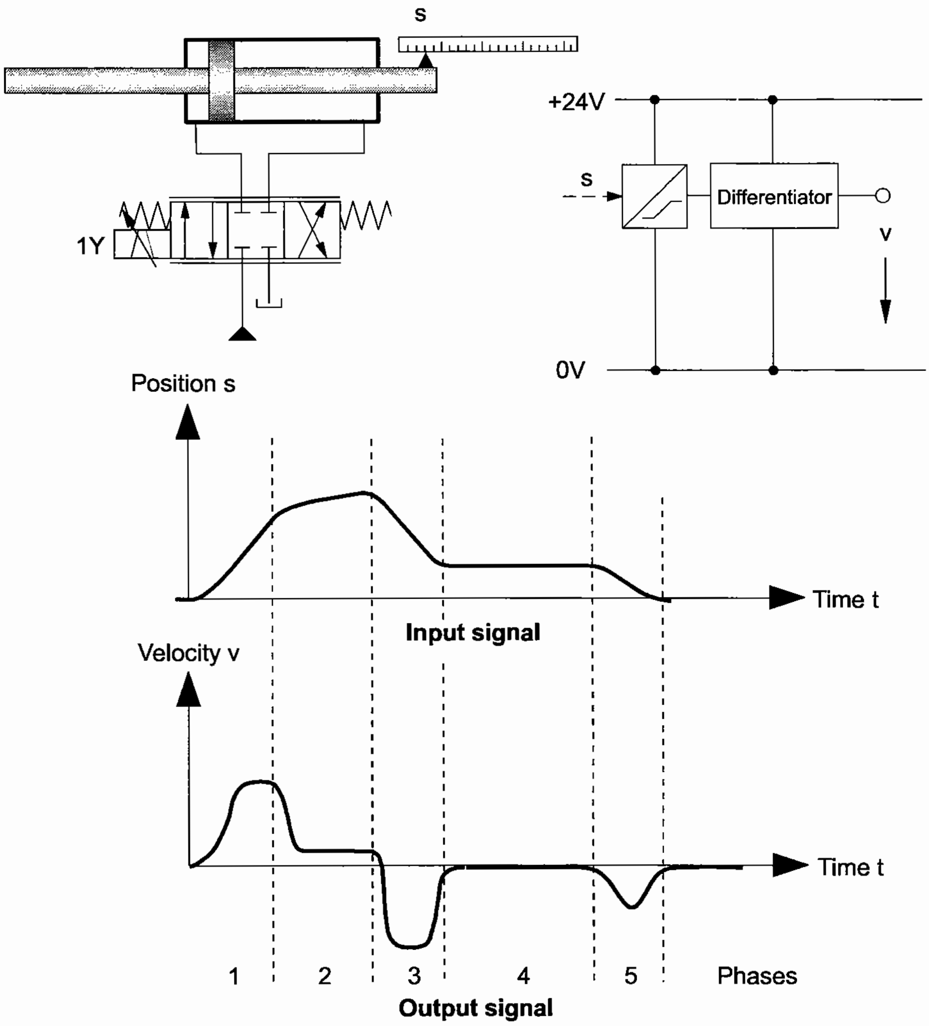


Fig. B1.25: Differentiation of a signal with peaks

The curve for the input signal in Fig. B1.25 exhibits peaks. This means that the gradient of the input signal changes abruptly. The output signal accordingly also exhibits step changes.

Fig. B1.26 shows an output-signal curve without peaks. The associated output signal of the differentiator has no step changes

Fig. B1.26:
Differentiation of a signal without peaks



Block diagram and transition function of a differentiator

When a step-change signal acts on the input of a differentiator, the transition function of this is obtained as the output signal. A distinction can be made between three phases:

- Initially, the input signal and output signal are zero.
- At the point in time t = 0, the input signal has a vertical edge. This corresponds to a very steep signal rise and produces a peak in the output signal.
- After the point in time t = 0, the input signal is once again constant. The output signal of the differentiator is zero.

The transition function is entered into the block diagram for the differentiator.

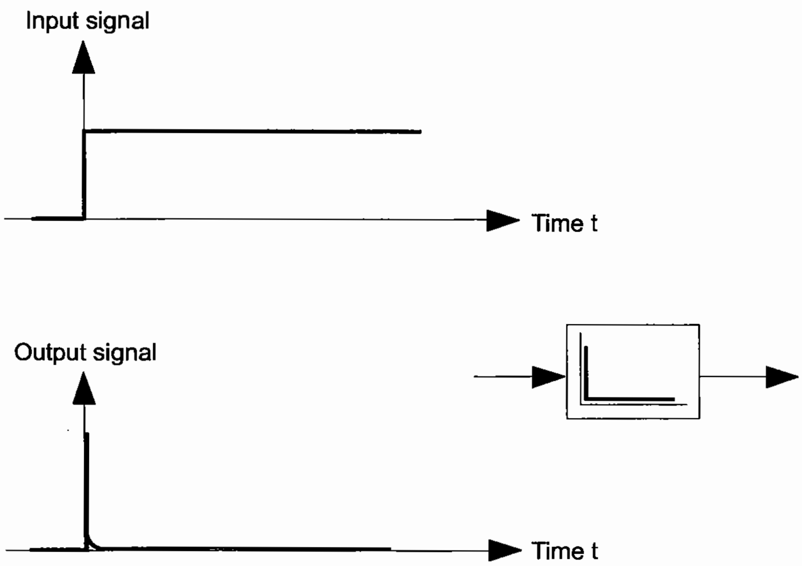


Fig. B1.27:
Block diagram
of a differentiator

Notation

Both the input signal (e) and the output signal (a) of a differentiator are functions of time. This is expressed by the designations e (t) and a (t). The following notation is accordingly used for differentiation:

$$a(t) = \frac{d}{dt} e(t)$$

The differentiation of a signal as a function of time is often also indicated by a dot:

$$\dot{e}(t) = \frac{d}{dt} e(t)$$

1.12 Integration of a signal

Fig. B1.28 shows an example of an application of an integrator.

- The velocity of the piston is measured with a speed sensor.
- The position of the piston is calculated from the velocity by integration.

When a signal is integrated, the value of the input signal affects the gradient of the output signal (Fig. B1.28):

- In phase 1, the velocity is positive. The input signal of the integrator lies above the zero line. The piston rod moves in the positive direction. The output signal of the integrator rises.
- In phase 2, the velocity is less than zero. The piston rod moves in the negative direction. The output signal of the integrator falls.
- During phase 3, the velocity is zero. The output signal, i.e. the position of the piston, is constant.
- In phase 4, the velocity is greater than zero but less than in phase 1. The output signal rises. The gradient of the output signal is less steep than in phase 1.
- During phase 5, the velocity is less than zero. The output signal falls. Since the output signal is not as far below the zero line as in phase 2, the downward gradient of the output signal is less steep.

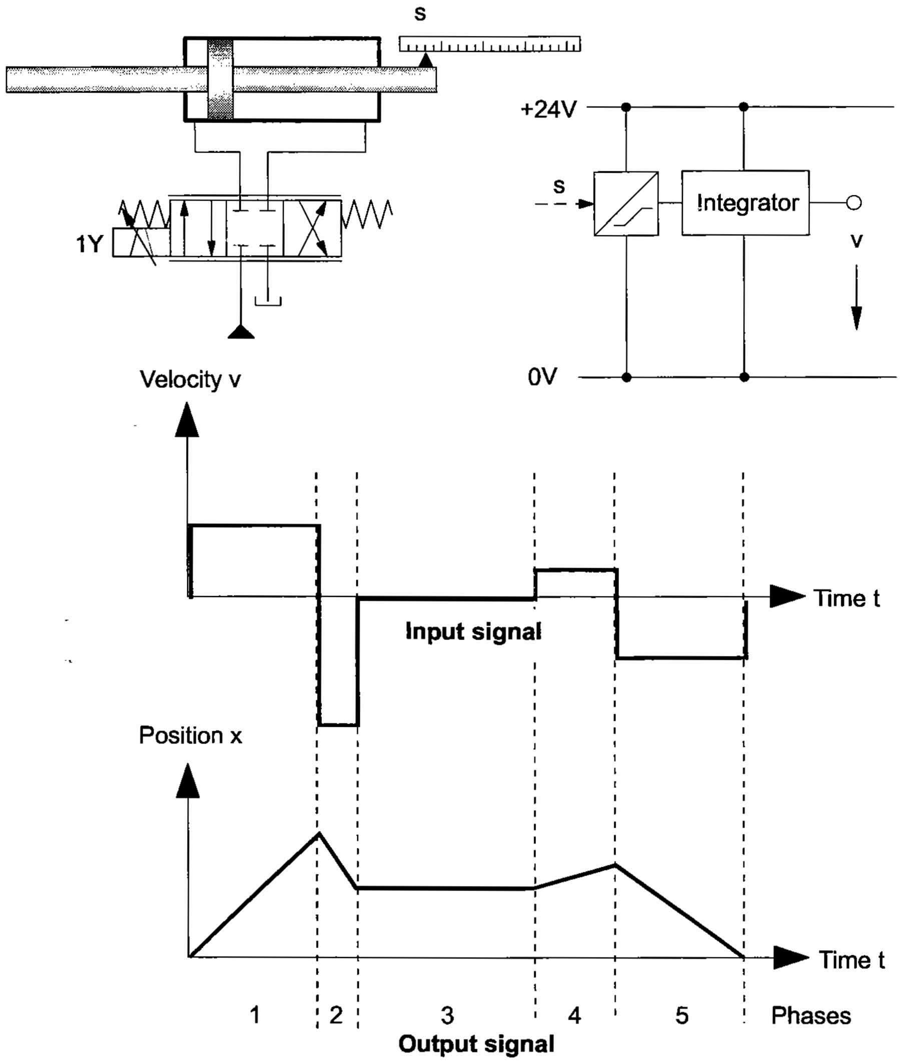


Fig. B1.28: Integration of a signal with peaks

In Fig. B1.28, the value of the input signal exhibits step changes. The gradient of the output signal thus also changes abruptly; in other words, the curve contains peaks.

If the value of the input signal changes continuously, the gradient of the output signal will also change continuously (Fig. B1.29).

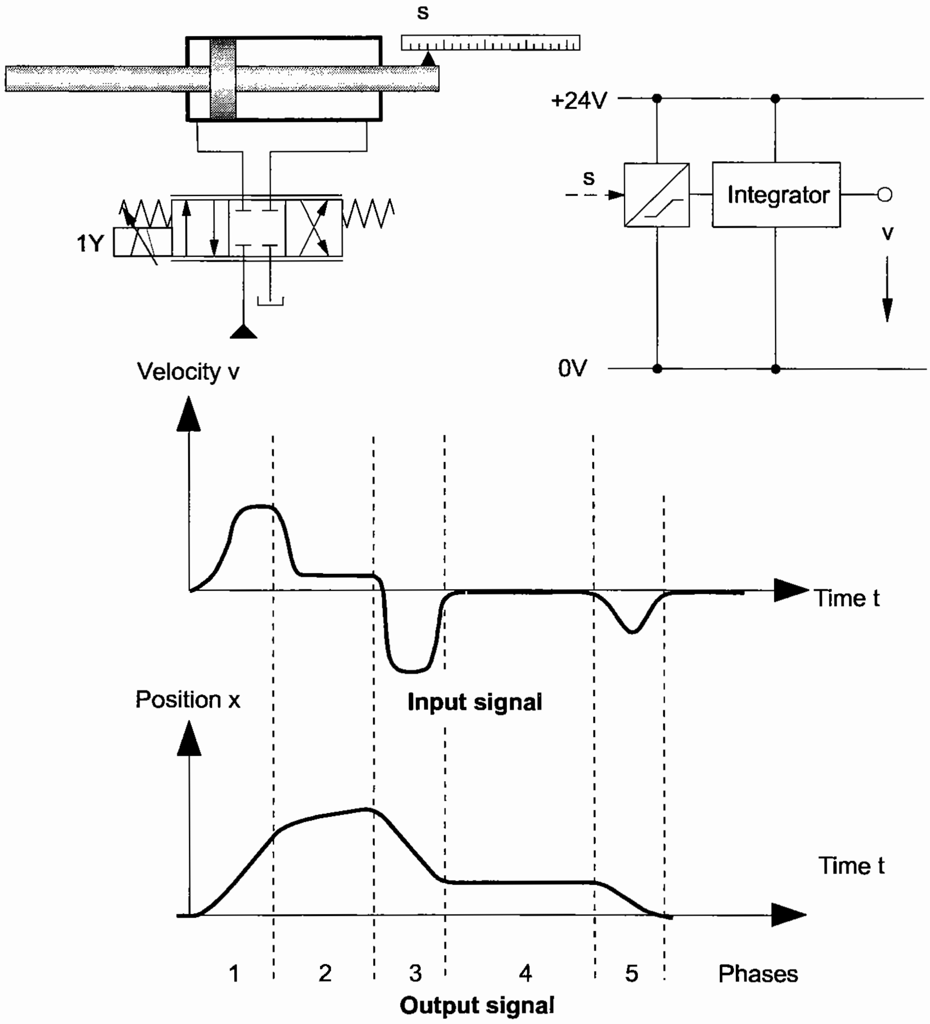


Fig. B1.29
Integration of a signal without peaks

Transient function of an integrator

The transient function is entered in the block diagram of the integrator. A distinction is made between two phases:

- Up to the point in time t = 0, the input signal and output signal are zero.
- From the point in time t = 0 onwards, the value of the input signal is 1. The output signal rises with a constant gradient.

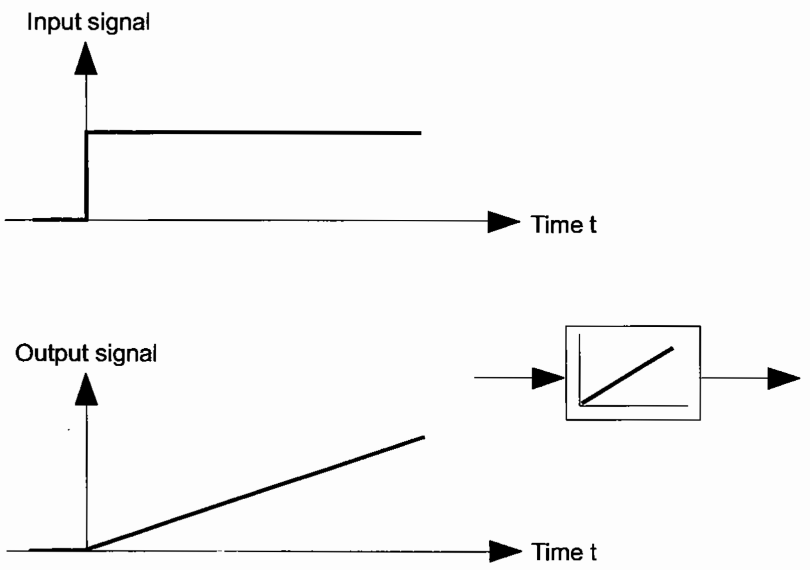


Fig B1.30: Block diagram of an integrator

Notation

The relationship between the input signal e (t) and the output signal a (t) of an integrator is described by the following formula:

$$a(t) = \int e(t)\,dt$$

Hydraulic closed-loop controlled systems

A controlled system consists of a final control element and a controlled-system element (Fig. B1.16). In hydraulic closed-loop controlled systems, the following components are used:

- Valves are generally used as final control elements.
- The controlled-system element comprises the tubing and, depending on the application, flow control valves, cylinders and/or reservoirs.

The behaviour of the controlled system is influenced not only by the hydraulic components but also variables such as load forces, frictional forces and masses. For example, a hydraulic cylinder actuator which has to move 50kg backwards and forwards will react more slowly than a similar actuator which has to move only 5kg.

Model

In order to achieve the best possible control behaviour, the controller which is used must be matched to the controlled system in question. Two steps must be carried out in order to select a suitable controller:

- In the first step, a model is created of the controlled system (Chapter B2). The model provides a simplified description of the behaviour of the controlled system.
- In the second step, a controller is selected which is suitable for the model of the controlled system (Chapter B3).

Hydraulic controlled systems can generally be described by one of the models in Table B2.1. Suitable models are specified below for various hydraulic controlled systems.

Controlled systems with compensation	*Controlled systems without compensation*
Zero order controlled system	1st order controlled system
1st order controlled system	2nd order controlled system
2nd order controlled system	3rd order controlled system
Controlled system with dead time	

Table B2.1: Examples of models of hydraulic controlled systems

2.1 Controlled systems with and without compensation

Controlled system with compensation

The controlled system shown in Fig. B2.1 consists of a switching valve and a hydraulic cylinder.

- The correcting signal for the valve forms the input signal for the controlled system.
- The velocity of the piston is measured with a sensor. This forms the output signal.

In order to determine the transition function, the valve is energised with a correcting signal which exhibits a step change at the point in time t = 0. We can distinguish between two phases:

Phase 1: The velocity of the piston increases. Oscillations may occur, depending on the type of cylinder actuator concerned.

Phase 2: The velocity reaches a constant value.

Since a new constant value for the output signal results after a step change in the input signal, we describe this system as a controlled system with compensation.

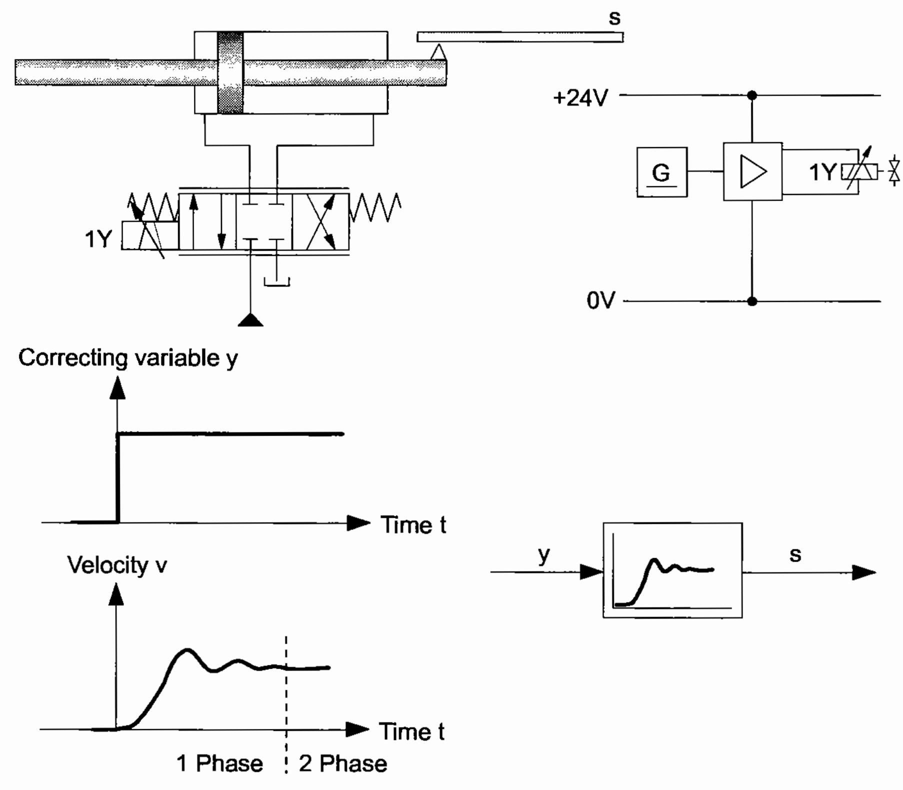


Fig. B2.1: Step response and block diagram for a controlled system with compensation

Controlled system without compensation

The position of the piston of the hydraulic cylinder actuator in Fig. B2.2 is measured. This forms the output signal of the controlled system.

The piston position changes when the valve is opened. Oscillations may occur after the piston has started to move. As soon as these oscillations have died away, the piston moves smoothly until it impacts against the stop.

The output signal does not settle to a constant value anywhere in the working range. This system is a controlled system without compensation.

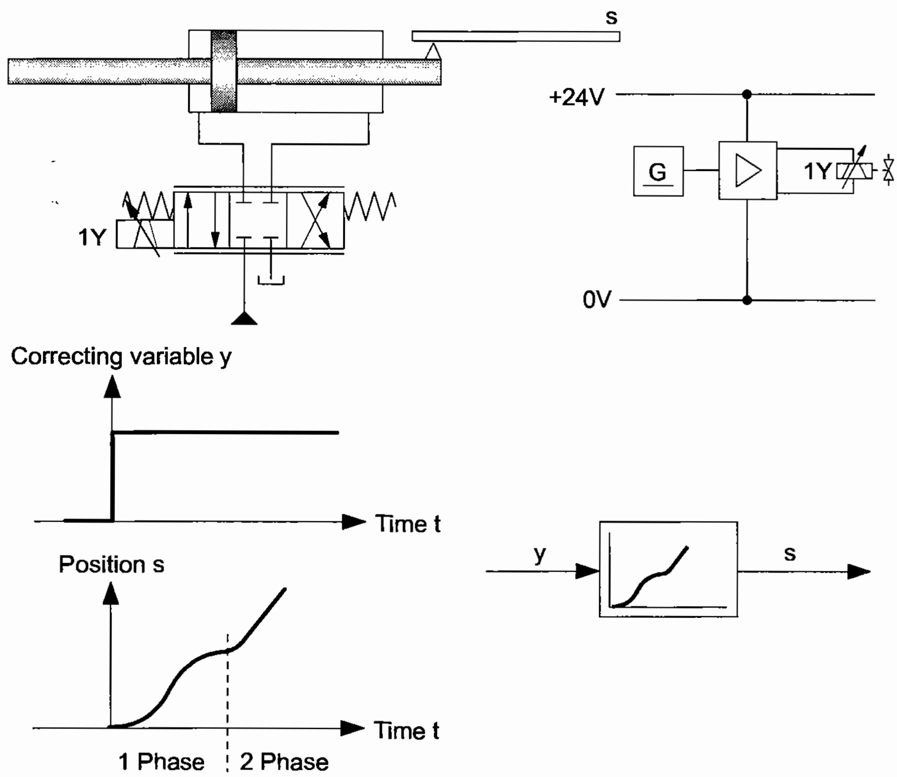
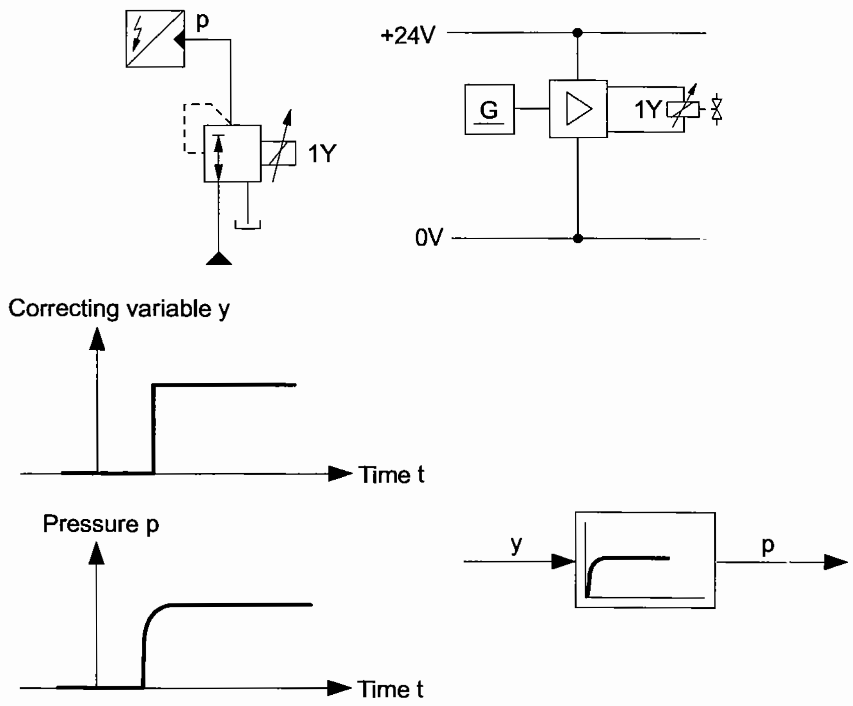


Fig. B2.2: Block diagram and transmission characteristics for a controlled system without compensation

2.2 Short-delay hydraulic controlled system

Fig. B2.3 illustrates a pressure control system. The pressure sensor is fitted directly into the outlet ports of the valve. When the valve energisation signal changes, the pressure follows with a very slight delay.

Fig. B2.3: Short-delay pressure control system



Delay-free controlled system

A very fast controlled system is generally considered in simplified terms to be delay-free. It is then referred to as a zero-order controlled system. A delay-free controlled system reacts to a step change in the input signal with a step change in the output signal.

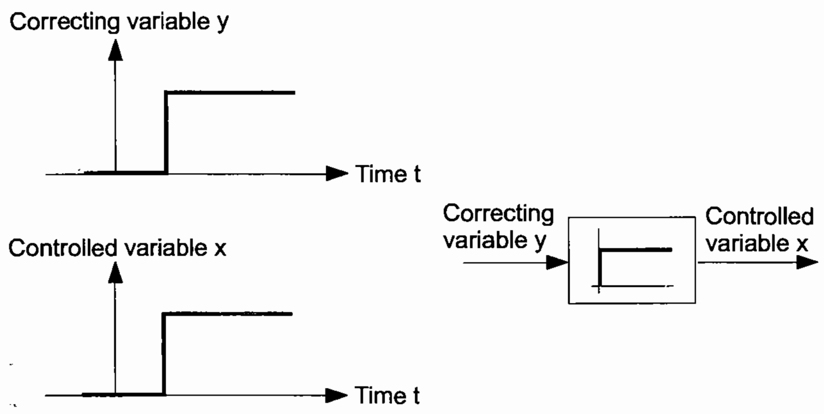


Fig. B2.4: Step response of a delay-free controlled system

2.3 First-order hydraulic controlled system

Controlled system with delay

If a reservoir is also included in the pressure control system, the pressure build-up becomes slower. A system of this kind is a controlled system with delay. Since the controlled system incorporates an energy storage device, we speak of a first-order system.

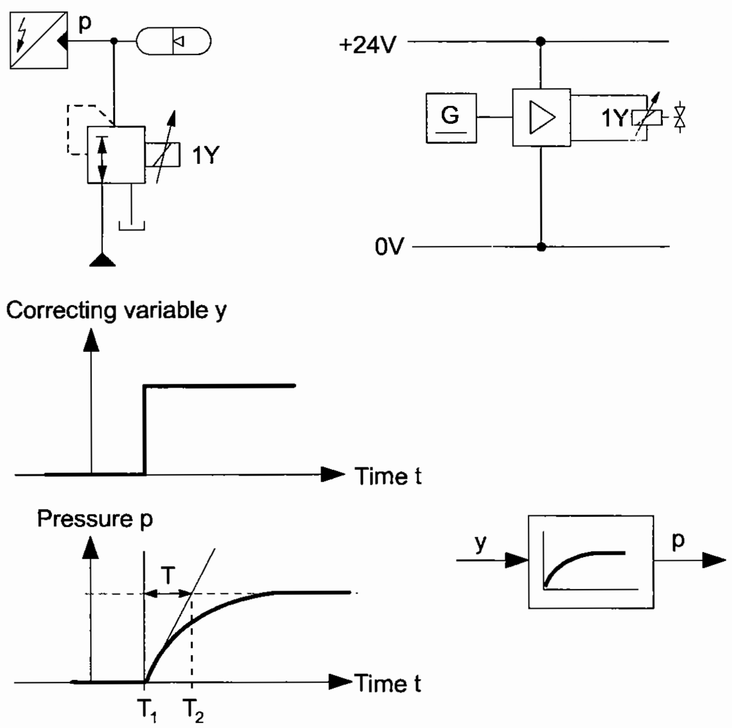


Fig. B2.5: Pressure control system with one reservoir

Time constant

When the correcting variable executes a step change, the controlled variable follows with a delay. The time constant T of the controlled system can be determined from the graph for the step response (Fig. B2.5).

2.4 Second-order hydraulic controlled systems

Similar energy storage devices

Fig. 2.6 shows a controlled system with two reservoirs connected in series. The two reservoirs are connected together by a small-diameter compressed-air line. Due to the fact that two energy storage devices are present, this is a second-order controlled system.

There are clear differences between the step responses of a second-order controlled system and a first-order controlled system:

- In the case of a first-order controlled system, the controlled variable rises immediately with a steep gradient.
- In the case of a second-order controlled system, the controlled variable initially rises only slightly. Only after this does the gradient of the curve become steeper.

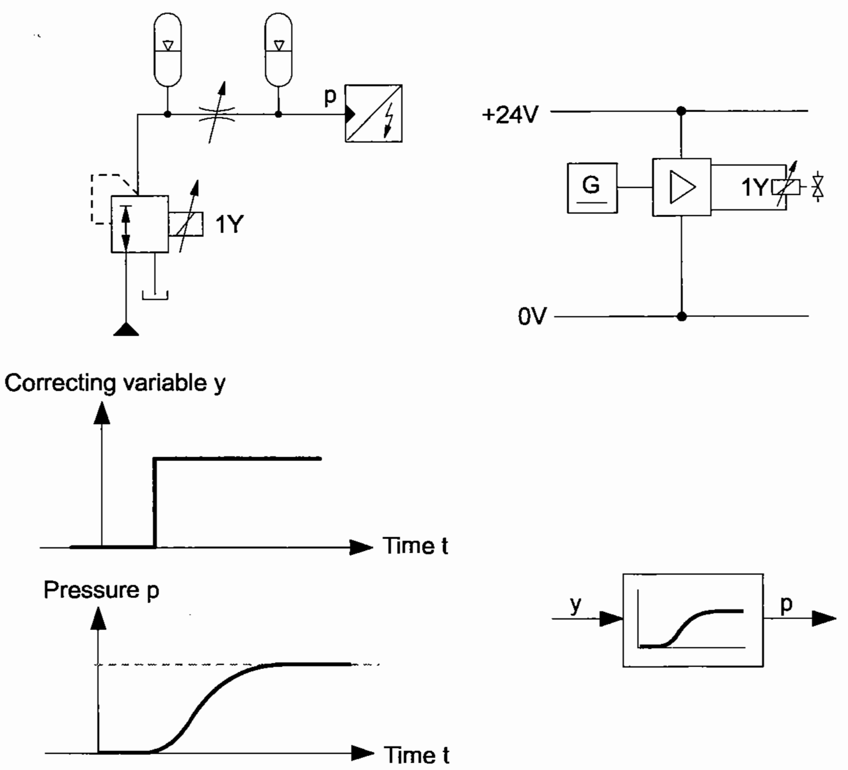


Fig. B.2.6: Pressure control system with two reservoirs

Dissimilar energy storage devices

Fig. B2.7 shows a controlled system consisting of a dynamic valve and a hydraulic cylinder actuator. The actuator moves a mass backwards and forwards. The velocity is measured by a sensor.

Energy is stored in this system in two ways:

- By the moving mass (kinetic energy)
- By the compression and expansion of air (potential energy)

The columns of air in the two chambers of the hydraulic cylinder can be regarded as air springs. The piston of the hydraulic cylinder is clamped between these springs. The spring/mass system is capable of oscillation. For this reason, oscillations may result from a step response.

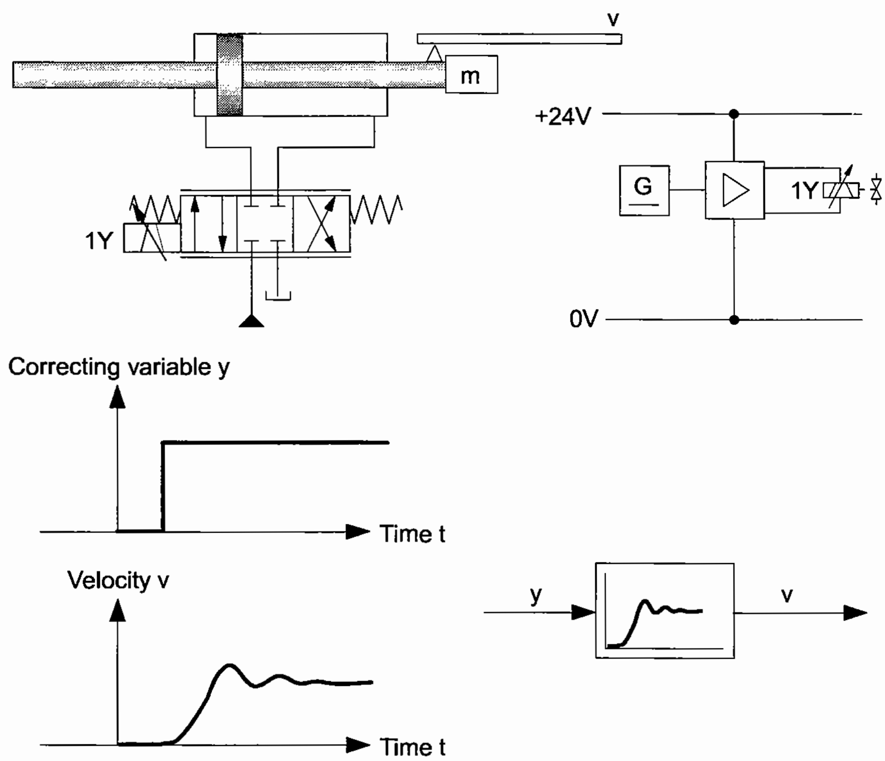


Fig. B2.7: Hydraulic cylinder actuator with velocity sensor

Comparison of second-order controlled systems

Table B2.2 shows a comparison of two second-order hydraulic controlled systems.

Energy storage devices	*Two identical energy storage devices*	*Two non-identical energy storage devices*
Step response	No oscillations	With oscillations
Example	Two hydraulic reservoirs	Hydraulic cylinders

Table B2.2: 2nd order controlled systems

2.5 Third-order hydraulic controlled system

The figure below shows a controlled system for position. The position of the piston rod is measured. The signal flow diagram shows this controlled system as two sub-systems:

- In the first sub-system, the valve energisation voltage V forms the input signal, and the velocity v the output signal. This part of the controlled system corresponds to the controlled system in Fig. B2.7. It is accordingly a second-order system.
- In the second sub-system, the velocity v forms the input signal, and the position x the output signal. This is an integrator, i.e. a first-order system.

The output signal of the integrator corresponds to the output signal of the controlled system.

The order of the overall controlled system is determined by adding together the orders of the two sub-systems (Fig. B2.8b).

The controlled system overall forms a third-order system. Since the second-order sub-system is capable of oscillation (Fig. B2.8b), the overall controlled system is also capable of oscillation. The oscillation can be seen in the block diagram for the overall controlled system (Fig. B2.8c).

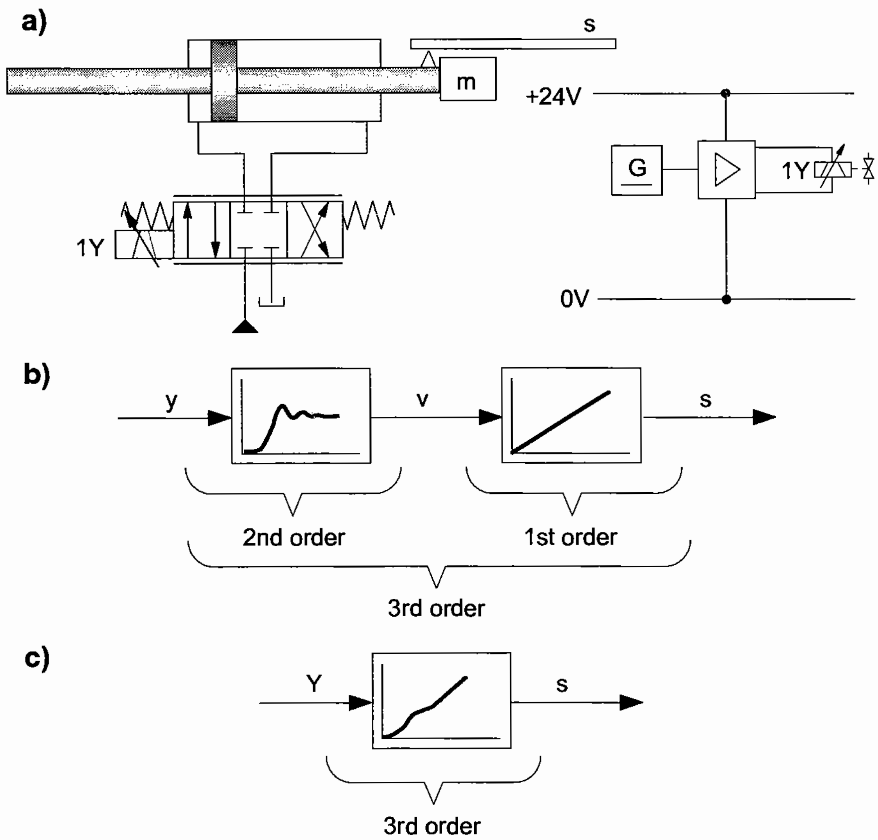


Fig. B2.8: Hydraulic cylinder actuator with position sensor

Variables influencing the order of a controlled system

The order of a controlled system depends, among other things, on

- the component parts of the controlled system
- the input signal
- the output signal.

The hydraulic actuator with speed sensor (second-order controlled system, Fig. B2.7) and the hydraulic actuator with position sensor (third-order controlled system, Fig. B2.8) have the same hydraulic components. The order of the two controlled systems is different because their output signals are different.

2.6 Classification of controlled systems according to their step response behaviour

In practice, it is useful to classify the various types of controlled systems according to their step response behaviour. Fig. B2.10 shows the step response behaviour of various different controlled systems.

It is difficult to distinguish between the transition function of a second-order controlled system and the transition function of a higher-order controlled system. The higher the order of a controlled system, the more its behaviour resembles that of a controlled system with dead time.

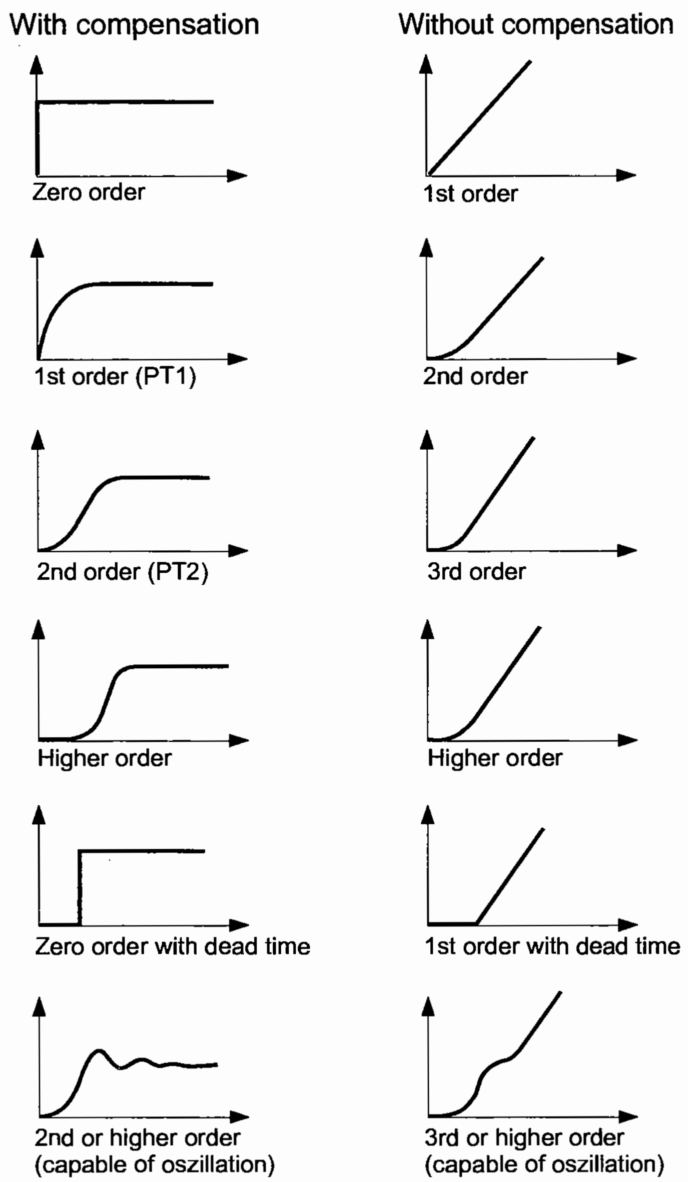
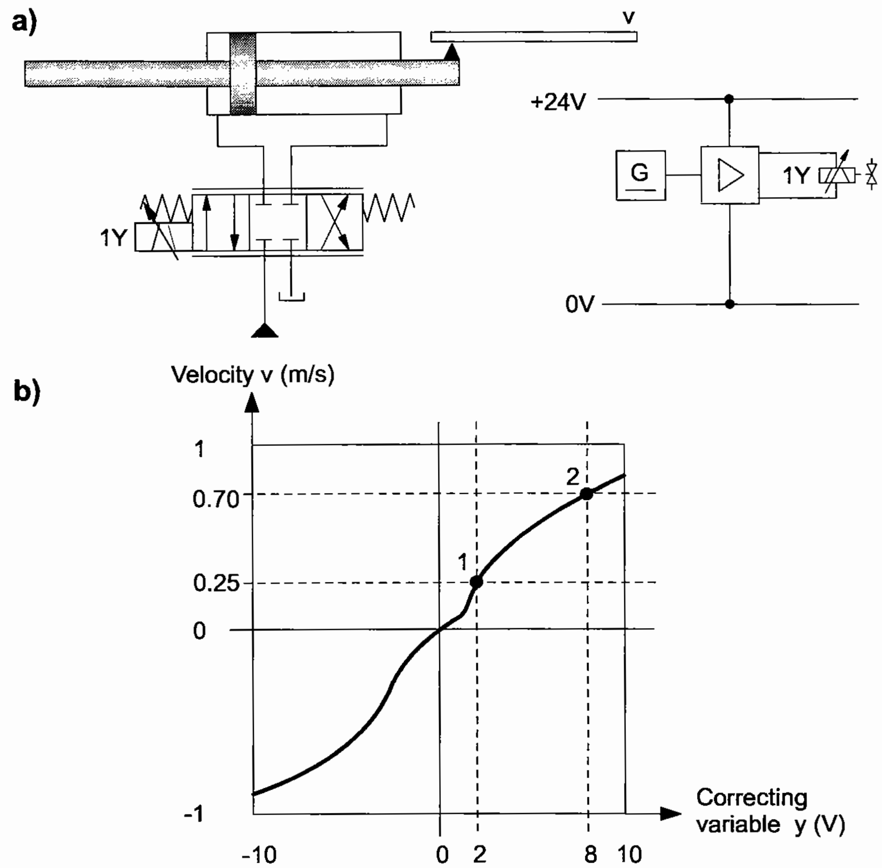


Fig. B2.9:
Step response behaviour of controlled systems

2.7 Operating point and controlled-system gain

The models for first-order, second-order and third-order systems represent a simplification of the actual behaviour of the controlled systems. It is frequently necessary to describe the behaviour of a controlled system more accurately. In cases of this kind, additional characteristics are used.

Fig. B2.10: Steady state characteristic for a hydraulic cylinder actuator



Characteristic for a controlled system with compensation

Fig. 2.11 shows a controlled system with compensation. It has the following properties:

- If the correcting variable remains constant, a constant velocity results as the controlled variable after settling.
- If another voltage is input as the correcting variable, another velocity results as the controlled variable after settling.

Each value of the correcting variable can be assigned a velocity. The relationship between the correcting variable and controlled variable can be represented as a characteristic (Fig. B2.10b).

Operating point

Each velocity is assigned a valve operating point. For a velocity of 0.25 m/s, the operating point is at 6V, while for a velocity of 0.7 m/s it is at 9V.

Controlled-system gain KS

The gain factor KS of a controlled system with compensation is defined as follows:

$$KS = \frac{\text{Change in output signal}}{\text{Change in input signal}} = \frac{\text{Change in controlled variable}}{\text{Change in correcting variable}} = \frac{\Delta x}{\Delta y}$$

The higher the controlled-system gain, the more sensitively the controlled system will react to changes in the correcting variable. The controlled-system gain influences the controller settings:

- With a high controlled-system gain, a low controller gain must be set.
- With a low controlled-system gain, a high controller gain must be set.

The controlled-system gain KS corresponds to the gradient of the characteristic in Fig. B2.10b. If the gradient of the characteristic changes, the controlled-system gain KS will also change.

In order to determine the changes in the input and output signals, the values of two points on the characteristic are read in the vicinity of an operating point. The changes in the correcting and controlled variables are calculated from this. Finally, the gain KS can be found by using the above formula (see table B2.3).

Table B2.3: Correcting variable, controlled variable and controlled-system gain for a hydraulic actuator

Factor	*Operating point 1*	*Operating point 2*
Correcting variable 1	2 V	8 V
Correcting variable 2	2.4 V	8.4 V
Change in correcting variable	0.4 V	0.4 V
Controlled variable 1	0.25 m/s	0.7 m/s
Controlled variable 2	0.29 m/s	0.72 m/s
Change in controlled variable	0.04 m/s	0.02 m/s
Controlled system-gain KS	$\frac{0.04\frac{m}{s}}{0.2\,V} = \frac{0.2\,m}{(sv)}$	$\frac{0.02\frac{m}{s}}{0.2\,V} = \frac{0.1\,m}{(sv)}$

Table B2.3 shows that, for the actuator under investigation, the controlled-system gain KS depends on the operating point. The steeper the characteristic in Fig. B2.10b, the higher the controlled-system gain. At operating point 1, the gradient of the characteristic is steeper and the gain KS higher than at operating point 2.

Controller structures

Fig. B3.1 shows a block diagram of a controller. Two input variables act on the controller:

- The reference variable w
- The controlled variable x.

The controller generates an output variable, the correcting variable y.

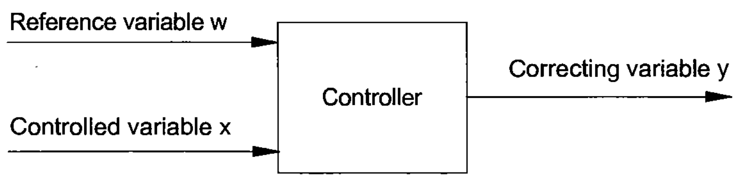


Fig. B3.1: Block diagram for a controller

Dynamic and non-dynamic controllers

Controllers are divided into two different classes:

- Non-dynamic controllers (alternative title: switching controllers)
- Dynamic controllers.

The characteristics of dynamic and non-dynamic controllers are shown in Table B3.1.

Properties	*Non-dynamic controllers*	*Dynamic controllers*
Correcting variable	Only a few different values	Continuously variable between minimum and maximum values
Hydraulic valve type	Switching valve	Dynamic valve
Advantage	Less expensive	Better control quality

Table B3.1: Dynamic and non-dynamic controllers

Both dynamic and non-dynamic controllers have a variety of controller structures.

Table B3.2: Controller types

Non-dynamic controllers	*Dynamic controllers*	
	Standard controllers	*Status controllers*
Two-step-action controllers	P controllers	Triple-loop controllers
Three-step-action controllers	I controllers	
Multi-step-action controllers	PD controllers	
	PI controllers	
	PID controllers	

Since hydraulic oil is only slightly compressible, non-dynamic controllers create strong pressure surges.

In the hydraulics industry, it is therefore largely dynamic controllers which are used in conjunction with proportional or servo valves. However, both types of controller are used in the motor vehicle industry.

3.1 Non-dynamic controllers

Non-dynamic controllers are used in hydraulic brake system in motor vehicles in order to prevent the wheels locking.

In the case of an automatic antilock system, also frequently referred to as ABS, the velocity of the wheels is influenced via separate closed control loops.

- In the case of each closed control loop, the wheel velocity forms the controlled variable and is measured by a separate sensor for each wheel.
- The reference variable for the wheel velocity is calculated from the maximum attainable braking deceleration.
- The correcting variable activates a switching valve, which acts on the pressure in the wheel brake cylinder and consequently the brake force.

Fig. B3.2 shows the respective hydraulic circuit diagram. Each switching valve is assigned to one wheel and can assume three different positions:

1. The controlled variable decreases more slowly than the reference variable (normal braking process). The switching valve is in the normal position. The wheel brake cylinder is connected to the main braking cylinder. The full brake pressure is transmitted.
2. The controlled variable decreases very quickly and become less than the calculated reference variable. The wheel overbrakes and is in danger of locking. The switching valve is closed. The pressure in the wheel brake cylinder remains constant.
3. The controlled variable is far too low. The wheel turns too slowly or has already locked and skids on the road. The switching valve connects the wheel brake cylinder to the low pressure reservoir. The pressure in the wheel brake cylinder and the braking torque is reduced. The wheel velocity increases.

Three-step action controller

The correcting variable and the final control element can assume three different position with this antilocking device, which is effectively a three-step controller.

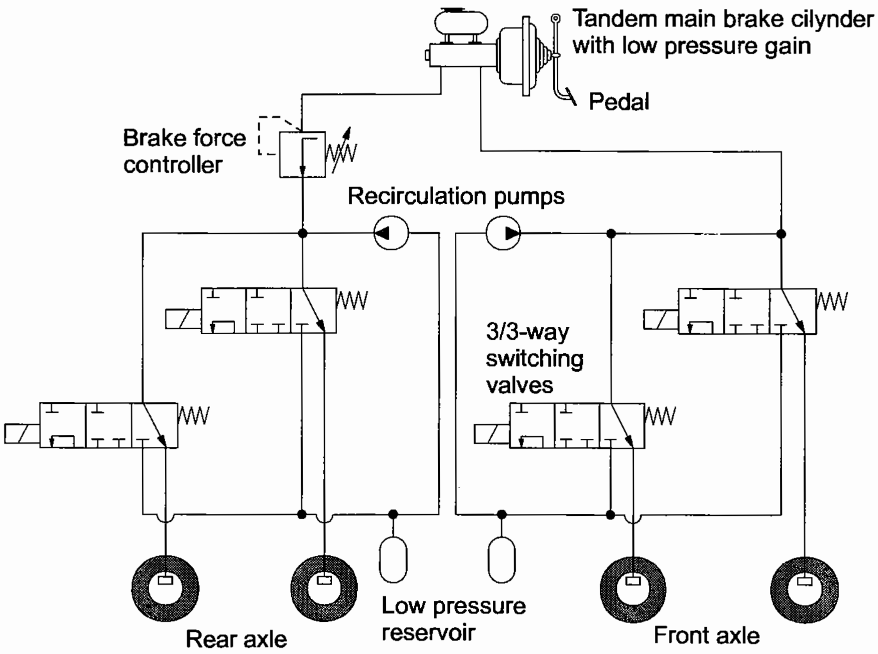


Fig. B3.2: Hydraulic circuit diagram of an automatic antilocking device (Bosch)

Two-step action controller

Simplified antilocking devices only have two switching positions.

1. During normal braking, the wheel brake cylinder is connected to the main brake cylinder.
2. If the wheel is in danger of locking, the wheel brake cylinder is connected to the low pressure reservoir.

In this event, a two-step controller comes into effect.

Multi-step controller

Multi-step controllers can assume more than three different switching positions and only rarely used in hydraulic circuits.

3.2 Block diagrams for non-dynamic controllers

Two-step, three-step and multi-step controllers are classified as non-dynamic controllers.

The function of a non-dynamic controller can be represented by a signal flow diagram with two boxes:

- In the first box, the difference is calculated between the reference and controlled variable. This box is known as a comparator.
- In the second box, the system deviation is used to determine the correcting variable. This box forms the closed-loop control element.

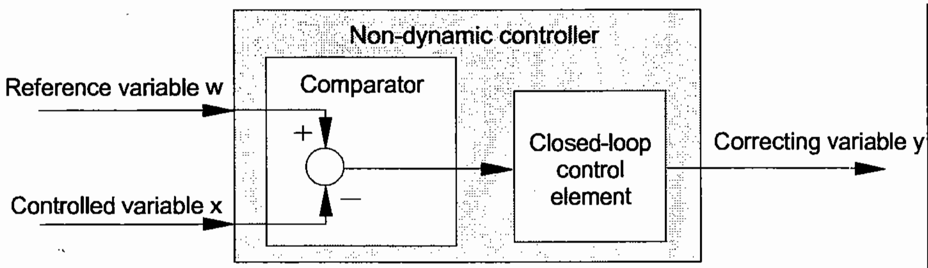


Fig. B3.3:
Signal flow diagram for non-dynamic controllers

Block diagrams for non-dynamic controllers

Fig. B3.4 shows block diagrams for various non-dynamic controllers. In the case of a controller with switching difference, two different characteristic branches are described for rising and falling system deviations.

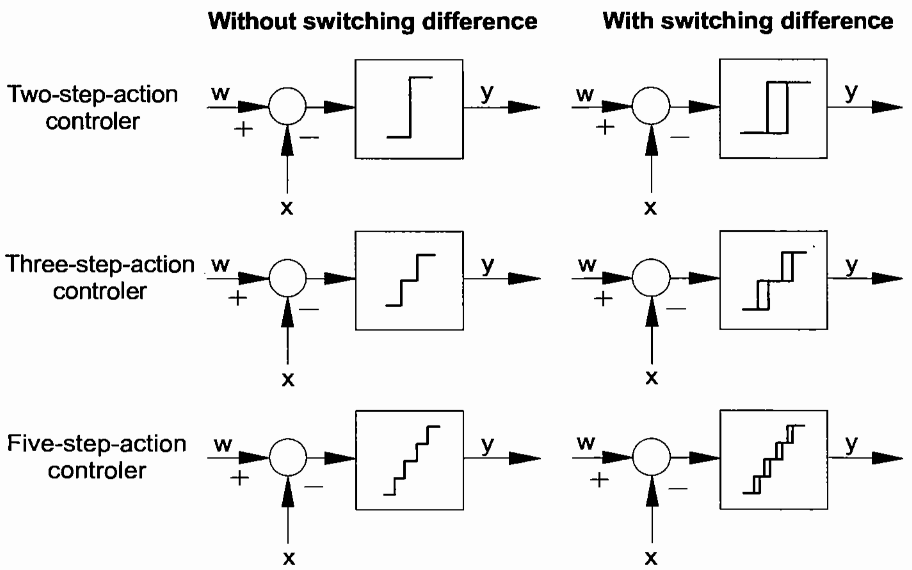


Fig. B3.4:
Block diagram for non-dynamic controllers

3.3 P controller

Proportional controllers are classified as dynamic controllers. This type of controller is referred to for short as a P controller.

Example of application

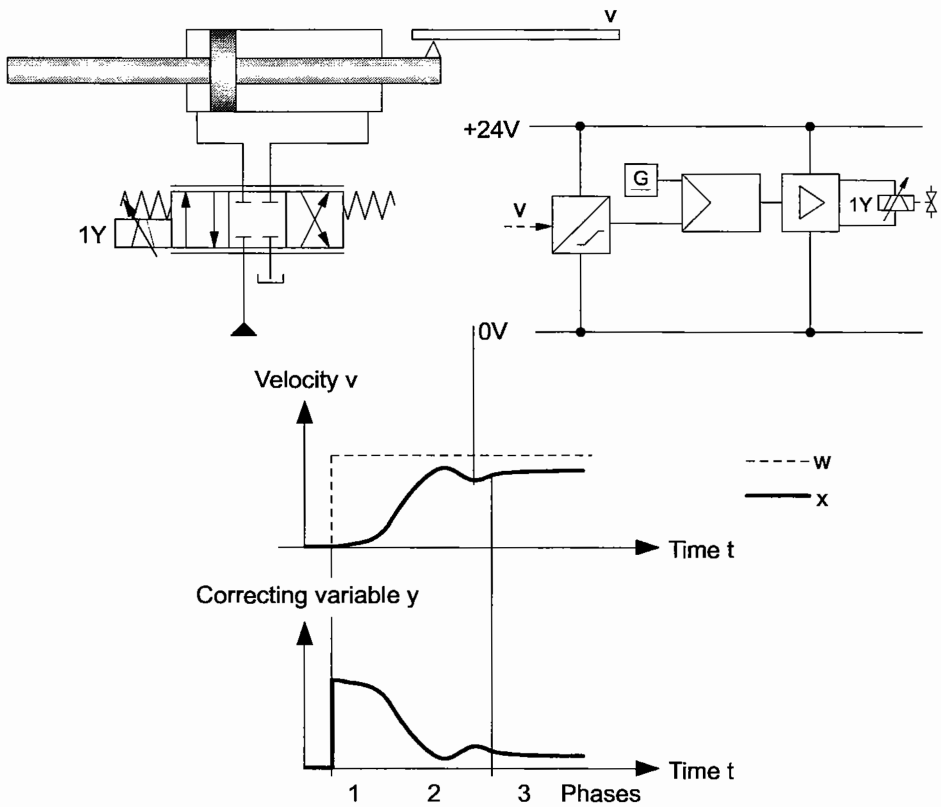
The figure below illustrates a closed-loop speed control circuit with proportional controller (P controller). When the reference variable executes a step-change, the closed control loop reacts as follows:

Phase 1: The system deviation is very large. The valve is wide open.

Phase 2: The system deviation becomes smaller. The correcting variable and the valve opening accordingly become smaller.

Phase 3: The system deviation, the correcting variable and thus also the valve opening are constant.

Fig. B3.5: Speed control with a proportional controller



Transition function of a P closed-loop control element

If the system deviation executes a step change with a proportional controller, the controller reacts with a step change in the correcting variable. Figs. B3.6b and B3.6c show two transition functions for proportional controllers with different proportional coefficients.

Equation for P closed-loop control element

The correcting variable y with a proportional controller is calculated in accordance with the following equation:

$$y = KP \cdot (w - x) = KP \cdot e$$

KP is known as proportional coefficient or a proportional gain. The correcting variable of a P controller becomes greater

- the higher the proportional gain KP and
- the larger the system deviation e

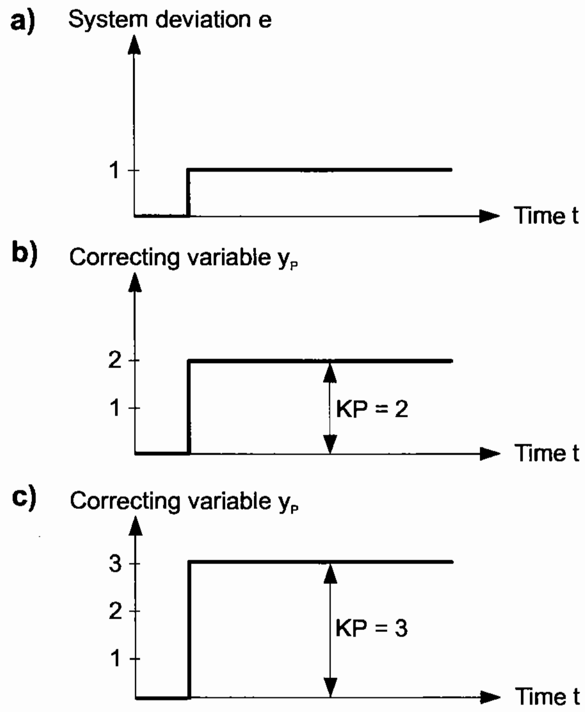


Fig. B3.6: Transition functions for two P controllers with different controller coefficients

3.4 I controller

Integral-action controllers are known for short as I controllers. The correcting variable is calculated by integration of the system deviation.

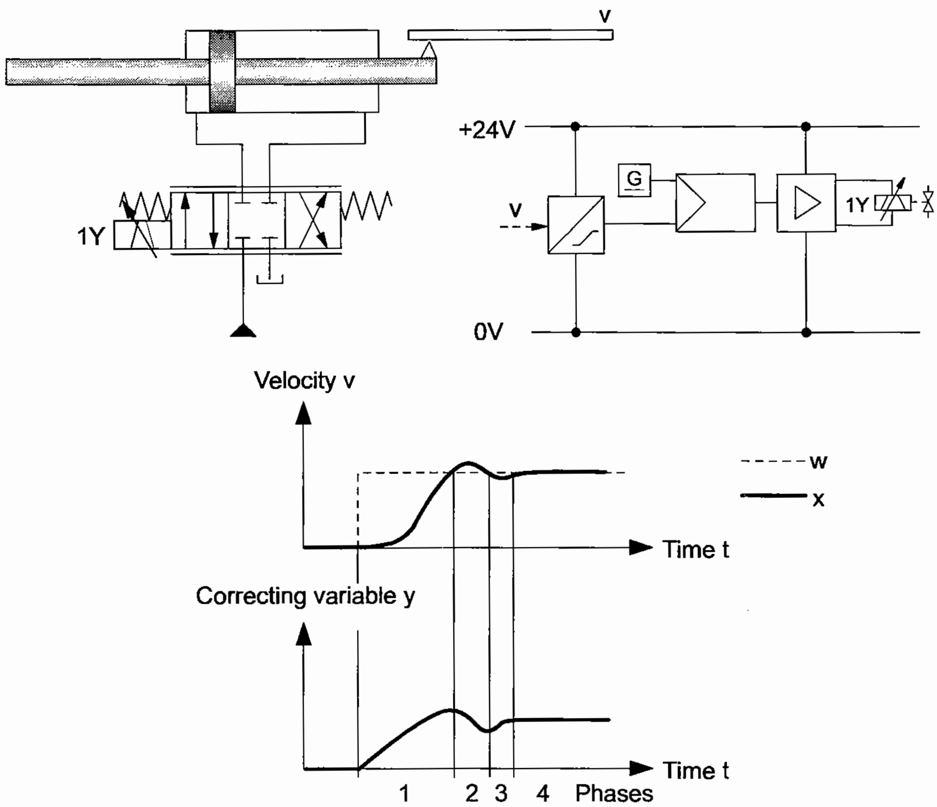
Example of application

Fig. B3.7 shows a closed-loop speed control circuit with an integral-action controller. If the reference variable executes a step change, the closed-loop control circuit exhibits the following reaction:

- In phases 1 and 3, the system deviation is positive and the correcting variable of the I controller increases.
- In phase 2, the system deviation is negative and the correcting variable becomes smaller.
- In phase 4, the reference variable and controlled variable are the same. The correcting variable is constant

In contrast to the closed-loop control circuit with a proportional-action controller (Fig. B3.6), no steady-state system deviation occurs in a closed-loop control circuit with an integral-action controller.

Fig. B3.7: Speed control with integral-action controller



Transition function of I closed-loop control element

When the system deviation executes a step change, the correcting signal exhibits a ramp change. The gradient is higher

- the greater the system deviation e
- the higher the controller gain KI or
- the smaller the time constant TI.

Figs. B3.8b and B3.8c show the transition functions for two integral-action closed-loop control elements with different controller gain values or time constants.

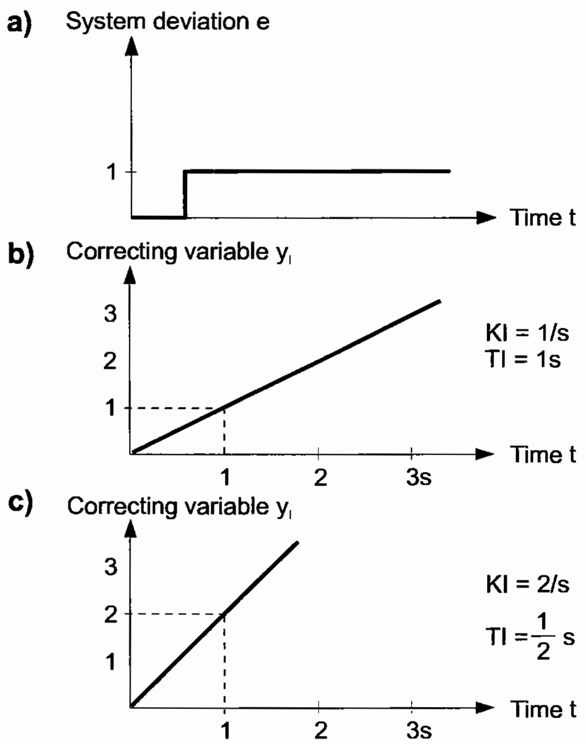


Fig. B3.8:
Transition function for two I controllers

Equations for I closed-loop control element

In the case of an I controller, the correcting variable is calculated using one of the two equations below:

$$y = KI \int (w - x)\, dt = KI \int e\, dt$$

$$y = \frac{1}{TI} \int (w - x)\, dt = \frac{1}{TI} \int e\, dt \text{ mit } TI = \frac{1}{KI}$$

TI is known as the time constant and KI as the controller gain or controller

3.5 D-controller component

A derivative-action controller is known for short as a D controller. The correcting variable is calculated by differentiation of the system deviation.

A derivative-action controller alone is not a suitable means of minimising the steady-state system deviation. D controllers are thus used only in combination with P and/or I controllers.

Example of application

Fig. B3.9 shows a closed-loop speed control circuit for a hydraulic cylinder. The reference variable is changed from the point in time T1 onwards in the form of a ramp. The reaction of the closed-loop control circuit depends on the type of controller used:

- Fig. B3.9b shows the behaviour of the closed-loop control circuit with a P controller. Fig. B3.9c shows the associated correcting variable. The system deviation is still very small directly after the time interval T1. The valve is accordingly opened only a little by the proportional-action controller. The closed-loop control circuit reacts only slowly to the change in the reference variable.
- Fig. B3.9d shows the behaviour of a combination of a P and D controller. As soon as the reference variable changes, the correcting variable component generated by the derivative-action controller component (Fig. B3.9e) executes a step change. The overall correcting variable thus immediately increases. The valve is abruptly opened further. The closed-loop control circuit reacts faster and more strongly to the change in the reference variable (Fig. B3.9d).

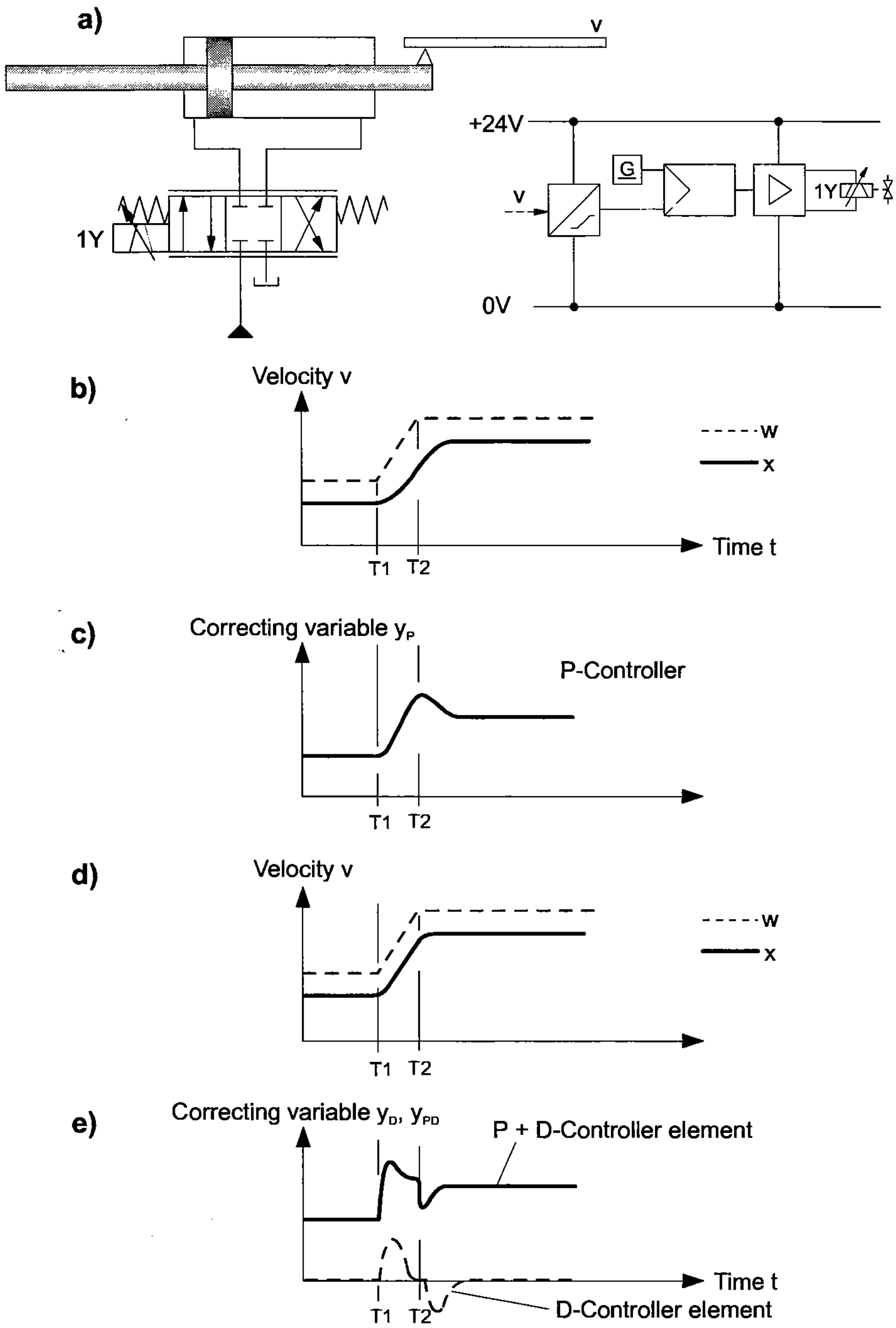


Fig. B3.9:
Effect of derivative-action controller component

Transition function of D closed-loop control element

During the transition function, the system deviation executes a step change. This results in the following correcting variable curve:

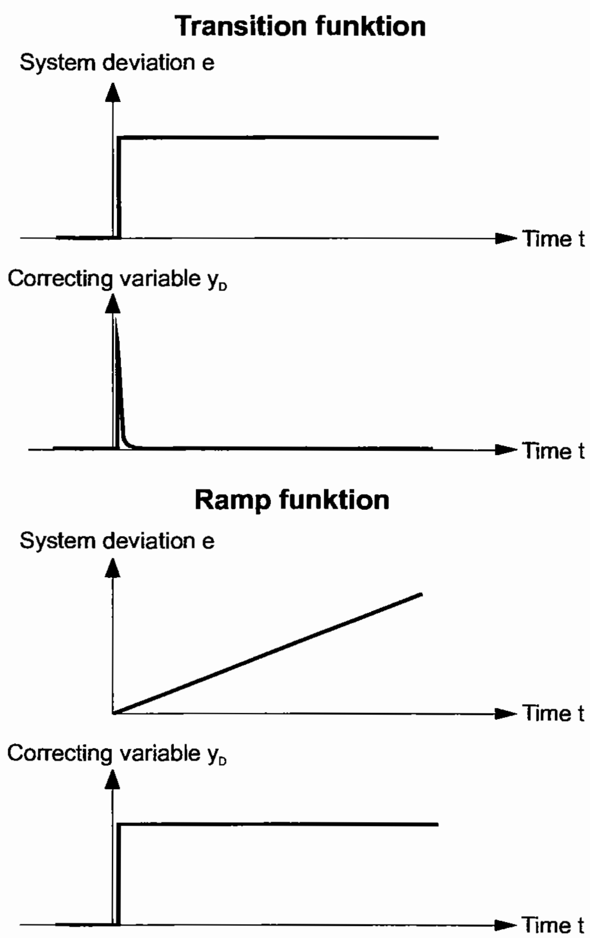
- At the point in time at which the system deviation changes, the derivative-action controller produces a peak in the output signal.
- Following this, the system deviation remains constant. The output signal of the derivative-action controller accordingly immediately falls back to zero.

Ramp function of D closed-loop control elements

If the system deviation increases with a constant gradient, the D controller component produces a constant correcting variable. The correcting variable is greater

- the higher the controller gain KD
- the steeper the gradient of the increase in the system deviation.

Fig. B3.10: Transition and ramp functions of D controller component



Equation for D closed-loop control element

The following equation is used to calculate the correcting variable generated by the D controller component:

$$y = KD \frac{d}{dt}(w - x) = KD \frac{d}{dt} e$$

The correcting variable generated by the D controller component is greater,

- the larger the controller coefficient KD and
- the faster the system deviation changes.

Practical implementation of a D closed-loop control element

Derivative-action control cannot be simulated precisely either with an analogue electrical circuit or a computer. In practice, a D controller component therefore exhibits only approximately derivative-action behaviour.

3.6 PI, PD and PID controllers

Table 3.3 compares the advantages and disadvantages of P, I and D controllers.

Table B3.3: Properties of P, I and D controllers

Advantages / Disadvantages	*P controllers*	*I controllers*	*D controllers*
Speed of reaction of closed-loop control circuit	Fast	Slow	Very fast
Steady state system deviation	Present	Zero	Cannot be controlled
Remarks			Cannot be used without additional controller component

In order to obtain the advantages of the various types of controllers at the same time, combinations of P, I and D controllers are used. Of all the possible controller combinations, PI, PD and PID controllers are the only ones of practical significance. The table below compares the properties of these controllers.

Table B3.4: Properties of PI, PD and PID controllers

Properties	*PI controllers*	*PD controllers*	*PID controllers*
Speed of reaction of closed-loop control circuit	Fast	Very fast	Very fast
Steady state system deviation	Zero	Present	Zero

PI controller

A PI controller combines the higher accuracy of an I controller with the fast reaction of a P controller. In order to achieve this, a P controller and I controller are connected in parallel in the signal flow diagram. The two correcting variables are added (Fig. B3.14). A PI controller is distinguished by two characteristic variables:

- Either by the proportional-action coefficient KP and the integral-action coefficient KI
- or by the proportional-action coefficient KP and the integral-action time Tn.

Integral-action time

The integral-action time Tn can be calculated from the proportional-action coefficient KP and the integral-action coefficient KI, using the following formula:

$$Tn = \frac{KP}{KI}$$

Transition function of PI closed-loop control element

The transition function of a PI controller is shown in Fig. B3.11. In order to determine the transition function, the transition functions of the P and I controllers are added using a graph. The proportional-action coefficient KP and integral-action time Tn can be read from the transition function.

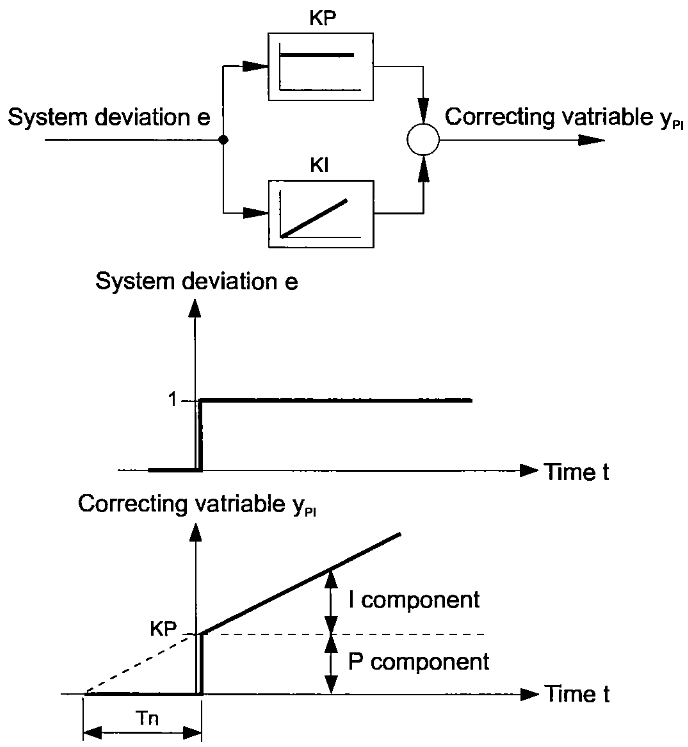


Fig. B3.11:
Signal flow diagram and transition function for PI controller

Equations for PI closed-loop control element

In the case of a PI controller, the correcting variable is calculated using one of the two equations below:

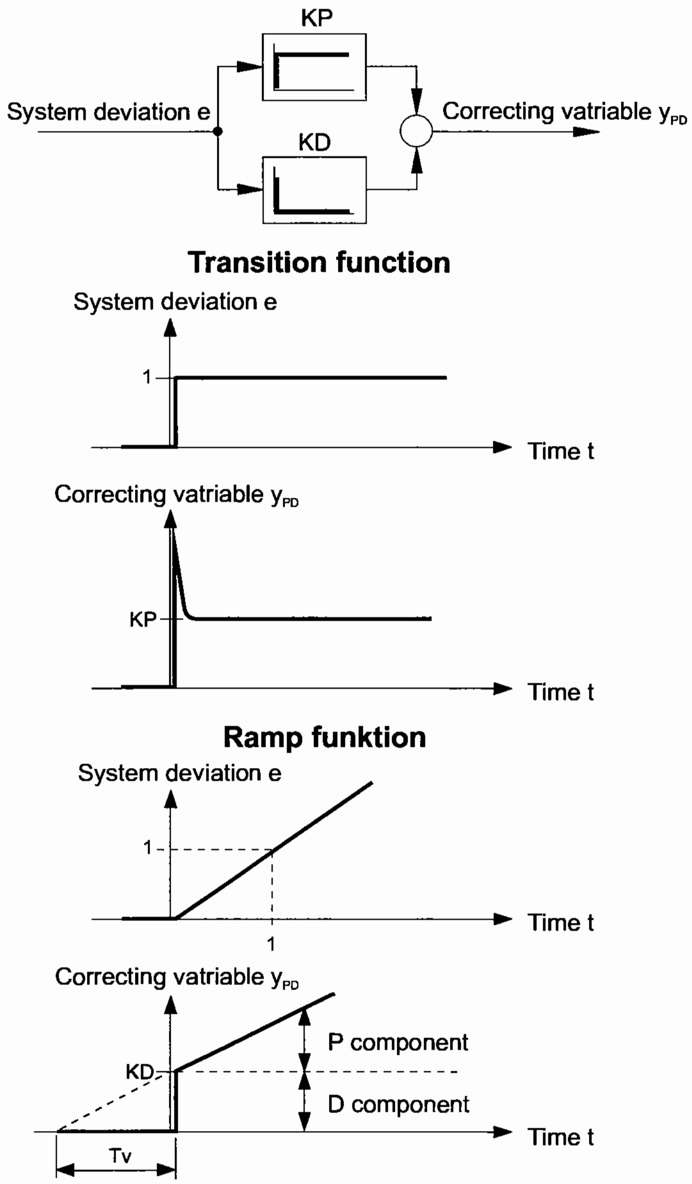
$$y = KP\,(w - x) + KI \cdot \int (w - x)\,dt = KP \cdot e + KI \cdot \int e\,dt$$

$$y = KP\,(w - x) + \frac{1}{TN} \cdot \int (w - x)\,dt = KP\,(e + \frac{1}{TN} \int e\,dt)$$

PD controller

Due to the additional D component. the PD controller reacts faster than a pure P controller. In the signal flow diagram for a PD controller, a P controller and a D controller are connected in parallel (Fig. B3.12).

Fig. B3.12: Signal flow diagram, transition and ramp functions for PD controller



The behaviour of a PD controller is determined by two characteristic variables:

- Either by the proportional-action coefficient KP and the derivative-action coefficient KD
- or by the proportional-action coefficient KP and the derivative-action time Tv.

Derivative-action time Tv

There is the following relationship between the derivative-action time Tv, the proportional-action coefficient KP and the derivative-action coefficient KD:

$$Tv = \frac{KD}{KP}$$

Transition and ramp functions of PD controller

The transition and ramp functions are shown in Fig. B3.12:

- The proportional-action coefficient KP can be read from the transition function.
- The derivative-action coefficient KD and the derivative-action time Tv can be read from the ramp response.

Equations for PD closed-loop control element

The correcting variable is calculated using one of the two equations below :

$$y = KP\,(w - x) + KD \cdot \frac{d}{dt}(w - x) = KP \cdot e + KD \cdot \frac{d}{dt} e$$

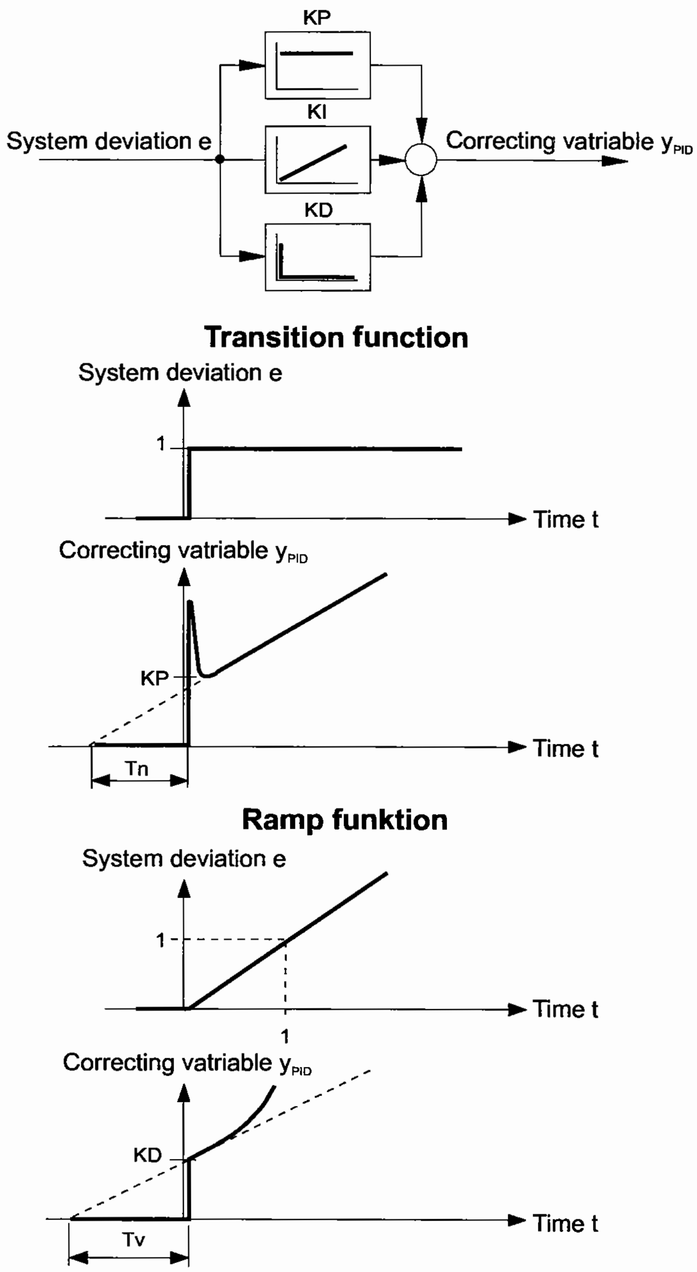
$$y = KP\,(w - x + TV \cdot \frac{d}{dt}(w - x)) = KP\,(e + TV \cdot \frac{d}{dt} e)$$

PID controller

A PID controller combines the advantages of P, I and D controllers. Fig. B3.13 shows the signal flow diagram. A PID controller is distinguished by three characteristic variables:

- Either by the proportional-action, integral-action and derivative-action coefficients (KP, KI and KD)
- or by the proportional gain, the derivative-action time and the integral-action time (KP, Tv and Tn).

Fig. B3.13:
Signal flow diagram, transition and ramp functions for PID controller



Derivative-action time Tv and integral-action time Tn

The derivative-action time and integral-action time are governed by the same formulae as for the PI and PD controllers:

$$Tv = \frac{KD}{KP}$$

$$Tn = \frac{KP}{KI}$$

Transition and ramp functions of PID closed-loop control element

Fig. B3.13 shows the transition and ramp functions of the PID controller:

- The proportional-action coefficient KP and the integral-action time Tn can be read from the transition function.
- The derivative-action coefficient KD and the derivative-action time Tv can be read from the ramp function.

Equations for PID closed-loop control element

The following equations are used to calculate the correcting variable:

$$y = KP\,(w - x) + KI \cdot \int (w - x)\,dt + KD \cdot \frac{d}{dt}\,(w - x)$$

$$= KP \cdot e + KI \cdot \int e\,dt + KD \frac{d}{dt} e$$

or

$$y = KP\,(w - x + \cdot \frac{\int (w - x)\,td}{Tn} + Tv \cdot \frac{d}{dt}\,(w - x)) = KP\,(e + \frac{\int e\,dt}{Tn} + Tv \frac{d}{dt} e)$$

3.7 Block diagrams for standard dynamic controllers

The signal flow diagrams for P, I, PI, PD and PID controllers consist of three elements:

- Summation of the reference and controlled variables (comparator or summation point)
- The actual controller function (closed-loop control element)
- A limiter for the correcting signal (limiter).

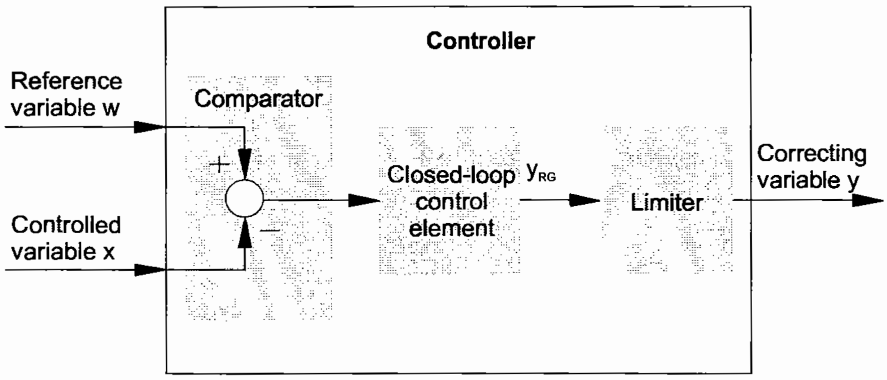


Fig. B3.14: Signal flow diagram for a standard dynamic controller

Example of application of correcting-signal limiter

Fig. B3.15 shows a closed-loop speed control circuit for a pneumatic cylinder. A proportional-action controller is used. The controller operation for a pronounced step change in the reference variable can be divided into two phases:

Phase 1: The step change in the reference variable results in a large system deviation. The output variable yP generated by the P closed-loop control element rises to a high value (Fig. B3.15b). The variable yP is larger in phase 1 than the maximum possible correcting variable for the valve. The peak of the correcting signal is accordingly cut off by the limiter (Fig. B3.15c).

Phase 2: The system deviation has become smaller. The output variable of the closed-loop control element has thus fallen again to a small value. In this phase, the curves in Figs. B3.15b and B3.15c are the same.

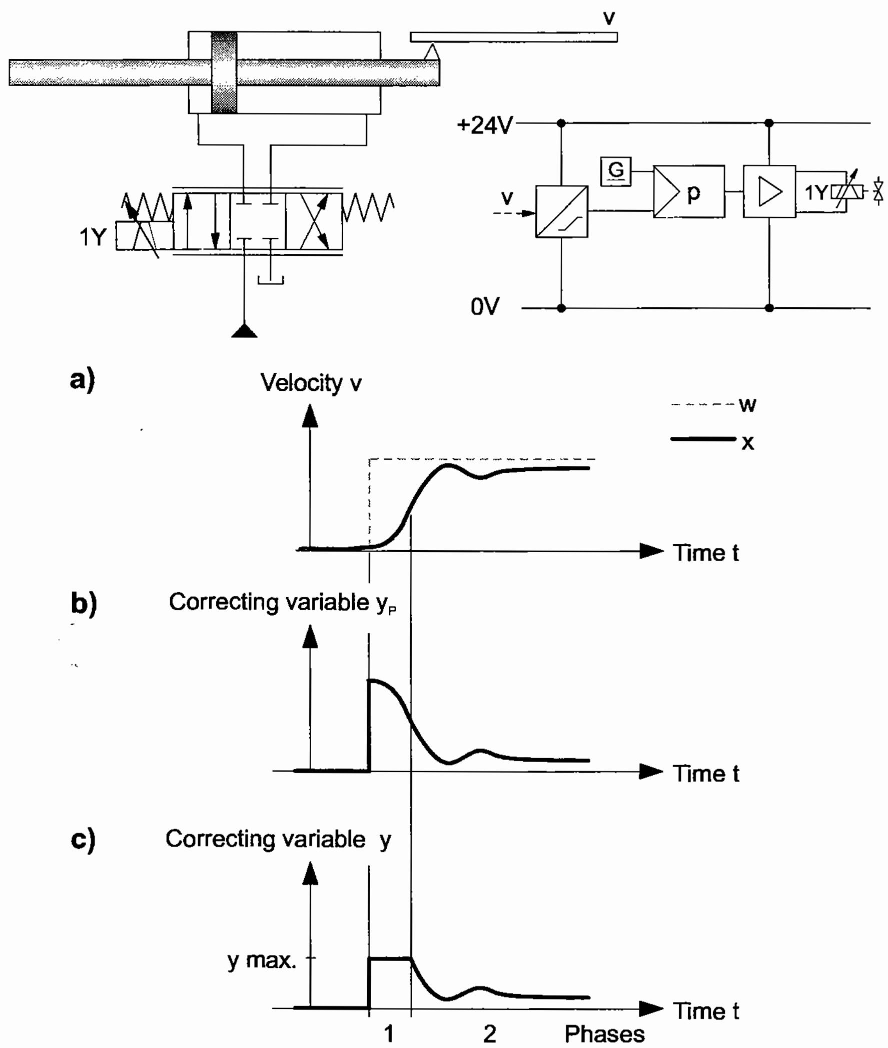


Fig. B3.15:
Speed control with correcting signal limitation

Characteristic for a limiter

The characteristic of a limiter is shown in Fig. B3.16. A distinction is made in the limitation of the correcting variable between the following operating ranges:

- In ranges 1 and 3, the limiter input signal lies outside the valve correcting range. The correcting variable is thus limited to the maximum or minimum value for which the valve is designed. In ranges 1 and 3, the valve is fully open.
- If the output signal lies within range 2, it is not limited. In this range, the valve opening varies in proportion to the controller output signal.

Fig. B3.16: Characteristics and block diagram for a limiter

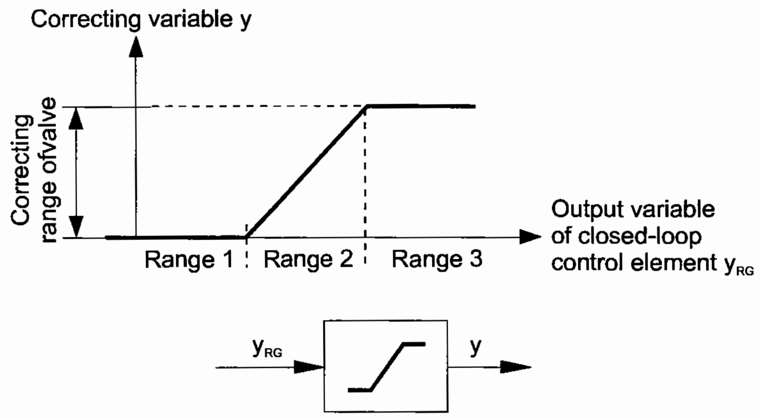
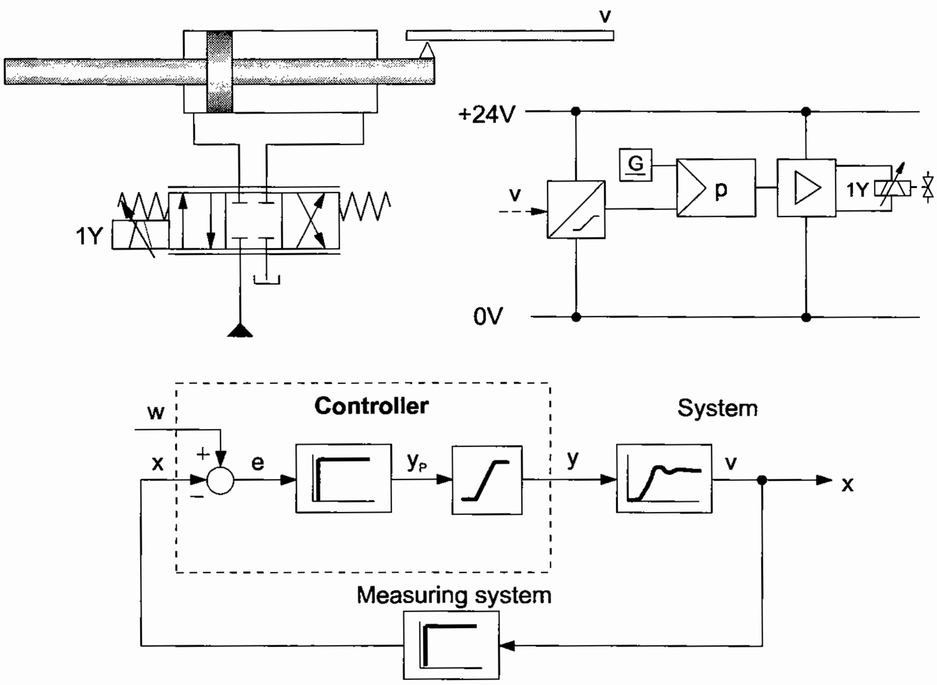


Fig. B3.17 shows the signal flow diagram for a closed-loop speed control circuit with a P controller. The signal flow diagram shows the component parts of the controller:

- Comparator
- Closed-loop control element
- Limiter.

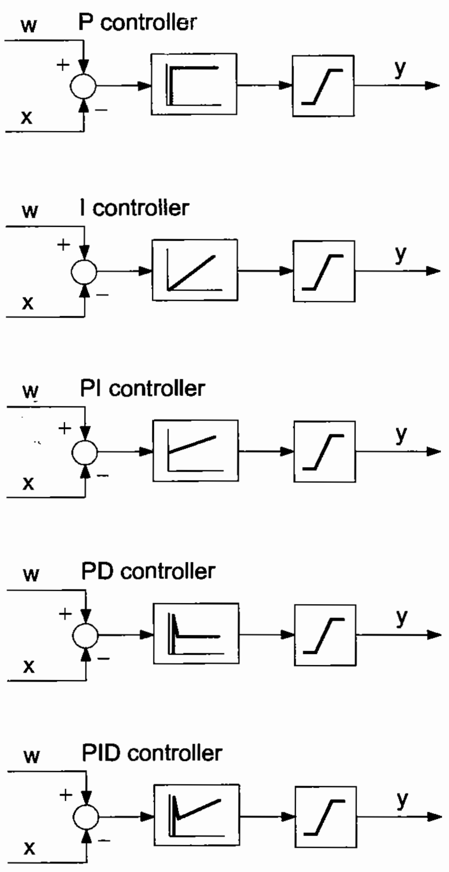
Fig. B3.17: Closed-loop control circuit with P controller



Block diagrams for dynamic controllers

Fig. B3.18 shows block diagrams for P, I, PI, PD and PID controllers.

Controller struktur



Controller	Coefficients and time constants
P controller	KP
I controller	KI or TI
PI controller	KP, KI or KP, TN
PD controller	KP, KD or KP, TV
PID controller	KP, KI, KD or KP, TV, TN

Fig. B3.18
Block diagrams for P, I, PI, PD and PID controllers

Conversion of controller parameters and controller time constants

PID controllers are usually distinguished by their proportional-action coefficient KP and time constants Tv and Tn. We also, however, frequently describe these controllers by using the proportional-action, integral-action and derivative-action coefficients. Table B3.4 summarises the equations which can be used to convert from one method of representation to another.

Table B3.4: Controller coefficients and time constants

Conversion of KP, Tv, Tn to KI, KD	*Conversion of KP, KI, KD to Tn, Tv*
$KI = \frac{KP}{Tn}$	$Tn = \frac{KP}{KI}$
$KD = KP \cdot Tv$	$Tv = \frac{KD}{KP}$

3.8 Status controller

Certain controlled systems cannot be controlled adequately with a PID controller. Status controllers are used in these cases.

In order to determine which variables are looped back in the status controller, a mathematical model of the controlled system is created. The number of status variables corresponds to the order of the model. Each status variable is measured and looped back. In the case of a second-order model, for example, two variables must be looped back.

Closed-loop control of a pneumatic positioning actuator

A hydraulic positioning actuator is one of the types of controlled systems which cannot be controlled adequately with a standard controller. A hydraulic positioning actuator is a controlled system without compensation which is capable of oscillation.

A third-order model will generally be selected for a hydraulic positioning actuator. It will then be necessary to loop back three variables in the status controller. The following three variables are generally selected:

- The position s of the piston
- The velocity v of the piston
- The acceleration a of the piston.

The controller is accordingly known as a triple-loop controller.

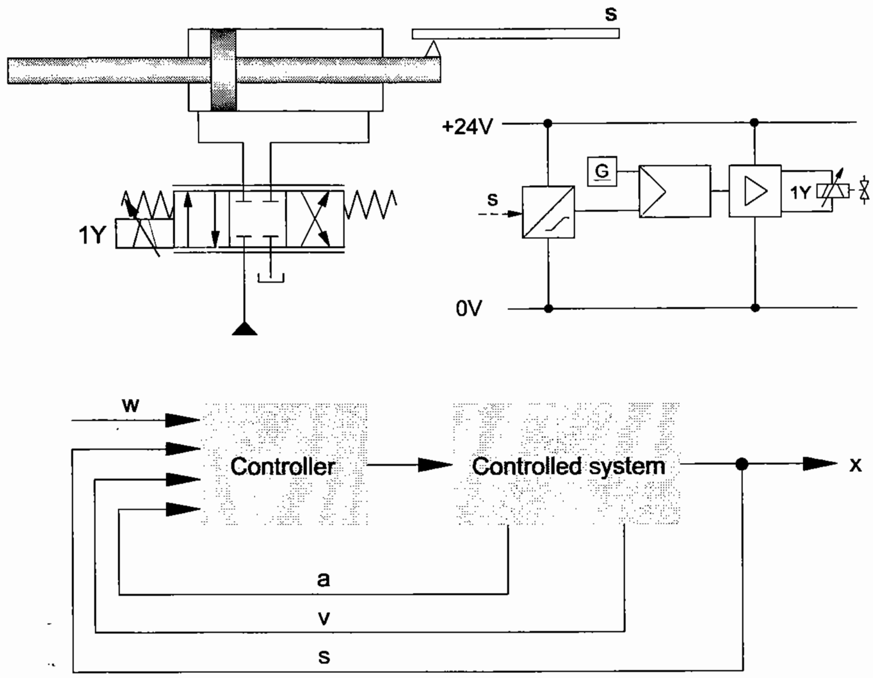


Fig. 3.19:
Closed-loop control circuit for a hydraulic positioning actuator

Differentiation

Hydraulic positioning actuators are equipped with a positional transducer.

In order to reduce costs, the velocity and acceleration are not measured with sensors. These must be calculated from the position by differentiation.

Controller equation

The following overall equation results for the calculation of the correcting variable:

$$y = KX\,(w - x) - K\dot{X} \cdot d\,\frac{x}{dt} \cdot d\,\frac{x}{dt} - K\ddot{X}\,\frac{d^2x}{dt^2}$$

Fig. B3.20 shows the associated signal flow diagram.

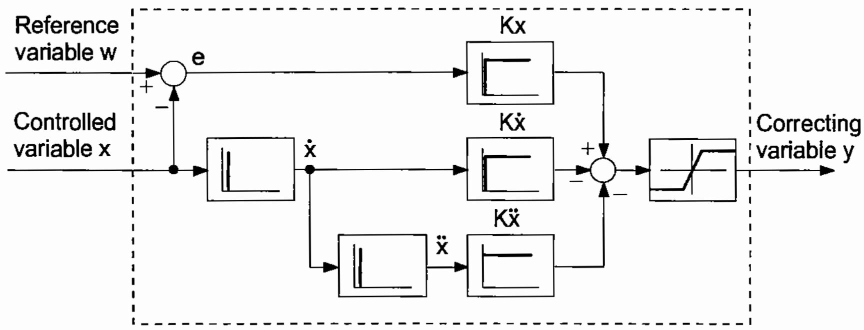


Fig. B3.20:
Signal flow diagram for triple-loop status controller

e = Position difference
ẋ = Velocity
ẍ = Acceleration

Kx = Position coefficient
Kẋ = Velocity coefficient
Kẍ = Acceleration coefficient

3.9 Selection of controller structure

The choice of controller structure depends on the type of controlled system concerned.

- Fig. B3.21 shows suitable controller structures for the various types of controlled systems with compensation.
- Fig. B3.22 provides a summary of suitable controllers for the various types of controlled systems without compensation.

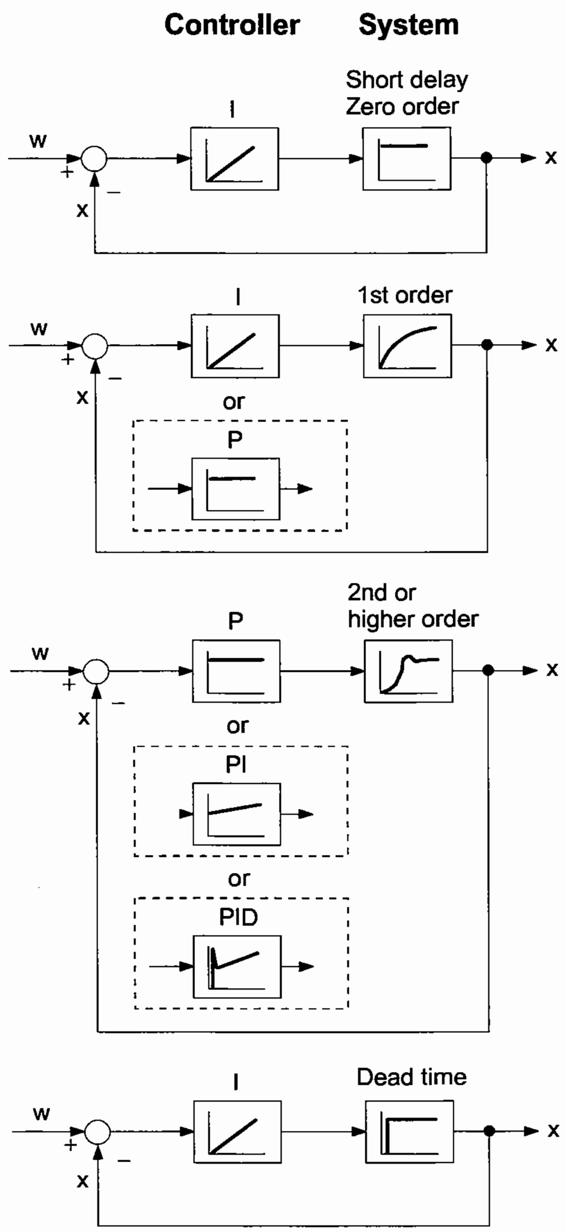
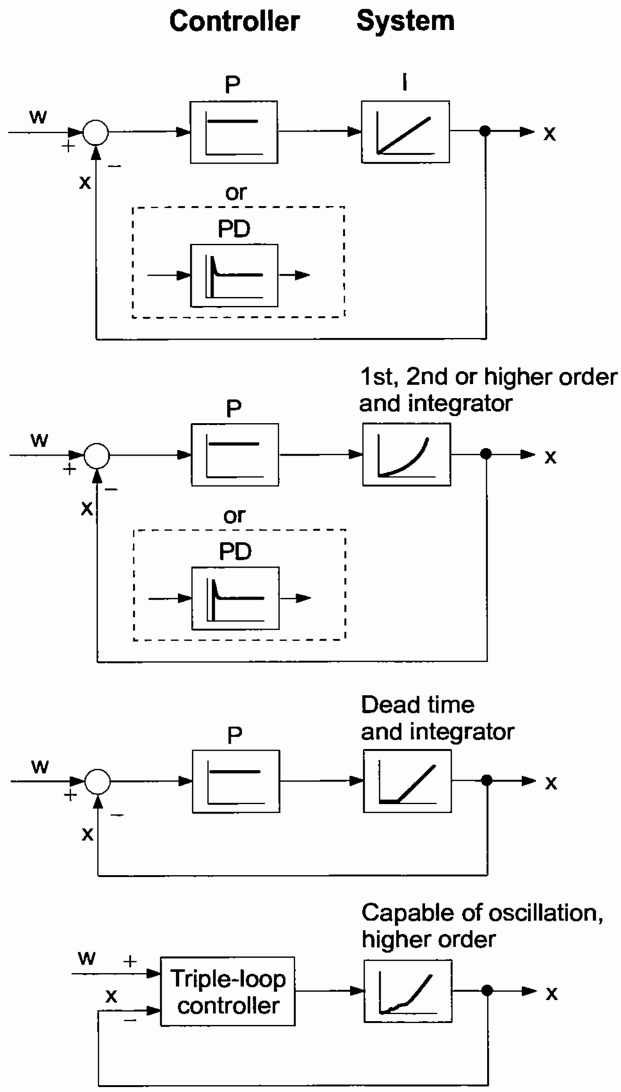


Fig. B3.21: Controller structures for controlled systems with compensation

Fig. B3.22: Controller structures for controlled systems without compensation



3.10 Response to interference and control factor

When a controlled system with compensation is used in combination with a P controller, the control factor is a measure of control quality.

An interference variable has the greatest effect on an open control loop. The control factor indicates the degree to which the effect of the interference variable is attenuated in a closed control loop.

$$\text{Control factor} = \frac{\text{Steady - state change in output variable (controlled variable) in closed control loop}}{\text{Steady - state change in output variable in open control loop}}$$

The control factor is always smaller than one. The smaller the control factor, the better the effect of the interference is attenuated.

Example of application

Fig. B3.23a shows a hydraulic open-loop control circuit. A constant velocity is produced with a constant correcting variable. This is a controlled system with compensation.

In Fig. B3.23b, a mass places a load on the pneumatic cylinder. The mass generates a force which acts on the piston rod. This force represents an interference variable affecting the motion of the piston. With the same correcting variable as before, the velocity with the load is significantly lower than without the load.

Fig. B3.23:
Response to interference
of an open control loop

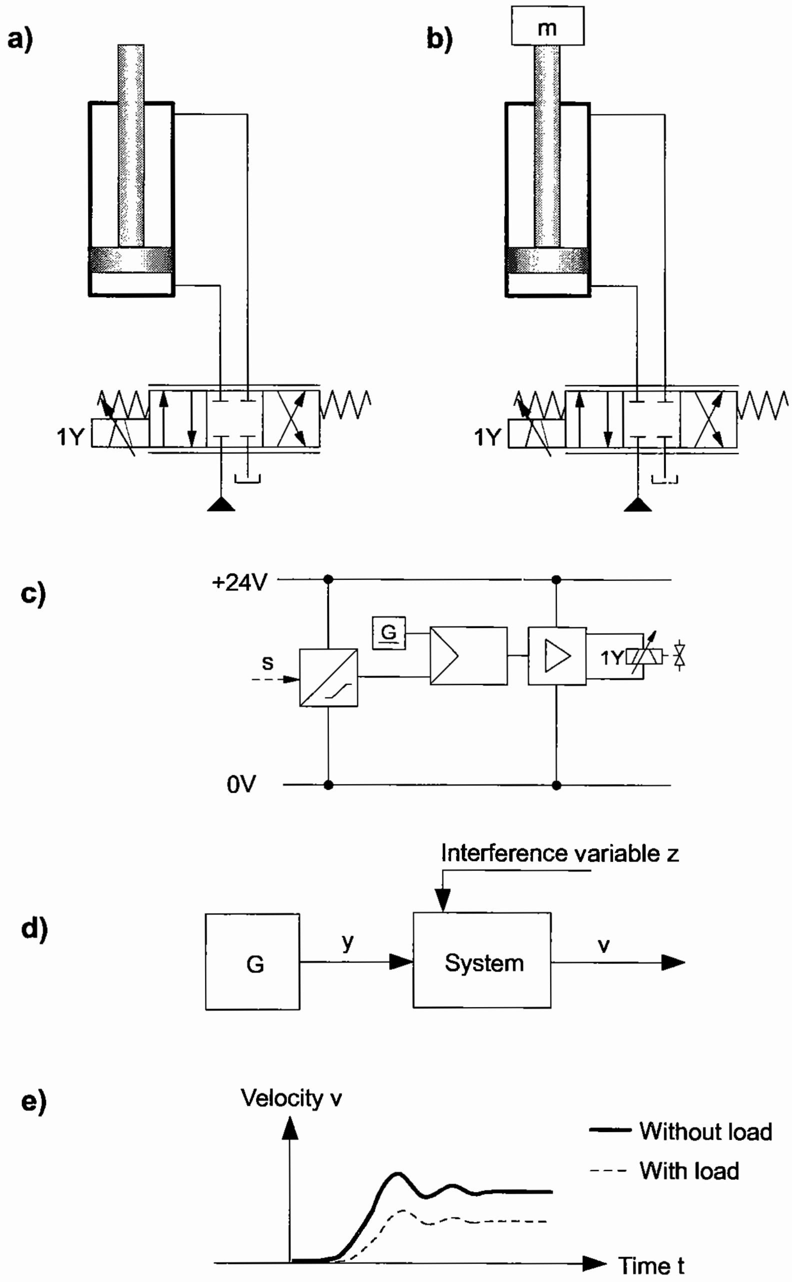


Fig. B3.24 shows a hydraulic actuator with closed-loop speed control. In the case of this actuator, too, the velocity is lower when the piston rod is subjected to a load.

The reduction in velocity in the closed-loop control circuit is much smaller than the reduction in velocity in the open-loop control circuit. The response to interference of the closed-loop control circuit is significantly better.

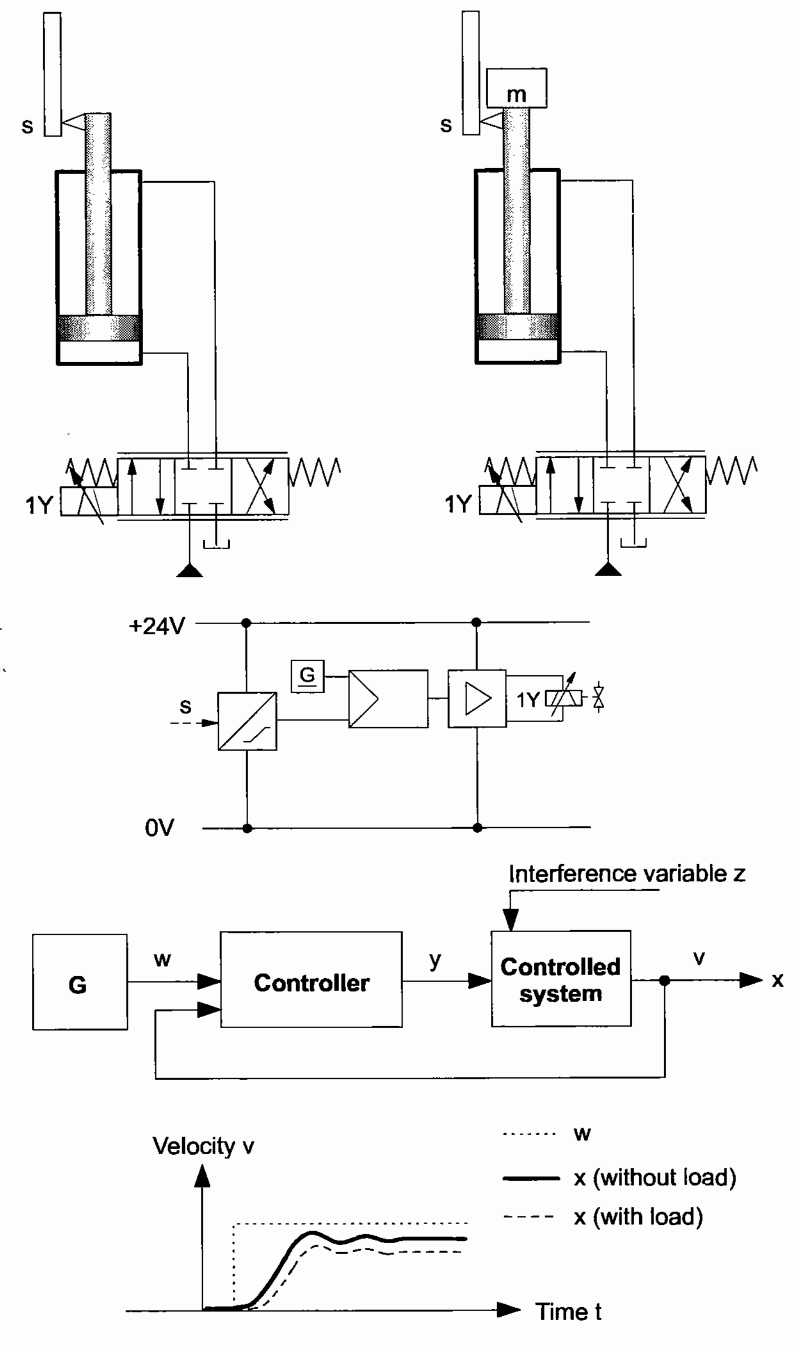


Fig. B3.24:
Response to interference of a closed control loop

Closed-loop gain

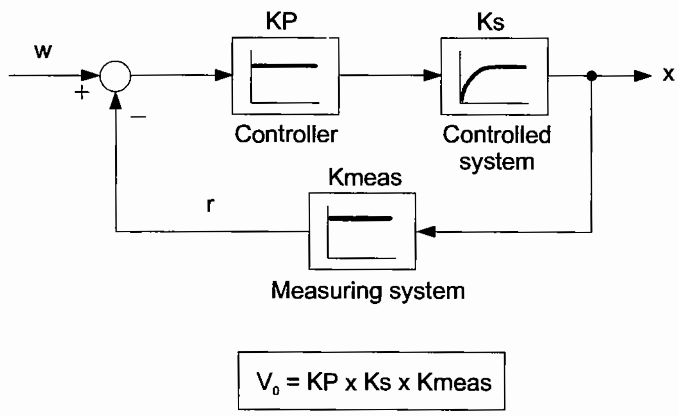
The closed-loop gain V_0 is required in order to calculate the control factor. When a signal passes once through the complete closed-loop control circuit, it is multiplied by the following factors (Fig. B3.28):

- In the controller by the factor KP
- In the controlled system by the factor Ks
- In the measuring system by the factor Kmeas.

The formula for closed-loop gain is thus as follows:

$$V_0 = KP \cdot Ks \cdot Kmeas$$

Fig. B3.25: Calculation of closed-loop gain



Calculation of control factor

The control factor is calculated from the closed-loop gain using the following formula:

$$r = \frac{1}{(1+V_0)}$$

Example of calculation of control factor

The following values have been determined for the closed-loop speed control circuit for a hydraulic actuator:

$$KP = 1.5$$

$$Ks = \frac{0.2\left(\frac{m}{s}\right)}{V}$$

$$Kmeas = \frac{10\ V}{\left(\frac{m}{s}\right)}$$

The closed-loop gain is thus:

$$V_0 = KP \cdot Ks \cdot Kmeas = 3$$

This closed-loop gain results in the following control factor:

$$r = \frac{1}{(1+V_0)} = \frac{1}{4} = 0.25$$

The closed-loop control circuit reduces the influence of interference variables by 75%.

Example of the effect of an interference variable

In the case of a hydraulic actuator operated as an open-loop control circuit, an interference force produces a reduction in the velocity from 30 cm/s to 20 cm/s. The deviation is 10 cm/s.

In order to improve the response to interference, the open-loop control circuit is replaced by a closed-loop control circuit with a control factor of 0.25. When the same force as before now acts on the closed-loop control circuit, the reduction in velocity is only from 30 cm/s to 27.5 cm/s, i.e. a reduction of 2.5 cm/s.

Technical implementation of controllers

4.1 Structure of closed-loop control circuits

A closed-loop control circuit includes the following functions:

- Generation of reference variable
- Controller
- Final control element
- Controlled-system element
- Measuring system.

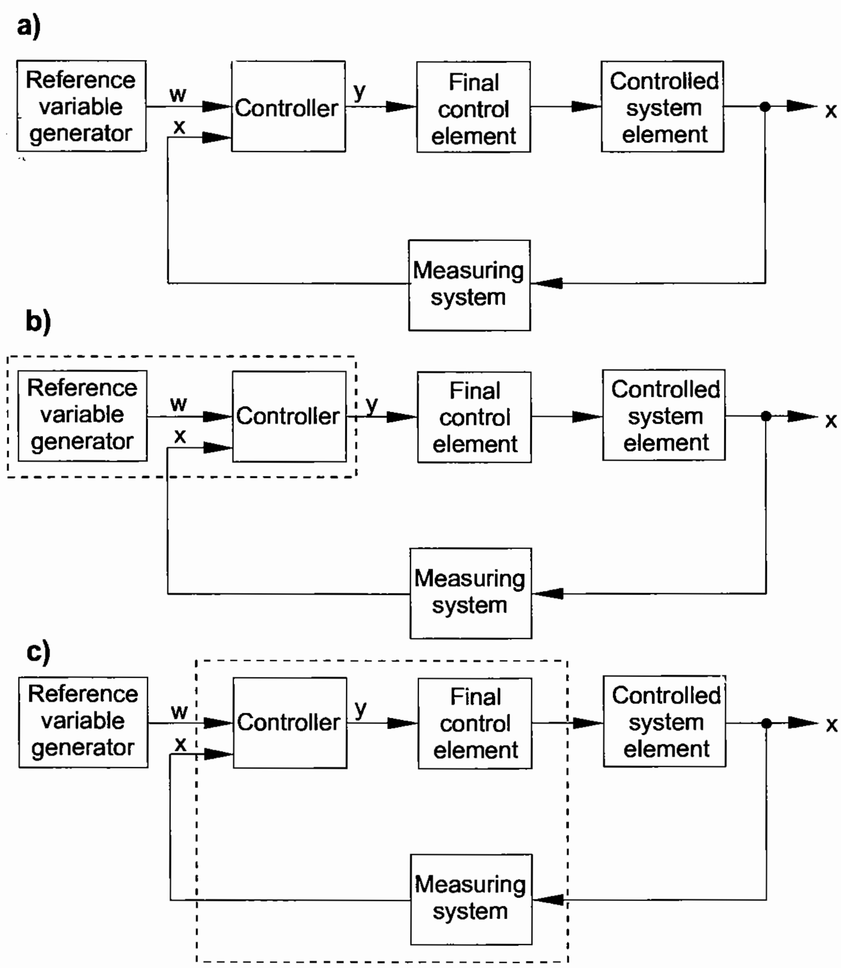


Fig. B4.1:
Closed-loop control circuit

There are a number of possibilities for the practical implementation of a controller:

- One unit assumes only the function of a controller (Fig. B4.1a).
- The controller is combined with other functions of the closed-loop control circuit to form a single unit. Various combinations are encountered in practice. Two possibilities of combining the controller with other functions are shown in Figs. B4.1b and B4.1c.

The advantages and disadvantages of combining several functions are shown in Table B4.1.

Table B4.1: Combination of several functions in one device

Advantages	*Disadvantages*
Closed-loop control circuit consists of small number of devices	Individual devices more expensive to replace
Lower cable and tubing costs	Device suitable only for certain types of closed-loop control circuits
Less expensive	
Cheaper maintenance	

Manually-operated pressure regulator

Fig. B4.2 shows a hydraulic pressure regulator. This valve has the following functions in the closed-loop control circuit:

- Controller
- Final control element
- Measuring system.

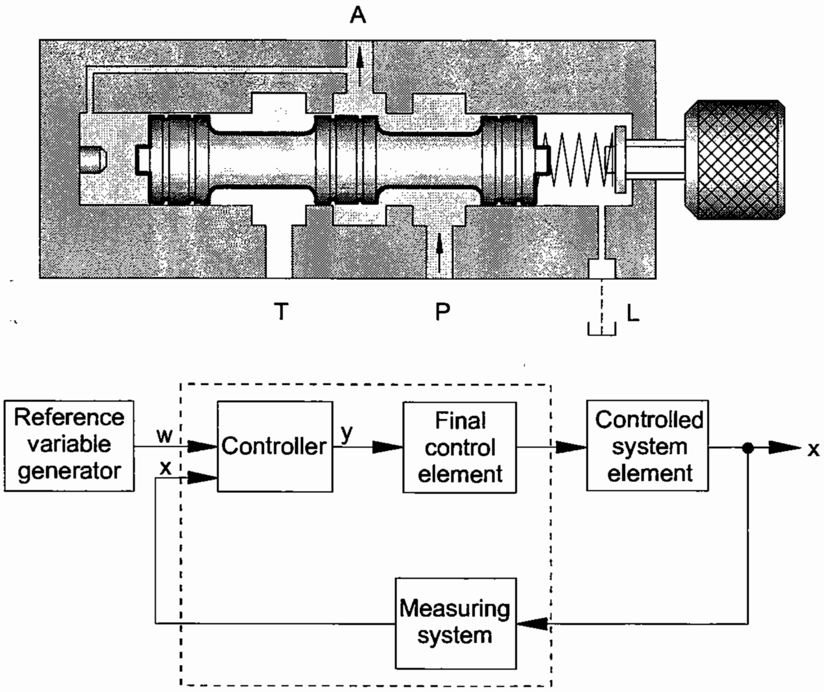


Fig. B4.2: Hydraulic pressure regulator with manual operation

Apart from the closed-loop control element, all the boxes of the signal flow diagram are combined in a single unit.

Single-axis control system with electrical controller

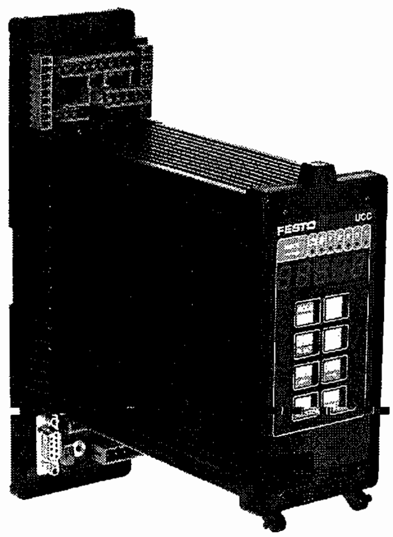
In the case of electrical controllers, two functions of a closed-loop control circuit are frequently combined in a single unit:

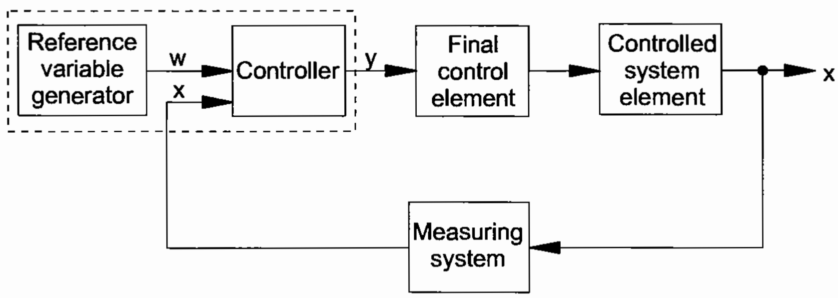
- Controller,
- Generation of reference variable.

In addition, the same unit often assumes other functions which do not form part of the closed-loop control circuit. The single-axis control system shown in Fig. B4.3, for example, has the following tasks:

- Generation of the reference variable for a hydraulic positioning actuator
- Closed-loop control of the hydraulic positioning actuator,
- Monitoring of the hydraulic positioning actuator
- Processing of binary signals (PLC functions).

Fig. B4.3:
Single-axis control system





Numerical control

The control system shown in Fig. B4.3 is numerical control. Numerical controls are used in order to control machines numerically, i.e. by using numbers. Examples of machines with which numerical controls are used include:

- CNC machine tools
- Robots
- Individual axes in production machines
- Handling devices
- Presses
- Plastics-production machines.

A common feature of all these machines is that they incorporate at least one closed-loop control circuit. The controller function is generally provided directly by the numerical control.

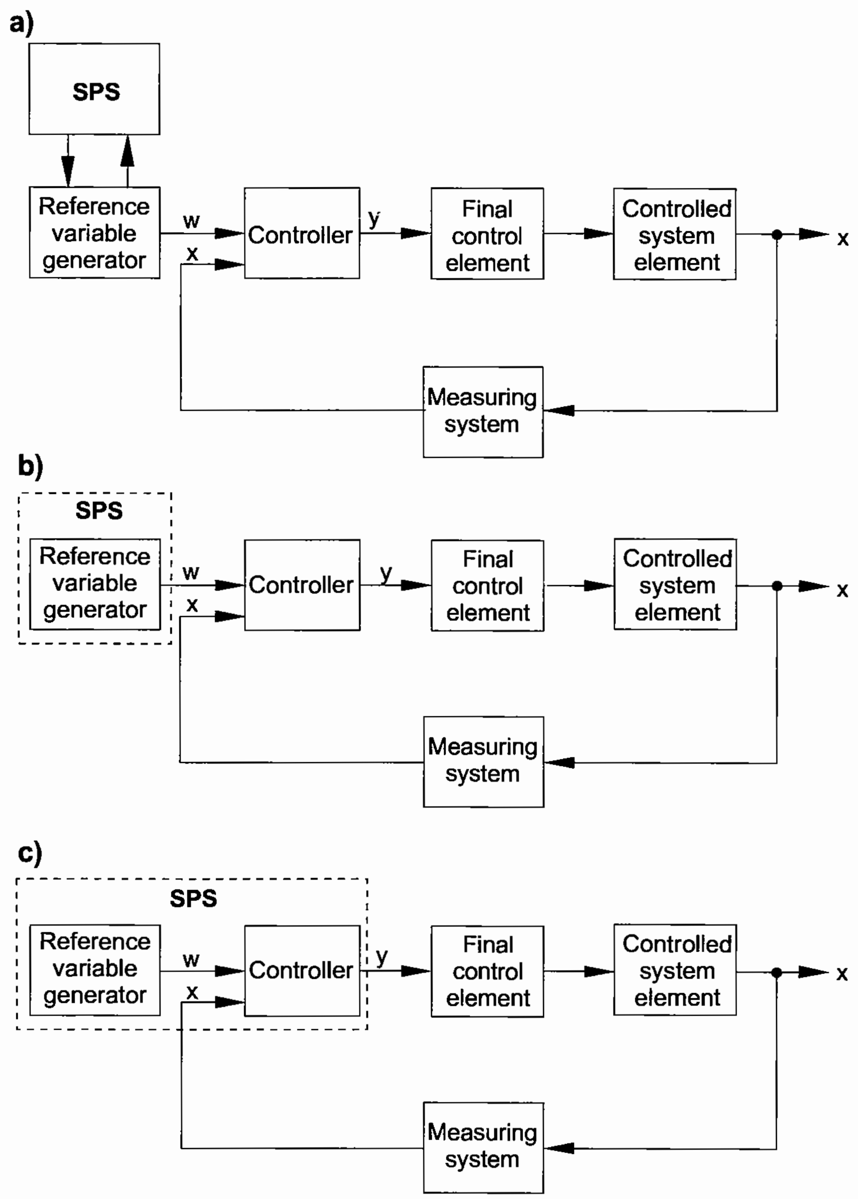
Programmable logic controller

Programmable logic controllers were primarily developed for the processing of binary signals. Controllers of this kind can be used only to monitor closed-loop control circuits (Fig. B4.4a).

Today, programmable logic controllers are also available which can process analogue and digital signals. Controllers of this kind are able to generate the reference variable for a closed-loop control circuit (Fig. B4.4b).

Certain programmable logic controllers provide both a reference-variable generation function and a controller function in a single unit (Fig. B4.4c).

Fig. B4.4:
Implementation of closed-loop control circuits with programmable logic controllers



4.2 Hydraulic/mechanical and electrical controllers

Controllers without auxiliary power supply

Fig. B4.1 shows a hydraulic pressure controller, which operates without an auxiliary power supply. The power required to adjust the opening cross-sections is obtained from the hydraulic oil under pressure.

A further example of a closed-control loop without auxiliary power is the hydraulic linear amplifier. This is used to control a movement of large force and capacity by means of movement of lesser force and capacity. Examples of application are

- Power-assisted steering in automobile design,
- Contour lathes in machine tool construction.

Fig. B4.5 shows a power-assisted steering system. The reference variable is set by the steering wheel. The valve spool is moved, if the reference variable is changed as a result of the steering wheel being turned. This causes the valve to open and oil to flow towards the cylinder. The piston of the hydraulic cylinder adjusts the degree of steering and moves the valve housing via the steering linkage, thus reducing the valve opening. As soon as the valve closes, the piston of the hydraulic cylinders comes to a stop. The controlled variable has followed the changed reference variable.

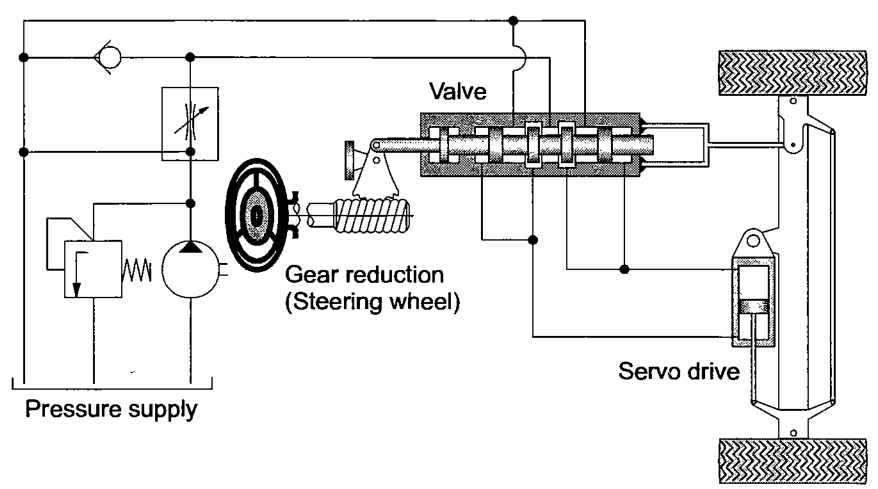
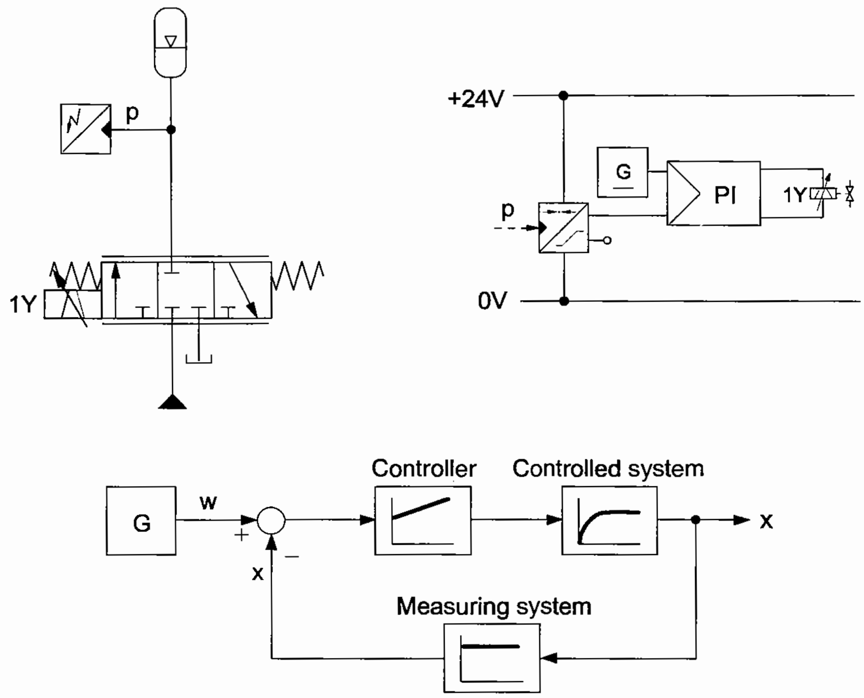


Fig. B4.5:
Power-assisted steering

Controllers with auxiliary power supply

Fig. B4.6 represents a hydraulic closed pressure control loop requiring an additional electrical power supply. The controller is supplied with electrical power and the valve reset electrically.

Fig. B4.6: Pressure control system with auxiliary power supply



Comparison of electrical and hydraulic controllers

The advantages regarding the application of electrical and hydraulic controllers are listed in table B4.2.

Table B4.2: Comparison of electrical and hydraulic controllers

Advantages of electrical controllers	*Advantages of hydraulic controllers*
Easier connection to electrical controls	Simpler design
Inexpensive way to produce complex closed-loop control systems (e.g. with more feedback signals and limiters)	Fewer devices generally required (no need for separate measuring system)
Improved response to errors (output of error messages)	Sturdy (unaffected by dust and humidity)

4.3 Analogue and digital controllers

Analogue and digital controllers differ in their internal configuration.

- Analogue controllers consist of analogue components. They operate internally with analogue signals.
- Digital controllers are produced using digital components. They operate internally with digital signals, i.e. numbers.

Analogue controllers include:

- All hydraulic and mechanical controllers
- Electrical controllers which also operate internally with analogue variables.

Digital controllers today are all of electrical design.

Analogue and digital controllers are compared in Table B4.3.

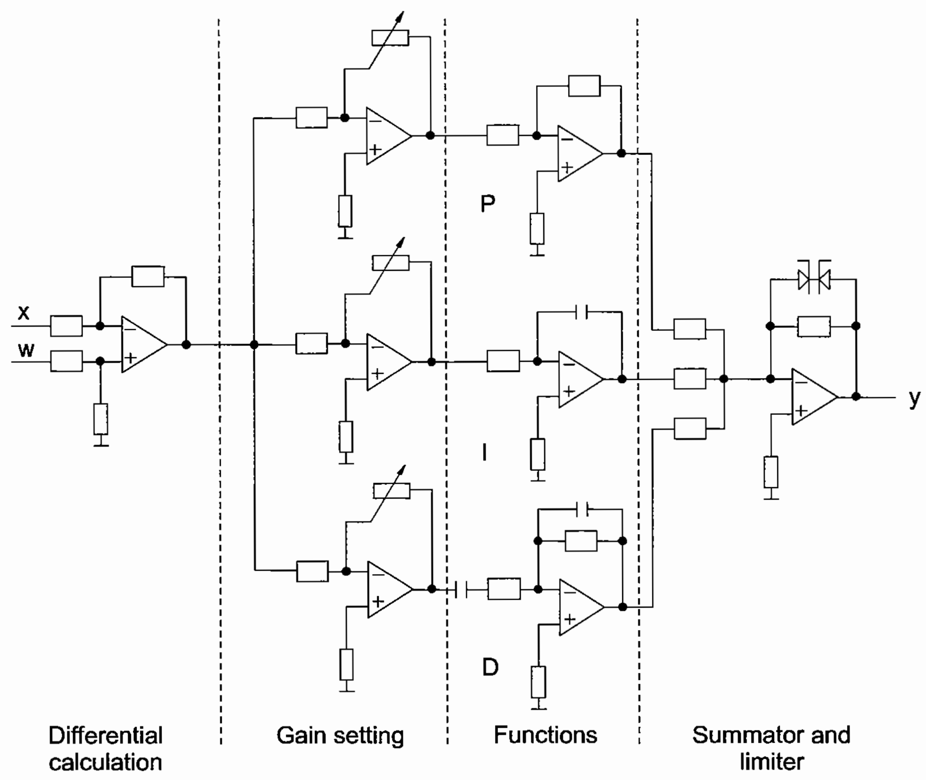
	Analogue controllers		*Digital controllers*
Energy form	*Hydraulic controllers*	*Electrical controllers*	*Electrical controllers*
Example	Power-assisted steering	Electr. PID controller	Controller for one axis of a CNC machine tool

Table B4.3: Analogue and digital controllers

Analogue electrical controller

Fig. B4.7 shows a circuit for an analogue electrical PID controller. The circuit consists of several operational amplifiers, equipped with capacitors and resistors.

Fig. B4.7:
Circuit for an analogue PID controller (simplified)



Digital controller

Fig. B4.8 shows the signal flow for a digital controller. The controlled variable and reference variable are each read in by an analogue/digital converter. Each converter produces a numerical output variable. The microprocessor carries out the following operations:

- Reading-in of the two numbers
- Comparison of the two numbers
- Further processing of intermediate result
- Output of the final result to the input of the digital/analogue converter.

In the digital/analogue converter, the result of the calculations is converted into a voltage. This voltage forms the correcting variable.

The operations of reading in the signal, further processing the signal and outputting the signal are repeated twenty to several thousand times a second, depending on the type of controller.

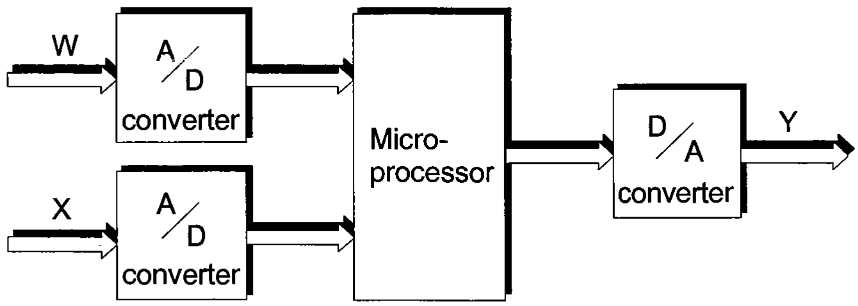


Fig. B4.8: Signal flow in a digital controller

The advantages of analogue and digital controllers are compared in Table B4.4:

Table B4.4: Advantages of analogue and digital controllers

Advantages of analogue controllers	*Advantages of digital controllers*
Less expensive, particularly with highly-dynamic closed-loop control circuits with a simple control structure	Higher accuracy can be achieved,
	Less change in behaviour due to ageing of components
	Easier to implement complex closed-loop control system
	Less affected by electrical interference

4.4 Selection criteria for controllers

The following steps are necessary in order to select a controller for a particular application:

- The requirements relating to the controller should first be defined and listed. Table B4.5 summarises the most important selection criteria.
- Different controllers should then be compared on the basis of the requirement list.
- The most suitable controller should then be selected.

Table B4.5: Selection criteria for controllers

Control quality	*Interfaces*
Necessary controller structure	Reference variable input of controller
Required control dynamics	Monitoring functions
Required control accuracy	Controlled variable input of controller
	Correcting variable
	Controller parametrisation

Operating conditions	*Safety requirements*
Ambient temperature	Response to interference
Dust	Response to power failure
Humidity	Emergency stop behaviour
Electrical interference fields	Output of error messages
Power supply	

Directional control valves

5.1 Valve designs

In hydraulics, differentiation is made between switching valves and dynamically adjustable valves. Both types of valve design are deployed in closed control loops:

- Switching valves in conjunction with dynamic controllers,
- dynamically adjustable valves in conjunction with dynamic controllers.

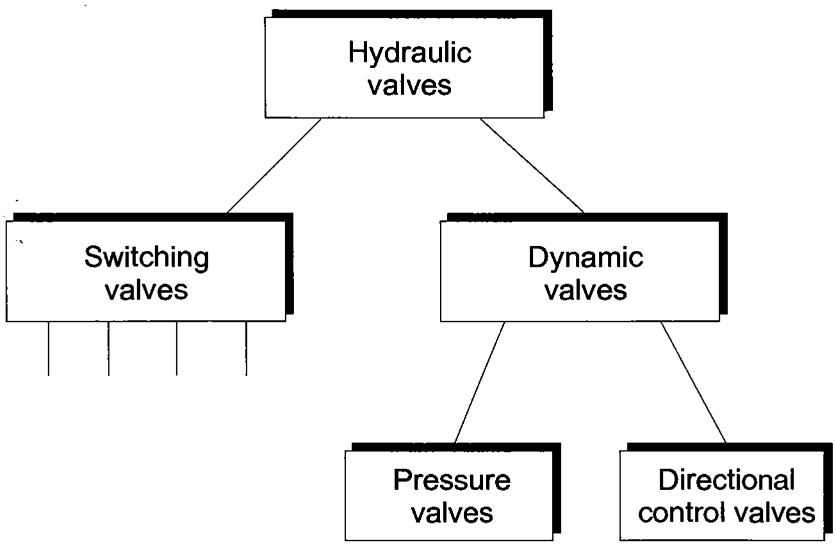


Fig. B5.1: Hydraulic valve designs

The mode of operation of hydraulic switching valves is explained in the Festo Didactic textbooks 501 and 601. The following details concern dynamically adjustable valves.

Pressure and directional control valves

Valves are divided into different groups according to their function, e.g. into pressure, flow and directional control valves. In the case of dynamic valves for hydraulics, differentiation is made between (Fig. B5.1):

- directional control valves, where the correcting variable determines the position of the valve spool,
- pressure valves, where the pressure is set at the consuming-device port in relation to the correcting variable.

5.2 Functions and components of a directional control valve

A directional control valve combines various valve connections in order to provide a correcting signal.

Purpose of a directional control valve in a hydraulic closed control loop

A directional control valve in a hydraulic closed control loop acts as a final control element. Directional control valves are used in various closed control loops:

- in a position control loop (e.g. hydraulic positioning drive),
- in a velocity closed control loop (e.g. hydraulic drive unit, which is to run at different velocities),
- in a rotary speed closed control loop (e.g. rotary cylinder or hydraulic motor),
- in a rotational angle closed control loop (e.g. rotary cylinder or hydraulic motor),
- in a closed flow control loop (e.g. in process engineering systems),
- for the closed-loop control of braking force (in motor vehicles).

Components of a directional control valve

An electrically actuated directional control valve comprises three functions blocks:

- the electrical amplifier to provide the electrical power,
- the electromechanical converter to position the valve spool,
- the mechanical components of the valve to influence the flow rate.

Fig. B5.2 illustrates the signal flow diagram with the three function blocks.

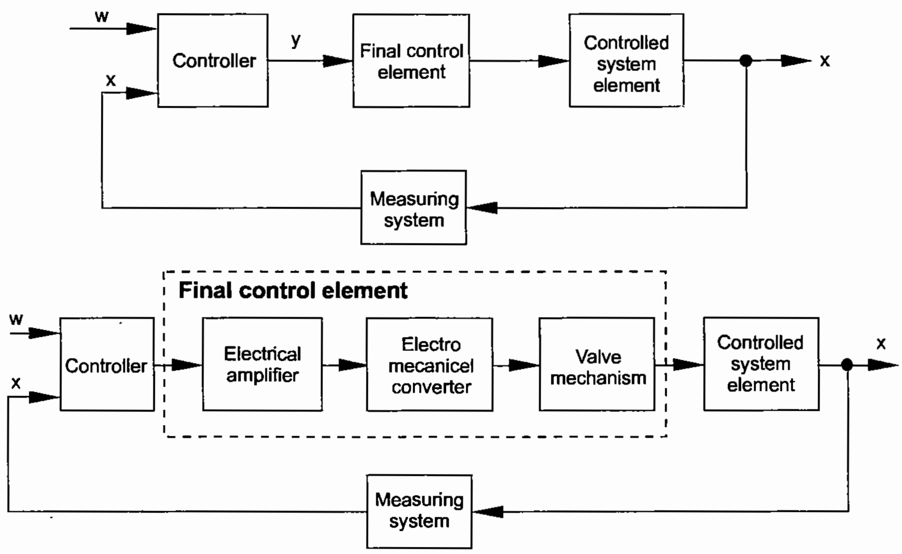
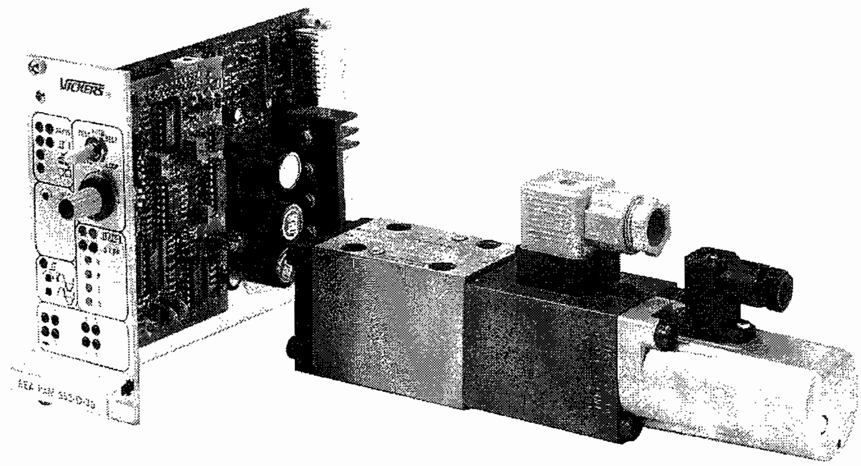


Fig. 5.2:
Dynamic directional control valve as a final control element in the closed control loop

The electromechanical converter and the mechanical components form part of an electrohydraulic directional control valve. There are various possibilities for the configuration of the electrical amplifier, e.g.:

- as a separate plug-in card (fig. B5.3),
- fitted directly in the valve housing (fig. B5.4),
- integrated into the valve plug.



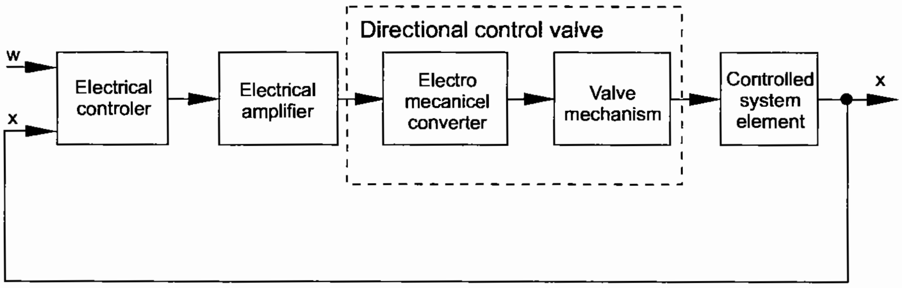
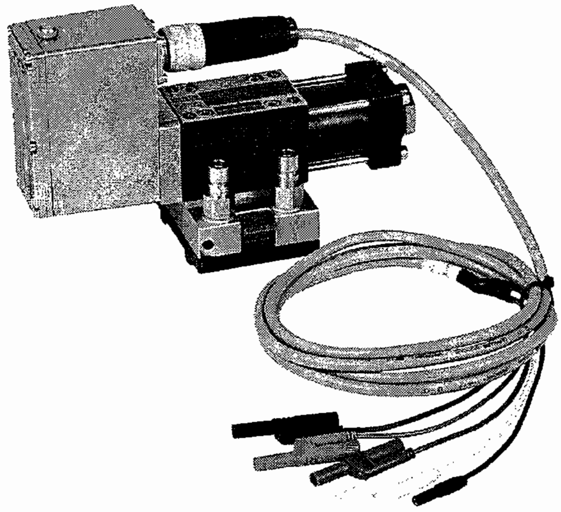


Fig. B5.3:
Directional control valve with separate plug-in card (Vickers)



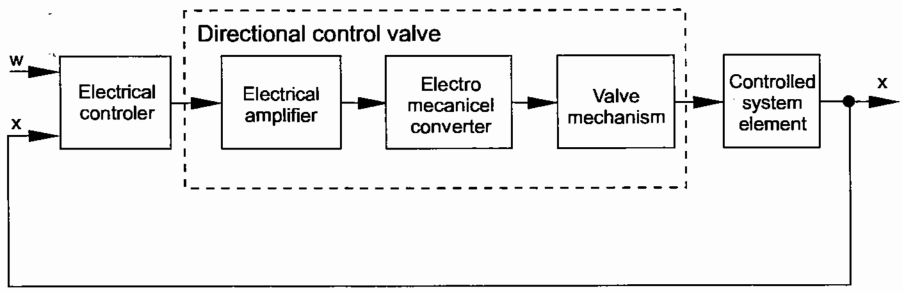


Fig. B5.4:
Directional control valve with integrated electronics (Moog)

5.3 Designations and symbols for dynamic directional control valves

Proportional and servo valves

Electrically actuated, dynamically adjustable valves, depending on design and technical data, are known as proportional or servo valves. The most important criteria used to distinguish between the valve classes are listed in the following table.

Table B5.1: Characteristic features of proportional and servo valves

Characteristics	*Proportional valves*	*Servo valves*
Dynamics	low	high
Robustness	high	low
Accuracy	low	high
Spool actuation	directly controlled	pilot actuated
Power gain	low	high
Price	low	high

A dynamic valve will frequently have the characteristic features of both a proportional and a servo valve. In cases of this kind, it is the manufacturer's decision as to whether to call the valve a proportional valve or a servo valve.

The (Moog) directional control valve

The Moog valve used in the Technology Package has

- some characteristic features of proportional valves, such as simple, robust and inexpensive design,
- some characteristic features of servo valves, such as high dynamics and high accuracy.

This valve can thus not be clearly assigned to one or the other categories. Because of its direct-controlled spool, the valve is described by Festo as a proportional valve.

Symbols for a dynamic directional control valve

The symbol of a dynamic directional control valve differs from that for a switching valve by having two additional features (fig. B5.5):

- one straight line each above and below the directional control valve symbol,
- an inclined arrow pointing upwards through the electro-mechanical converter.

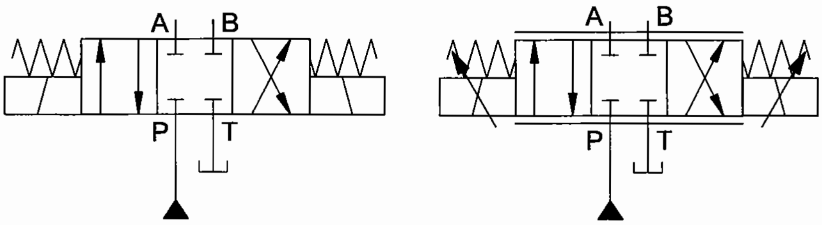


Fig. B5.5: Symbols for switching and dynamic directional control valves

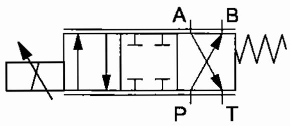
Examples of symbols

Fig. B5.6 shows three examples of symbol for dynamic valves:

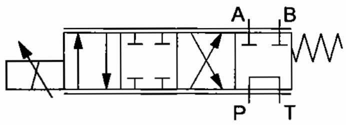
- Fig. B5.6a shows the symbols for a dynamic 4/3-way valve. The valve spool is actuated by a proportional solenoid. The return force is provided by a spring.
  This valve is open in the de-energised state.
- Fig. B5.6b shows the symbol for a dynamic 4/4-way valve. It is actuated in the same way as the valve in fig. B5.11a.
  This valve switches to the tank by-pass position.
- Fig. B5.6c shows the symbol for the Moog dynamic directional control valve. In contrast to the valves shown in fig. B5.6a/fig. B5.6b the valve spool is position controlled and actuated via an electrical linear motor. The linear motor can, in contrast with the proportional solenoid, exert a force on the valve spool in both directions. In the de-energised state, the spool moves to the mid-position, i.e. all control edges are closed.

Fig. B5.6: Symbols for dynamic directional control valves

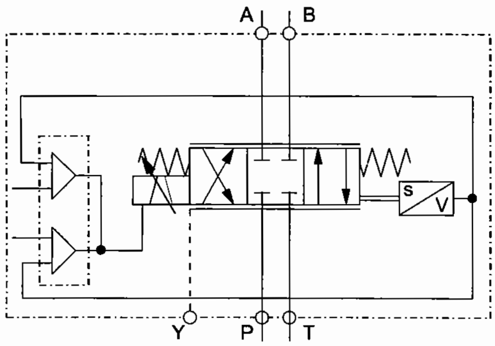
a) dynamic 4/3 - way valve



b) dynamic 4/4 - way valve



c) Moog D 633 dynamic directional control valve



Circuit variants

With many applications, such as closed-loop pressure control systems or a single-acting cylinders, one valve with one consuming-device connection is sufficient. The preferred valve here is a 3/3-way valve.

In the case of a hydraulic positioning drive with double-acting cylinder, a valve with two consuming-device ports is required. The preferred valve in this case is a 4/3-way valve.

5.4 Mode of operation of a dynamic 4/3-way valve

The following illustration shows the signal flow in a dynamic directional control valve.

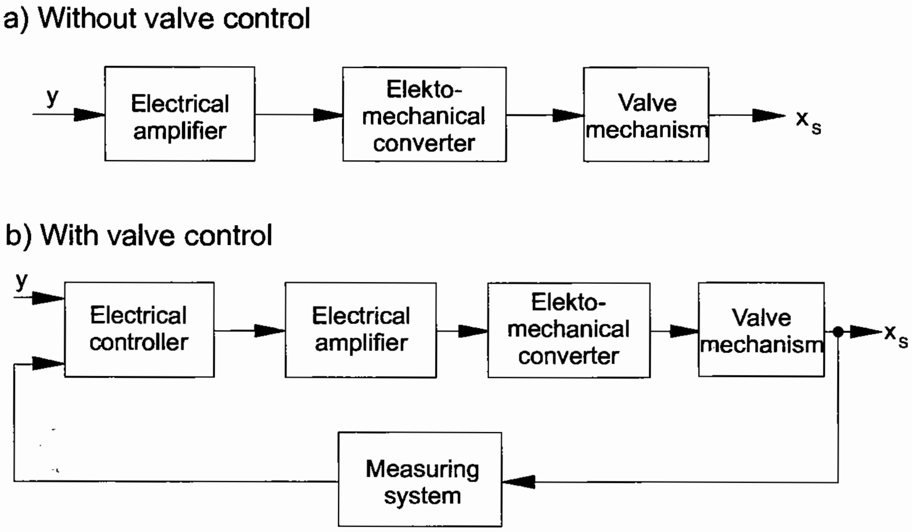


Fig. 5.7: Signal flow in dynamic directional control valves

Distinction is made with the signal flow

- Valves without closed-loop control of the valve spool position,
- Valves with closed-loop control of the valve spool position.

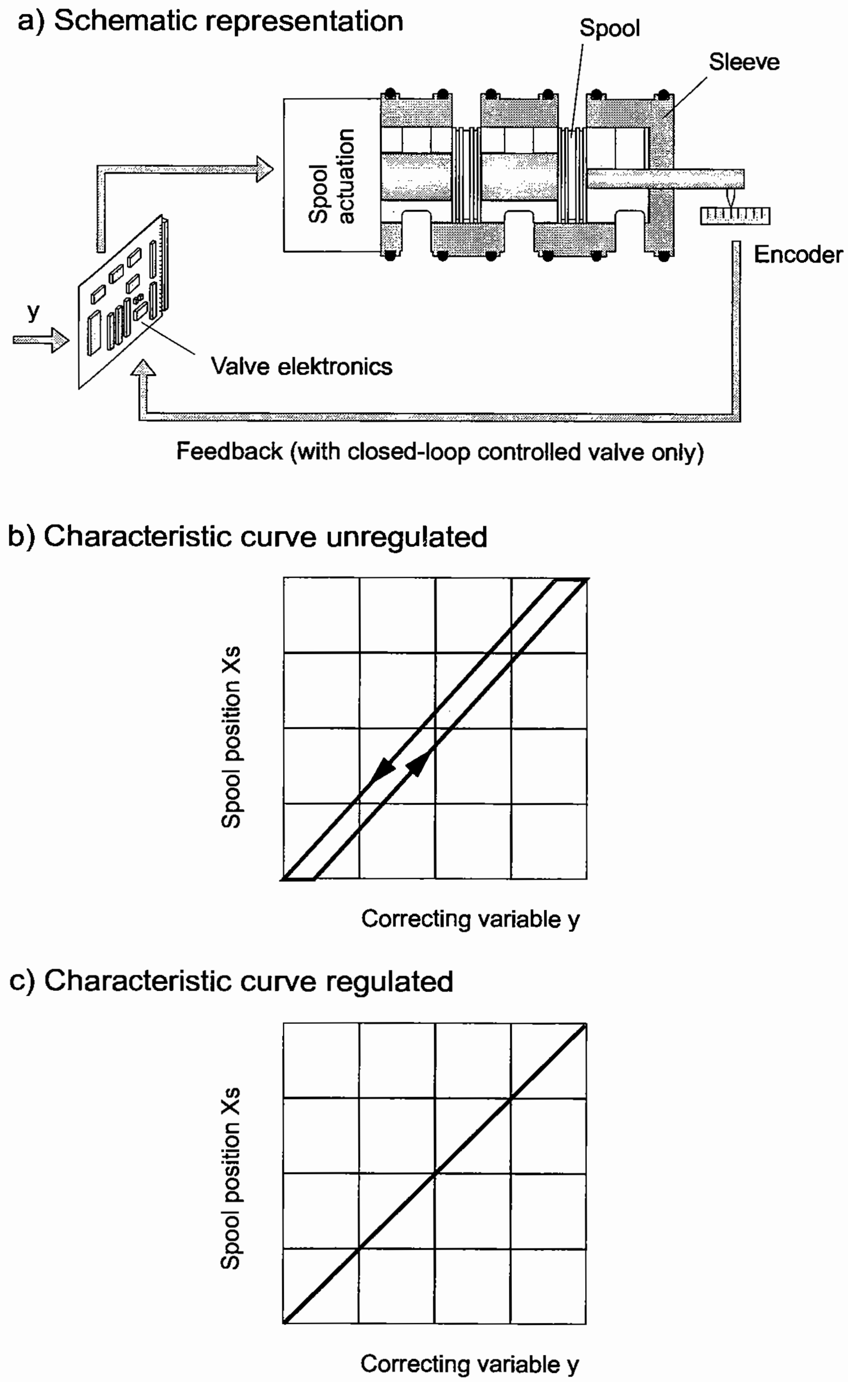
Signal flow in a valve without closed-loop control

In the case of a valve without integrated closed-loop control (fig. B5.7a), the correcting variable y acts directly upon the electrical amplifier, which on its part energises the valve spool actuation. A plunger coil, a torque motor or a proportional solenoid may be used for the valve spool actuation. The greater the flow, the higher the activating force and the more the displacement of the spool.

Signal flow in a valve with closed-loop control

In the case of a valve with integrated position control, the position of the valve spool is constantly measured and the measured signal compared with the correcting variable. The electrical amplifier is not actuated by the valve input signal, but actuated by the controller output signal.

Fig. B5.8:
Valve spool position of a dynamic directional control valve in relation to the correcting variable



Influence of frictional and flow forces

Fig. B5.8 shows a schematic representation of the correlation between the correcting variable y and the valve spool position xs in the form of characteristic curves.

- Without valve spool closed-loop control, two different curves are followed for the increasing correcting variable and the decreasing correcting variable (fig. B5.8b). Moreover, the frictional and flow forces have a very pronounced effect.
- In the case of a valve with closed-loop controlled spool, the positioning direction hardly influences the spool position (fig. B5.8c). The influence of flow and frictional force is compensated to a large extent. Closed-loop controlled valves are always used whenever the highest possible accuracy is crucial.

Signal flow using a controlled valve

Fig. B5.9 shows the signal flow of a pressure control loop with controlled directional control valve. The signal flow diagram exhibits two closed control loops, one nested within the other:

- The outer closed control loop acts as the pressure control.
- The inner closed control loop acts as a closed-loop control for the valve spool.

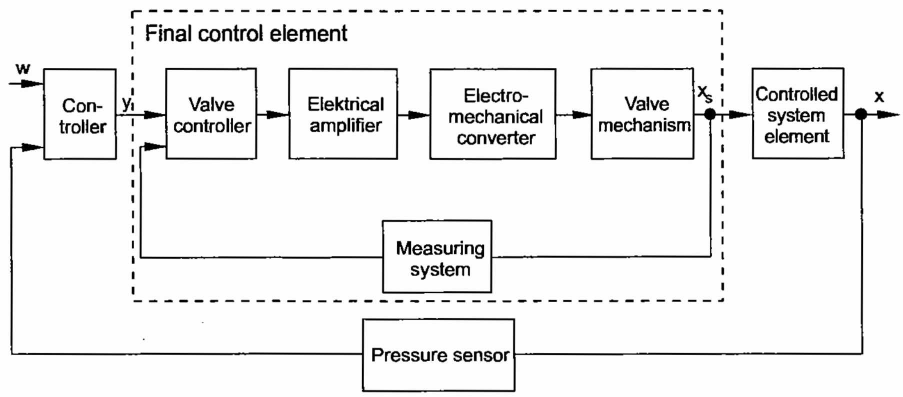
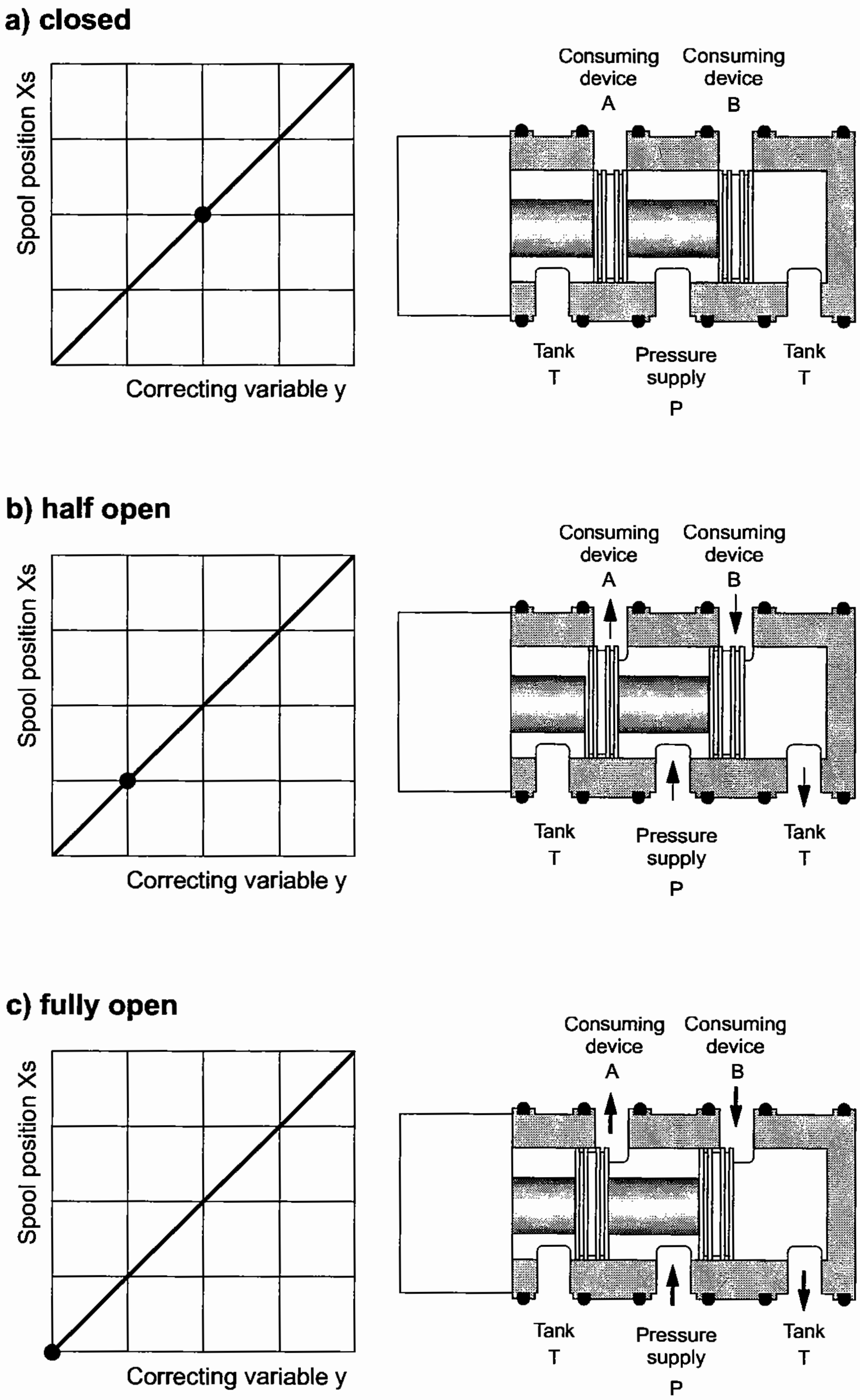


*Fig. B5.9:
Valve with position controlled spool in the higher-order closed control loop*

Valve spool settings

Figs. B5.10 and B5.11 illustrate the valve spool setting for the selected control signals.

Fig. B5.10: Spool settings of a dynamic directional control valve for selected control signals



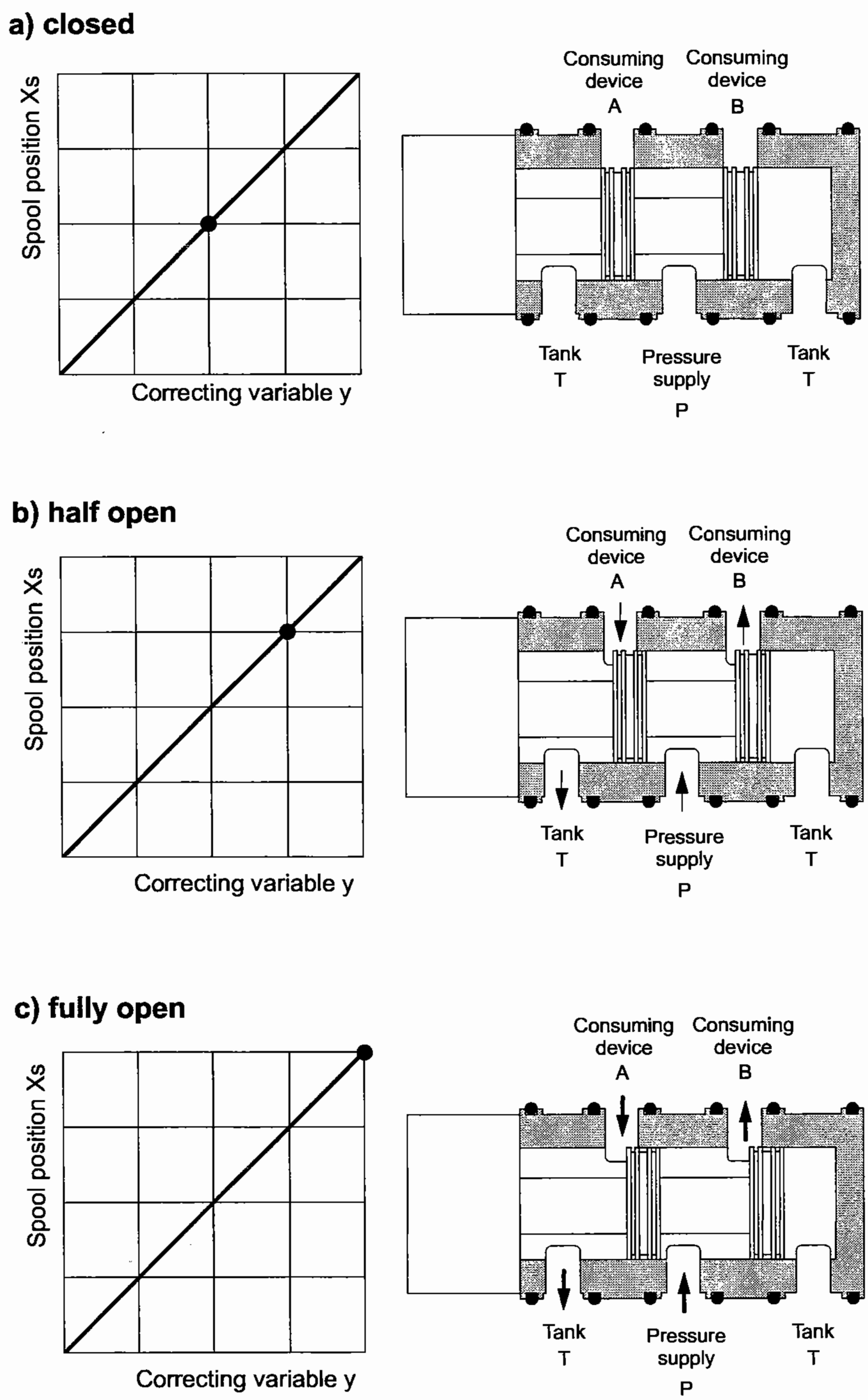


*Fig. B5.11:
Spool positions of a dynamic directional control valve for selected control signals*

- When a control signal is specified, whose value lies in the middle of the correcting range, then the valve spool moves to its mid-position (fig. 5.10a). All control edges are closed in the mid-position of the spool. Consequently, no oil passes through the valve other than a slight leakage.
- If the correcting variable is varied in the negative direction, the valve spool will move to the left. Figs. B5.10b and 5.10c show examples of valve spool positions with half value and full value activating signals. In these two spool positions, oil flows from the pressure supply to the consuming device connection A, while the consuming device connection B is connected to the tank connection of the valve. A comparison between fig. B5.8b and fig. B5.10c shows that the flow cross-sections become larger when the valve spool is displaced further to the left. The greater the flow cross-sections at the control edges, the higher the flow rate through the valve.
- If the correcting variable is adjusted in the positive value direction, the valve spool moves to the right (figs. B5.11b and B5.11c). The consuming device port A is connected to the tank connection and the consuming device port B to the pressure port. The valve can also be reversed. Once again: The further the spool is moved away from its mid-position, the greater the flow through the cross sections and thus the flow rate.

Due to dynamic operation of the valve, the valve spool can assume not only the positions shown in figs. B5.10 and B5.11, but also any number of other desired positions.

Advantages of a dynamic directional control valve in comparison with a switching valve

A dynamic directional control valve can be used to control both large and very small volumetric flow rates, depending on how wide the valve is opened. The valve thus combines the advantages of large-size and small-size valves.

5.5 Steady-state characteristics of dynamic directional control valves

The data sheets for dynamic directional control valves generally give two stationary characteristic curves:

- the flow/signal function,
- the pressure/signal function.

The purpose of these characteristic curves is,

- to compare the characteristic features of several valves,
- to select an appropriate valve for a specific task.

Flow/signal function

The flow/signal function for a directional control valve is determined by means of a circuit as shown in fig. B5.12. The flow given by a specified pressure drop is measured via a control edge (10bar or 70bar). During the measurement, various correcting variables are set across the entire correcting range and the respective flow measured. Following this, the measured values are plotted in a graph and linked to form a characteristic curve.

The following correlations can be read from the characteristic curve (fig. B5.12c):

- The valve is closed in the mid-position. No oil can flow through the valve.
- Starting from the mid-position, the flow rises as the valve opening increases.

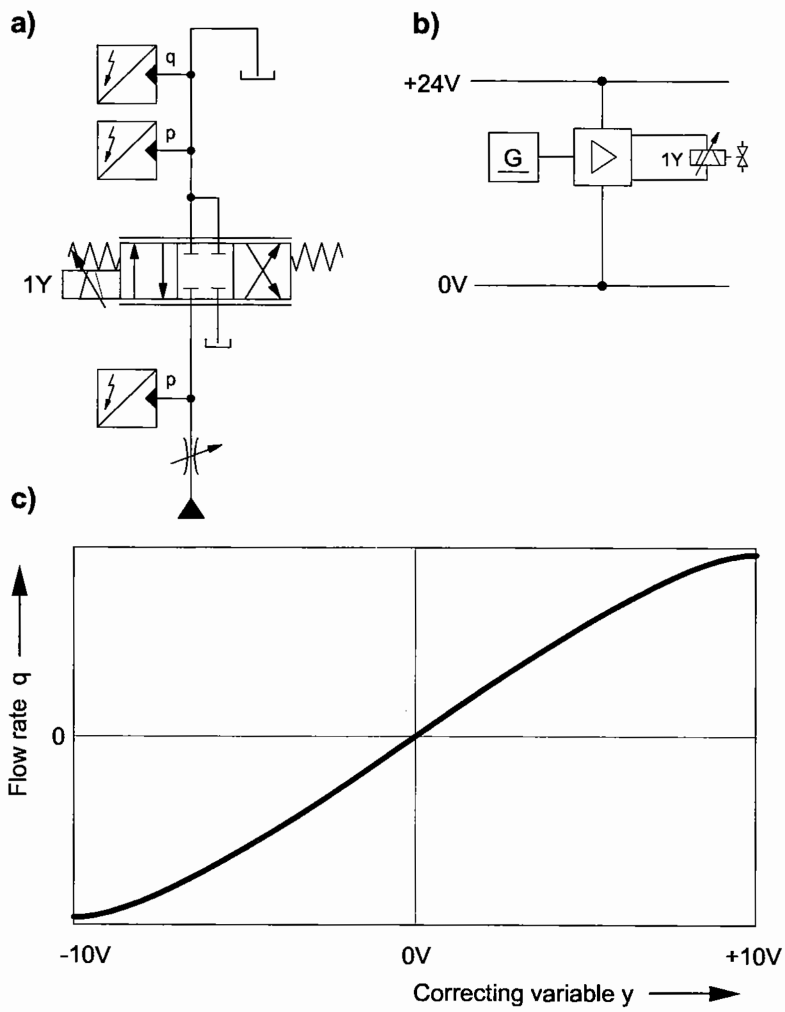


Fig. B5.12:
Flow/signal function

Measuring pressure/signal function

In order to measure the pressure/signal function, a pressure sensor is connected to the consuming-device port of the directional control valve (fig. B5.13a and B5.13b). The correcting variable is varied across the entire correcting range. The resulting pressure is to be plotted. In accordance with the number of pressure sensors, the pressure/signal function consists of

- one characteristic branch in the case of a 3/3-way valve,
- two characteristic branches in the case of a 4/3-way valve.

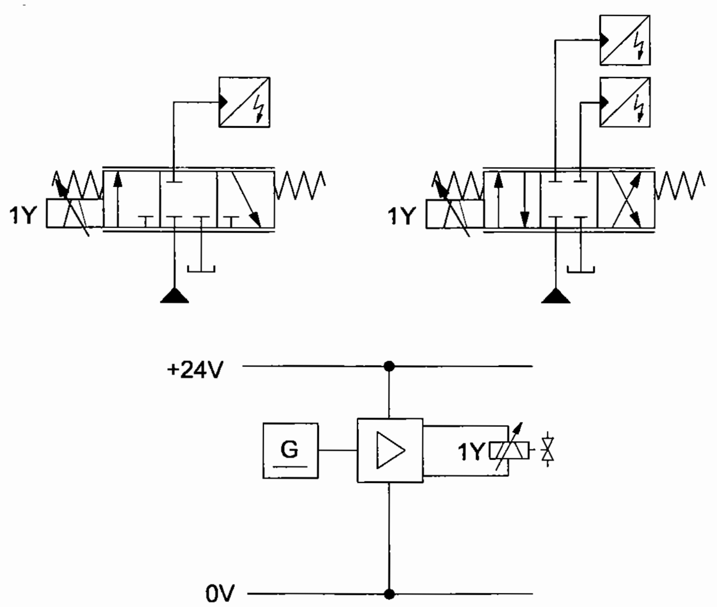


Fig. B5.13: Test assembly for pressure/signal function

Pressure/signal function with negative overlap

Fig. B5.14a shows the valve spool and cartridge for a 4/3-way valve with negative overlap. The valve spool is shown in its mid-position. The negative overlap means that a small gap remains open at all four control edges.

The negative overlaps affects the pressure/signal function.

- If the correcting signal lies in the mid-position range, all the control edges will be open slightly with negative overlap. The control edges act as flow resistors. The pressure at each of the two consuming-device ports lies between the supply pressure and the tank pressure. The precise value of the pressure depends on the overlap conditions at the individual control edges and on the spool position.
- If a strongly negative correcting signal is present, the valve spool will have been displaced from its mid-position to the left (figs. B5.10b and B5.10c). In this case, port A will be connected to the pressure port, where maximum pressure prevails. Port B is connected to the tank connection, where ambient pressure is present.
- If a strongly positive correcting signal is applied, the valve spool will have been displaced from its mid-position to the right (figs. B5.11b and B5.11c). Tank pressure is present at port A, while supply pressure is present at port B.

Pressure/signal functions with zero overlap

With zero overlap, the edges of the spool in its mid-position coincide exactly with the edges of the cartridge (fig. B5.14b). Even if the valve spool is only slightly deflected, one consuming-device outlet will be connected to the pressure port and the other to the tank port. The pressure/signal gradient accordingly exhibits a very steep slope in the mid-position range.

Pressure/signal function with positive overlap

In the case of positive overlap, the spool and the cartridge overlap at the control edges (fig. B5.14c). If the correcting variable is varied only slightly in the mid-position range, all four control edges remain closed. The pressure/signal function therefore exhibits a flattening of both characteristic curves in the vicinity of the mid-position.

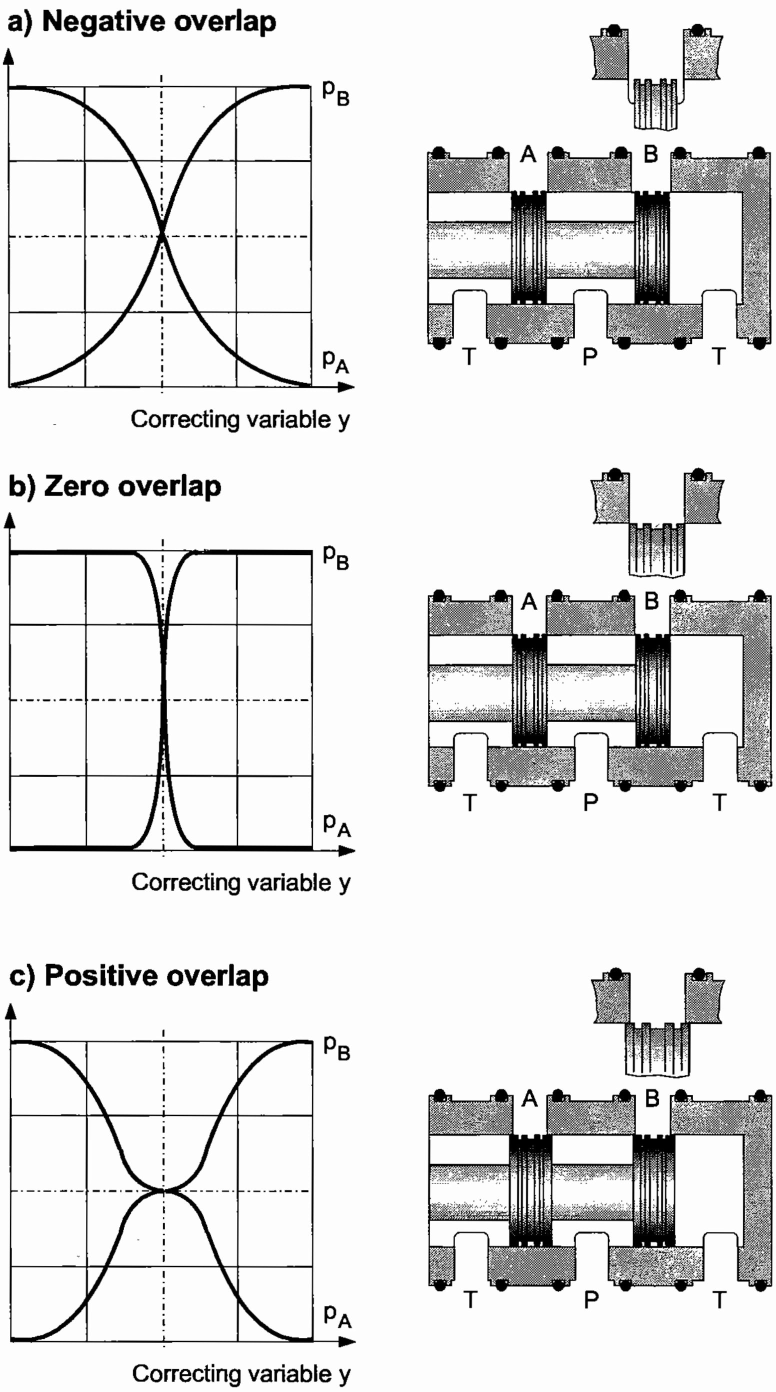


Fig. B5.14:
Overlap and
pressure signal function

Overlap and leakage

With a dynamic directional control valve, the overlap has a strong influence on leakage rate:

- In the case of negative overlap, the leakage with the spool in the mid-position is very high. This means high energy consumption.
- With zero overlap, there is a noticeable leakage with the spool in the mid-position, since a seal is provided only by the metal edges.
- In the case of valves with positive overlap, the leakage rate is very low.

Selection of overlap

In practice, valves with positive and zero overlap are primarily used. The characteristic features of these are summarised in table B5.2.

Table B5.2: Characteristic features of directional control valves with zero and positive overlap

Advantages of zero overlap	*Advantages of positive overlap*
improved accuracy if used in a closed control loop	less expensive valve production
	Reduced leakage

The overlap conditions depend not only on design specifications but also on production tolerances. There may therefore be noticeable differences between valves of the same series.

5.6 Dynamic behaviour of dynamic directional control valves

In many applications, such as hydraulic positioning drives, the valve spool position must not only be as accurate as possible, but also follow the control signal as quickly as possible. Cases of this kind require valves which react especially fast to changes in the correcting variable.

Measuring the dynamic properties of valves

In order to measure the dynamic properties of valves, the valves are actuated with a sine-wave correcting variable (fig. B5.15). The position of the valve spool is measured with a sensor. The correcting variable y and the spool position xs are displayed in graphic form on an oscilloscope. As shown in fig. B5.16, the valve spool oscillates at the same frequency as the activating signal.

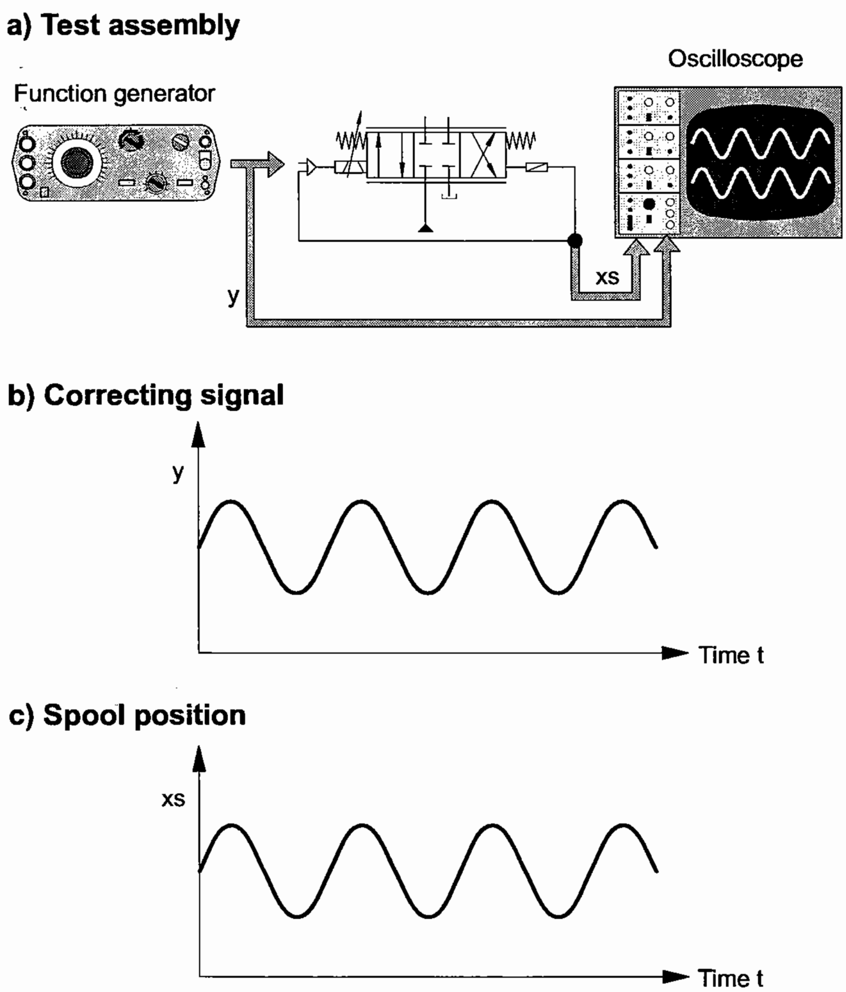


*Fig. B5.15:
Measuring the transfer behaviour with a dynamic directional control valve*

If the activating frequency is increased while leaving the energisation amplitude, the frequency at which the valve spool oscillates will also increase (fig. B5.16).

At a very high energisation frequency, the valve spool can no longer follow the rapid changes of the correcting signal. This can be seen by comparing figs. B5.16d and B5.16e: Amplitude A2 is noticeably smaller than amplitude A1.

Limit frequency

The limit frequency is generally specified as a characteristic value of the dynamic properties of the valve.

In the case of the limit frequency, the amplitude of the valve oscillation has dropped to 70.7% of the amplitude at very low frequencies. In order to measure the limit frequency, the frequency of the input signal is increased until the amplitude of the output signal has fallen to 70.7% (fig. B5.16).

The limit frequency is also referred to in the data sheets as -3dB frequency. The expression "-3dB" (minus three decibels) indicates that the amplitude has fallen to 70.7% of the initial value.

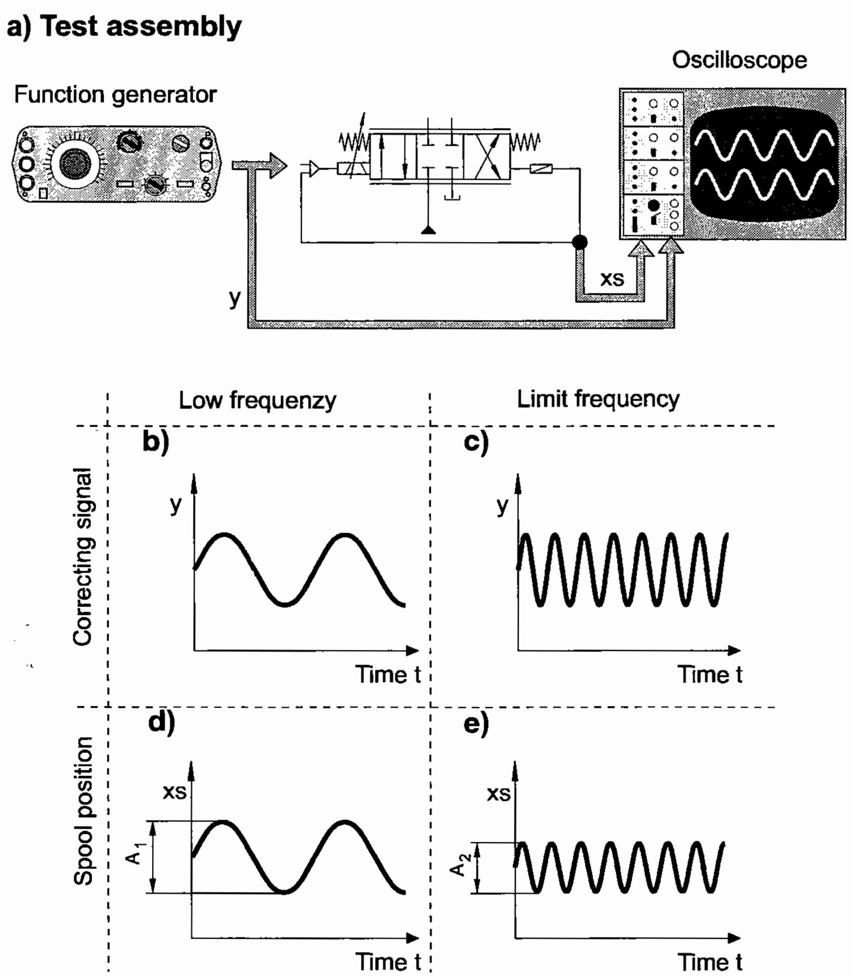


Fig. B5.16: Measuring the limit frequency of a dynamic directional control valve

Limit frequencies of dynamic directional control valves

The limit frequencies of dynamic hydraulic valves lie between approx. 5 and 200Hz plus, depending on valve type.

Frequency response of a valve

The data sheet of a valve will often quote the frequency response instead of the limit frequency.

In order to determine the frequency response, the valve is energised with a sine-wave signal. The amplitude of this signal is specified in percentage of the maximum possible amplitude. An amplitude of 3V corresponds to 30% in the case of a valve with a correcting range between -10V and +10V.

The measurements of the correcting variable and the position of the valve spool are carried out for different frequencies. At high frequencies, the oscillation amplitude becomes smaller and a phase shift occurs. Two diagrams are produced by plotting the amplitude and phase shift across the entire frequency range:

- The amplitude response,
- The phase response.

The two diagrams together describe the frequency response of the valve.

Amplitude response

The ratio of the amplitude at the measuring frequency and the amplitude at very low frequency is specified in dB. An amplitude ratio of -20dB, for example, means that the amplitude has dropped to a tenth of the amplitude at a low frequency. The amplitude response is obtained by plotting the amplitude ratios for all measured values against the measuring frequency.

The limit frequency can also be read from the amplitude response. A limit frequency results from the frequency response in fig. B5.17 of approximately 65Hz at 10% of the maximum possible signal amplitude.

Phase response

The delay of the output signal relative to the input signal is given in degrees. A phase shift of 360 degrees means that the output signal is delayed relative to the input signal by a complete cycle. The phase response is obtained by plotting all phase values against the measuring frequency.

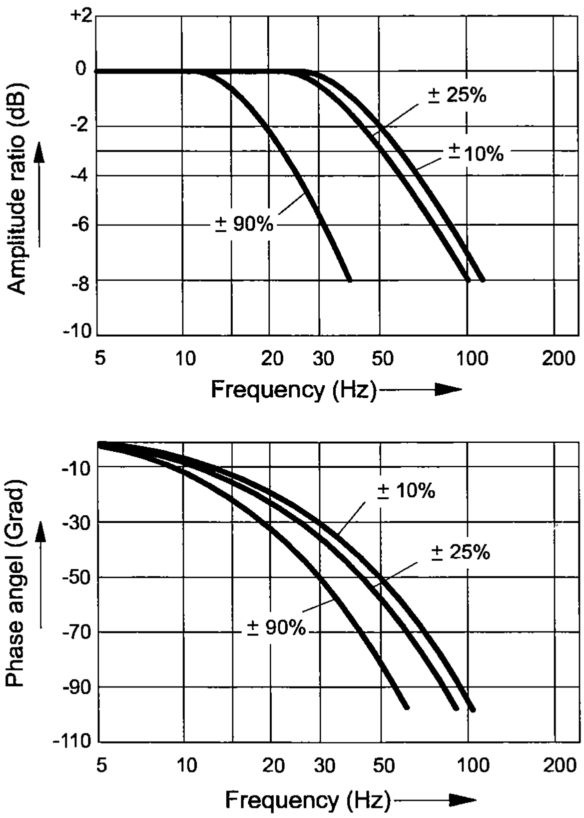


*Fig. B5.17:
Frequency response of a dynamic directional control valve (Moog D633)*

Bode diagram

A Bode diagram is obtained by plotting a graph of the amplitude and phase response.

5.7 Selection criteria for directional control valves

Table B5.3 provides a summary of the selection criteria for directional control valves.

Table B5.3:
Selection criteria for
directional control valves

Operating conditions	*Control quality*
Ambient temperature	Pressure/signal function
Filtration of hydraulic fluid	Flow/signal function
Dust, Humidity	Limit frequency
Power supply	Hysteresis
Installation dimensions	
Interface	*Safety requirements*
Correcting variable	Response to pressure supply failure
Nominal valve size	Response to electrical power failure
Cost	
Mechanical components	
Electrical components	

Pressure regulators

6.1 Functions of a pressure regulator

With a pressure regulator, a handwheel, adjusting screw or electrical signal is used to adjust the pressure at the consuming-device port.

A hydraulic pressure regulator has the following functions in a closed control loop:

- Controller,
- Final control element,
- Measuring system

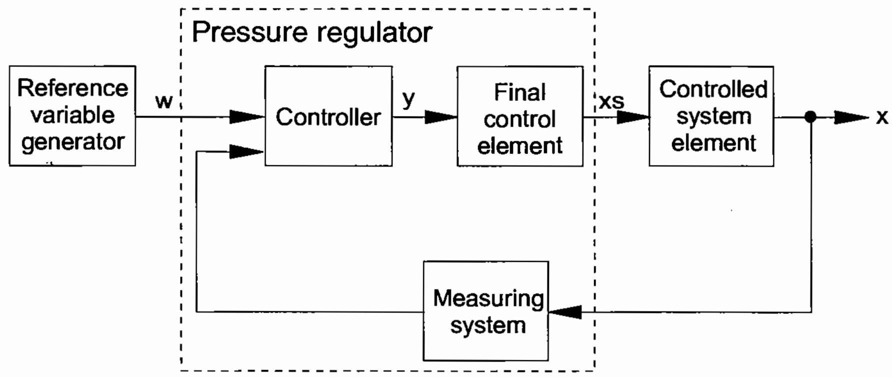


Fig. B6.1: Signal flow diagram of a pressure regulator in a closed control loop

Fig. B6.1 shows the signal flow diagram of a closed control loop with a pressure regulator.

- The reference variable w acts on the pressure regulator as an input signal.
- The controlled variable x, i.e. the pressure at the consuming-device output of the valve, acts as a further signal.
- The controller built into the valve adjusts the valve opening xs as a function of these two signals.

Adjustment of pressure and torque

Pressure regulators are used for various applications, e.g.

- to reduce the pressure for individual consuming devices in a hydraulic system,
- to adjust the force on a press,
- to set the torque on a hydraulic motor.

6.2 Pressure regulator designs

Differentiation is made between manually-operated and electrically actuated pressure regulators.

The advantages of manual and electrical actuation are compared in table 6.1.

Table B6.1: Manual and mechanical input of reference variable

Reference variable input	*manual (by hand)*	*Electrical*
Advantages	Less expensive	Remote control adjustment capability
		Considerably faster adjustment
		Can be adjusted automatically (e.g. by a PLC)

Pressure regulator

The controller can either be of mechanical or electrical design. The advantages of electrical and mechanical pressure regulators are set out in table B6.2.

Table B6.2: Electrical and mechanical pressure control

Controller	*Mechanical*	*Electrical*
Advantages	Fewer components	Smaller steady-state system deviation
	Less expensive	Higher control dynamics

Different valve variants may be used for pressure regulation in a hydraulic circuit:

- a mechanically actuated pressure regulator with integrated mechanical control,
- an electrically actuated pressure regulator with integrated mechanical control,
- an electrically actuated directional control valve in conjunction with a sensor and an electrical controller.

6.3 Mode of operation of a pressure regulator

A distinction is made according to the number of connections and switching positions:

- 2-way pressure regulators,
- 3-way pressure regulators.

3-way pressure regulator

The purpose of the 3-way pressure regulator shown in fig. B6.2, is to maintain constant pressure at output A.

- In fig. B6.2a, the pressure at the consuming-device outlet A is lower than the reference variable set via the adjusting screw. The valve spool is pushed to the right by means of a pre-tensioned spring, thereby allowing oil to flow from pressure port P to the consuming-device outlet A. The pressure at port A rises.
- If the pressure at the consuming-device port is too high, an increased force is applied to the left-hand front surface of the valve spool. The piston moves to the right (fig. B6.2b). Oil flows from port A to the tank connection. The pressure at port A drops.
- If the pressure at the consuming-device port corresponds to the pre-set reference variable, the valve remains closed.

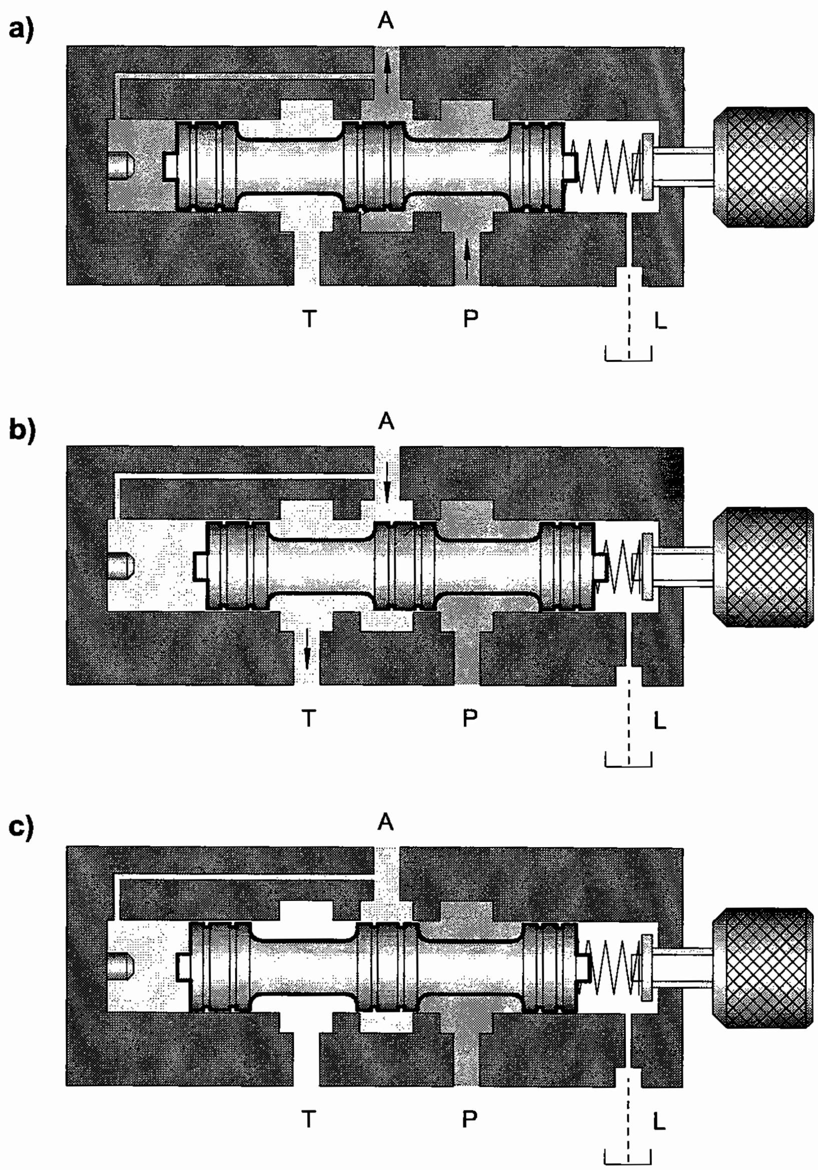
The greater the difference between the reference variable and the controlled variable, the larger the opening of the valve. Hence the control behaviour corresponds to that of a P controller.

Generation of reference variable

The reference variable can be adjusted by means of an adjusting screw.

- If the pre-tension of the spring is increased by an adjustment of the screw, the spring pushes against the valve spool with increased force. A higher pressure is required at output A in order to establish an equilibrium of force. An increase in the spring pre-tension thus produces an increase in the reference variable.
- If the screw is adjusted in the opposite direction. the pre-tension of the spring decreases. The force acting on the valve spool becomes less. Hence a lower pressure is required to establish an equilibrium of force. The reference variable is reduced.

Fig. B6.2: Mechanical pressure regulator (schematic)



Signal flow diagram for pressure control loop

Fig. B6.3 shows the signal flow in a mechanical pressure regulator. The controller and the final control element are incorporated in the pressure regulator.

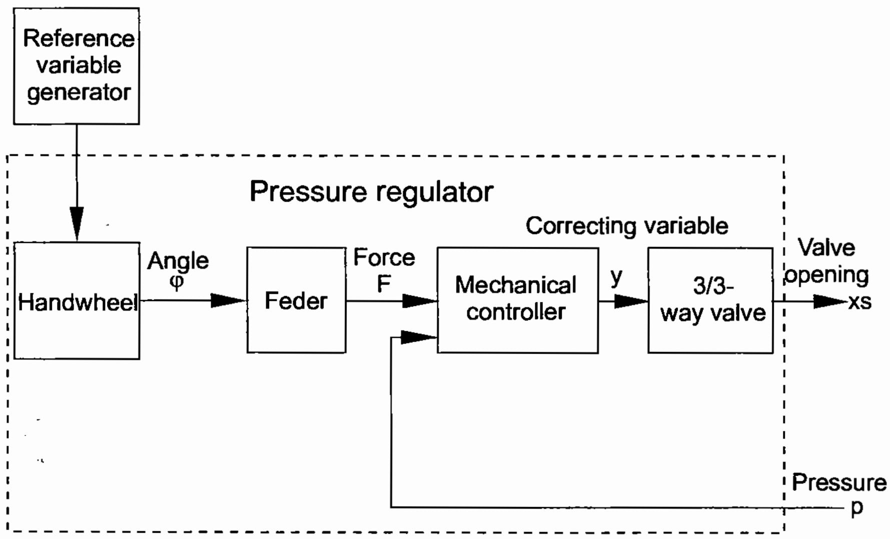


Fig. B6.3: Pressure regulator: Signal flow diagram

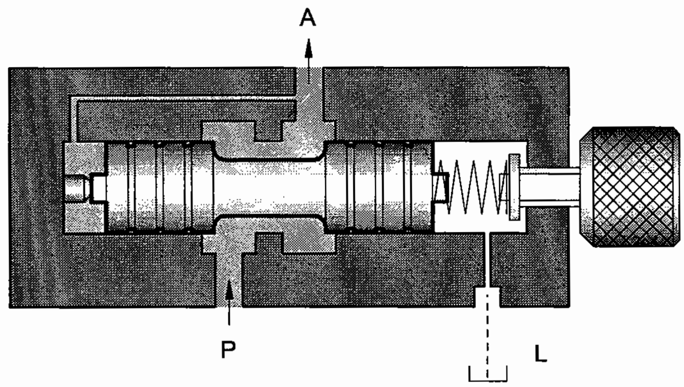
2-way pressure regulator

2-way pressure regulators, as shown in the schematic representation in fig. B6.4, are used in many applications.

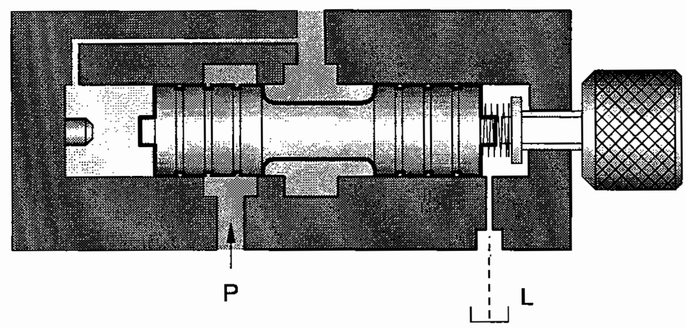
- If the pressure at the consuming-device port A is lower than the reference variable, the valve opens.
- If the pressure at the consuming-device port A is higher than the desired reference variable, the 2-way pressure regulator remains closed. This means that with this valve, it is not possible to reduce excessive pressure at the consuming-device port A.

Fig. 6.4: 2-way pressure regulating valve

a)



b)



Electrically actuated pressure regulator

An electrically actuated pressure regulator is obtained, if the adjusting screw and spring shown in fig. B6.2 are replaced by a proportional solenoid. The comparison between reference variable and controlled variable is still made via the equilibrium of force at the valve spool, i.e. mechanically.

6.4 Pressure regulation with a directional control valve

A pressure regulator combines several functions of a closed control loop in a single component. However, pressure control loops may also be of discrete design, i.e. they may consist of several components (fig. B6.5a):

- a directional control valve as a final control element,
- a pressure sensor as a measuring system,
- an electrical controller.

Signal flow diagram for closed control loop

Fig. B6.5b shows a signal flow diagram for the closed control loop. The directional control valve merely assumes the function of the final control element. Pressure sensor and pressure regulator are not incorporated in the valve.

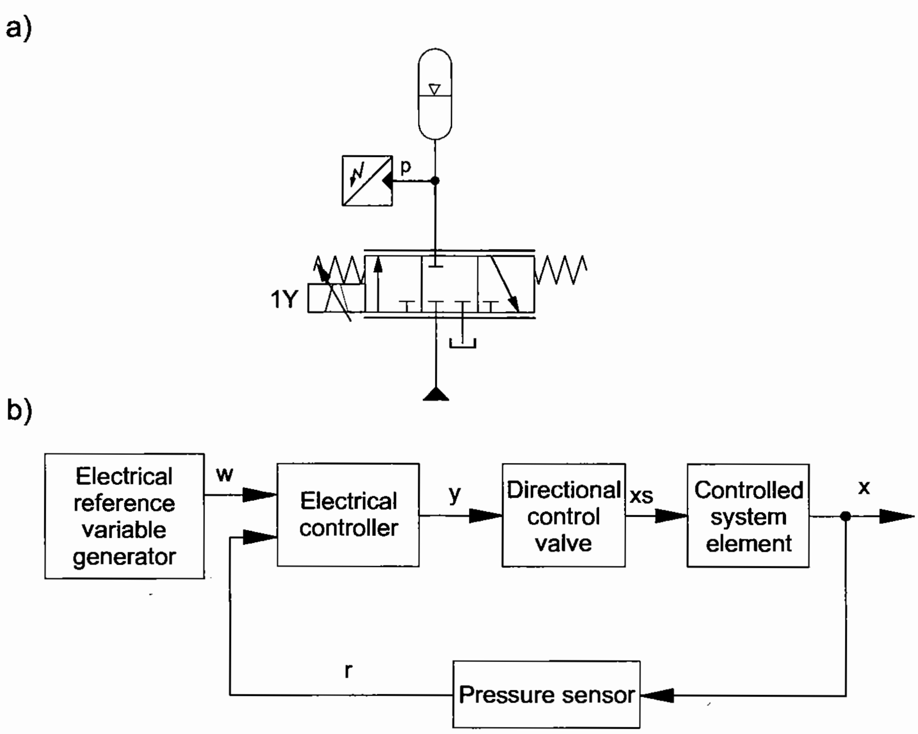


Fig. 6.5:
Hydraulic circuit and signal flow diagram of a pressure control loop with a directional control valve

6.5 Selection criteria for pressure regulators

Table B6.3 summarises the selection criteria for pressure regulators.

Table B6.3: Selection criteria for pressure regulators

Operating conditions	*Control quality*
Ambient temperature	Characteristic curves
Filtration of pressure medium	Hysteresis
Protection	Controller structure
Power supply	
Installation dimensions	
Interface	*Safety requirements*
Correcting variable	Response to oil pressure failure
Nominal valve size	Response to electrical power failure
Cost	
Mechanical components	
Electrical components	

Measuring systems

7.1 Purpose of a measuring system

A measuring system converts an input signal into a different, easier to evaluate output signal. This process is known as measurement.

The input signal may, for instance, be a pressure or a velocity, while the output signal may be an electrical current or an electrical voltage.

Function of a measuring system in a closed control loop

The function of a measuring system is to,

- acquire the controlled variable,
- generate the feedback variable.

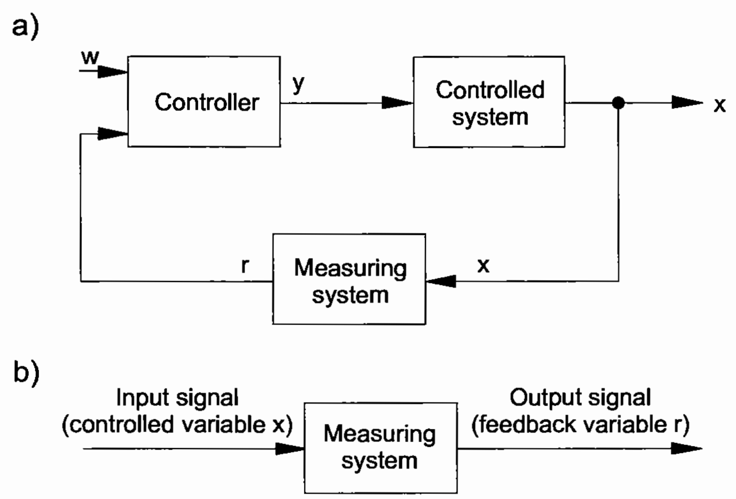


Fig. B7.1: Function of measuring system in closed control loop

A measuring system is required in all cases where an electrical controller is used in a closed control loop. In the case of a closed control loop with hydraulic or mechanical feedback, the controlled variable frequently acts directly on the controller. This means that the function of the measuring system is integrated into the controller and a separate measuring system is not required.

7.2 Measuring system designs and -interfaces

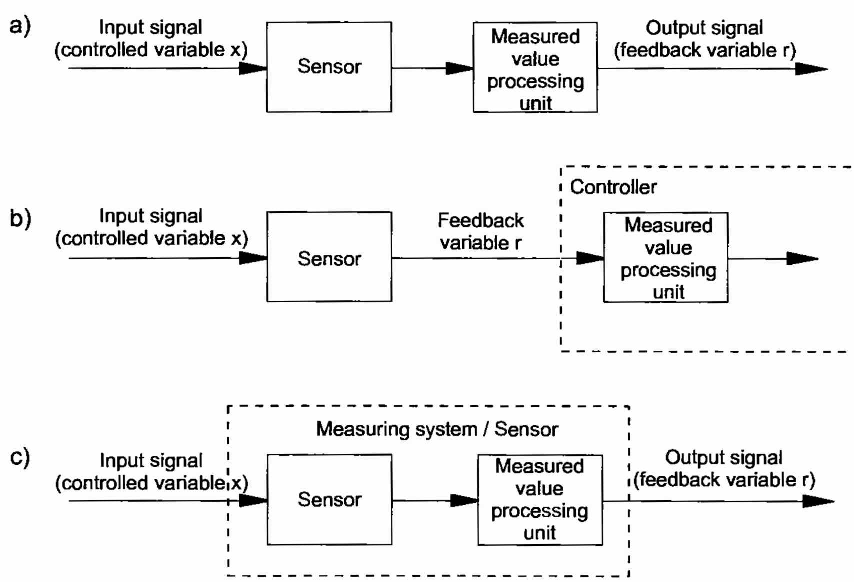
A measuring system consists of two components:

- the linear encoder or sensor,
- the measured value processing.

Fig. B7.2 provides an overview of measuring system designs.

- Fig. B7.2a shows the signal flow diagram, in which the sensor and the measured-value processing unit are two separate devices. Inductive position sensors are constructed according to this principle. In addition to the actual sensor, an amplifier is also required for signal evaluation.
- Fig. B7.2b shows the signal flow diagram for a measuring system, in which the measured-value processing unit is incorporated into the controller. This configuration is frequently used for digital displacement measuring systems. In this case, the measured-value processing unit is located directly on the controller card of a numerical control system.
- The sensor and measured-value processing unit are often combined into one device (fig. B7.2c). This design is widely used due to the ease with which it can be handled. Examples include pressure sensors and gap sensors.

Fig. B7.2: Structure and interface of a measuring system



Input signal

In a closed control loop, the reference variable forms the input signal of the measuring system. Table B7.1 provides an overview of the measuring systems used in closed loop hydraulics.

The title given to a measuring system is generally determined by the type of input signal.

Input signal	*Designation*	*Sample application*
Pressure	Pressure sensor	Plastics processing machine
Force	Force sensor	Force-controlled hydraulic press
Rotational speed	Tachometer	Machine tools
Angle of rotation	Shaft encoder	Hydraulic rotary actuator
Position	Position encoder	Hydraulic positioning drive

Table B7.1: Measuring systems for closed-loop hydraulics

Output signal

On the basis of the output signal a distinction can be made between

- binary measuring systems,
- analogue measuring systems,
- digital measuring systems.

Table B7.3 shows which combinations of controller and measuring system are used in practice.

- Binary measuring systems are used only in combination with dynamic controllers. A pressure sensor can, for instance, be used in combination with a two-step-action controller. A circuit of this kind can be used to keep pressure constant.
- An analogue measuring system can be combined with any variant of controller: dynamic or non-dynamic, digital or analogue. Tachometers and pressure sensors are examples of analogue measuring systems.
- Digital measuring systems can be combined with digital controllers. Examples are digital linear and rotary displacement encoders in CNC machine tools.

Table B7.3: Combinations of controllers and measuring systems

Controller type	*Controller design*	*Output signal of measuring system*
non-dynamic	analogue	analogue binary
non-dynamic	digital	analogue binary digital
dynamic	analogue	analogue
dynamic	digital	analogue digital

Interface

The output signal of the sensor acts upon the controller in the form of an input signal. Sensors with analogue output signals are used for electrical analogue controllers. Assuming that the signal conditioning is carried out within the measuring system, the output signal will be

- an electrical current
- or an electrical voltage.

The output signal of the measuring system and the input signal of the controller must be matched. This means:

- identical physical variable,
- identical signal range.

Table B7.4 provides an overview of the usual types of interfaces between sensor and controller.

Table B7.4: Output signals of analogue measuring systems

Interface	*Range of measuring system output signal*
Current interface	4 – 20mA
Voltage interface	0 – 10V 0 – 5V

If the distance between sensor and controller is large, this may result in a voltage drop in the cable. This will falsify the signal in the case of a voltage interface. A current interface should therefore be selected in the case of long signal lines.

7.3 Selection criteria for measuring systems

Table B7.5 summarises the most important selection criteria for measuring systems.

Input signal	*Cost*
Variable to be measured	Cost of sensor
Measuring range	Cost of measured value processing
Output signal	*Environmental conditions*
Interface to controller	Installation space
Dynamics	Connection dimensions
Linearity	Temperature range
Drift	Electrical fields
Noise	Degree of protection (dust/humidity)
Production tolerances	Supply voltage
Service life	

Table B7.5: Selection criteria for measuring systems

Assembly, commissioning and fault-finding

8.1 Closed control loop in automation

In automation technology, a closed control loop will generally form part of a larger installation.

Example of application

Fig. B8.1 shows part of an installation for the production of fruit juice. This installation includes a closed-loop-controlled hydraulic positioning actuator used for palletising.

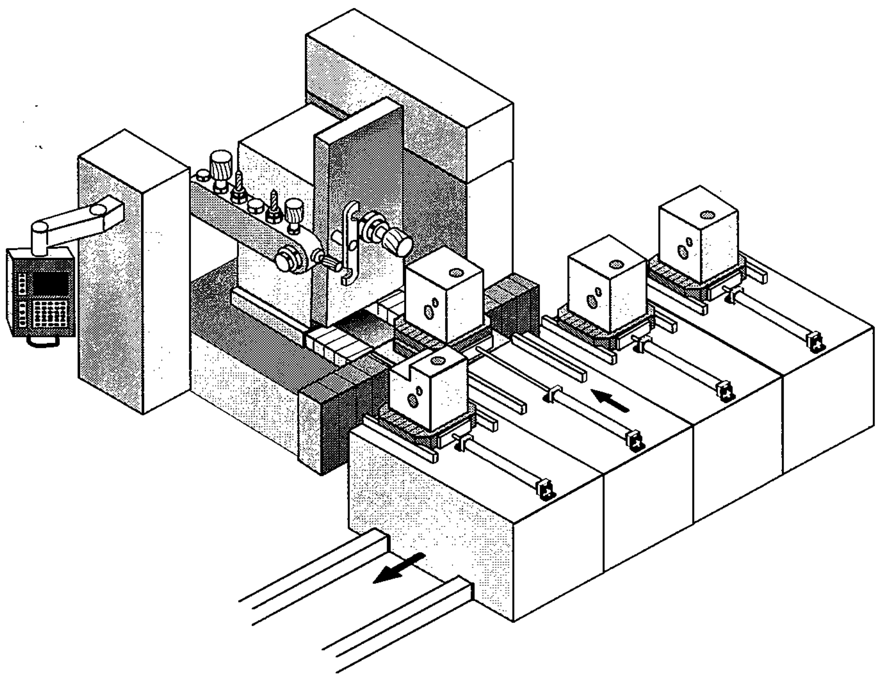


Fig. B8.1: Closed control loop as part of a production installation

Procedure for the implementation of an installation

The implementation of an installation of this kind involves a large project. It is therefore advisable to proceed as follows (Fig. B8.2):

- The project is divided into several sub-projects. The implementation of a closed-loop control circuit forms one such sub-project. The interfaces between the sub-projects must be defined precisely.
- The individual sub-projects are executed in parallel.
- Finally, all the sub-projects are re-combined to form an overall project.

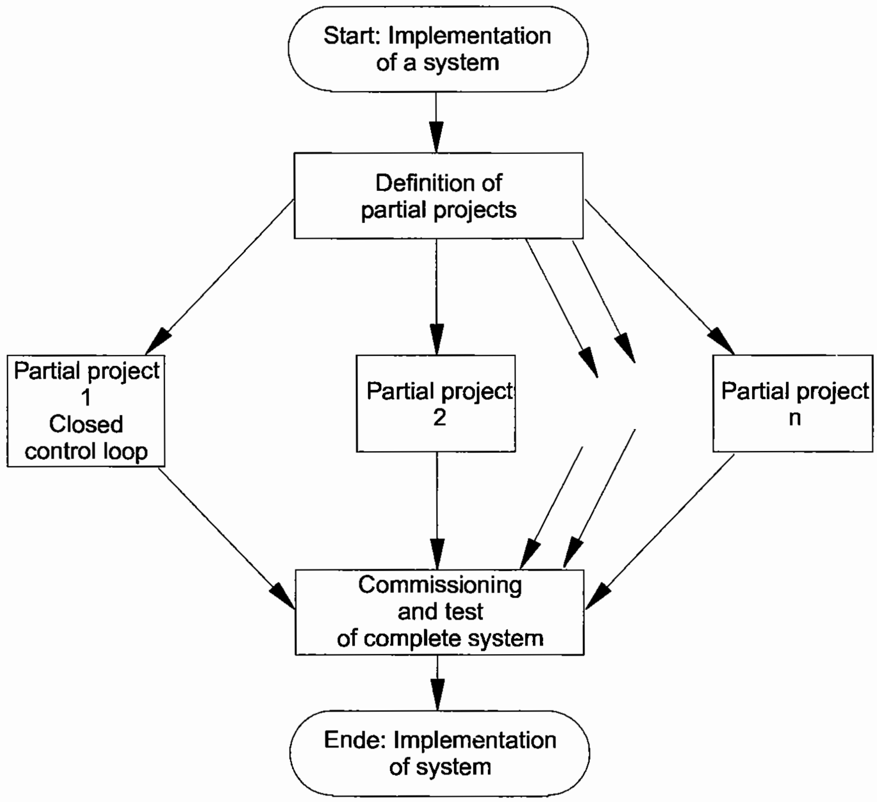


Fig. B8.2: Implementation of an automated installation

Procedure for the implementation of a closed control loop

Fig. B8.3 shows the flow diagram for the implementation of a closed control loop.

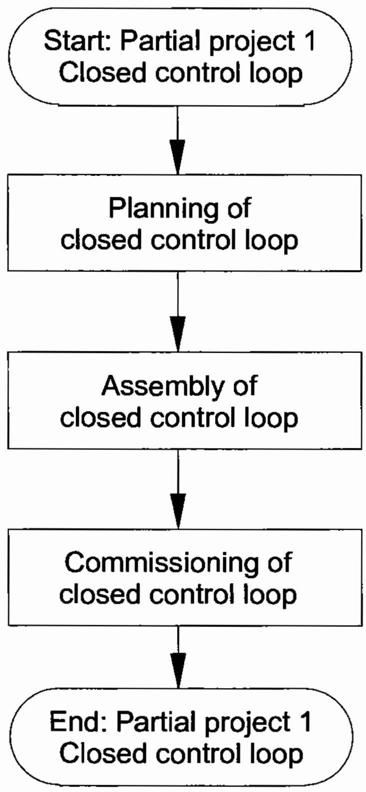
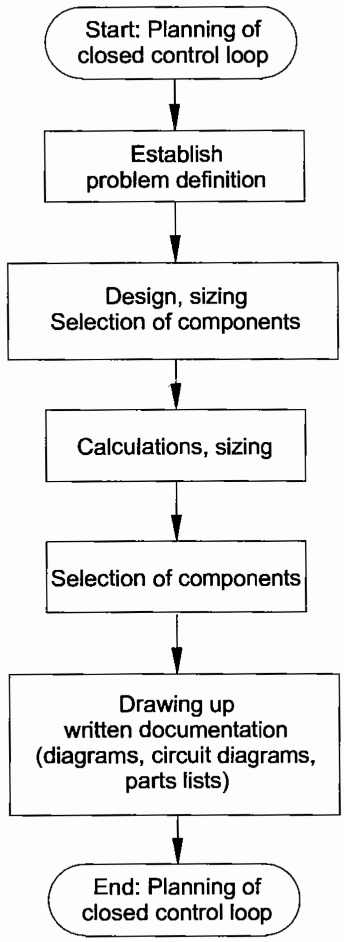


Fig. B8.3:
Working steps for the implementation of a closed control loop

8.2 Planning

The flow diagram in Fig. B8.4 shows the various steps in the planning of a closed-loop control circuit.

Fig. B8.4: Planning of a closed-loop control circuit



Defining the problem

The first step is to specify the requirements placed on the closed-loop control circuit. The following outlining of problem definition are some of the questions that must be answered:

- What is the purpose of the closed-loop control circuit?
- How is the closed-loop control circuit to be incorporated into the control system of the installation?
- What are the operating conditions involved?
- What performance data must the closed-loop control circuit provide?
- What requirements regarding environmental protection must be met?
- What safety requirements must be met?

Drafting, selection and sizing

The flow diagram in Fig. B8.5 shows the procedure for the

- drafting of the closed-loop control circuit
- selection of the components for the closed-loop control circuit
- sizing the closed-loop control circuit.

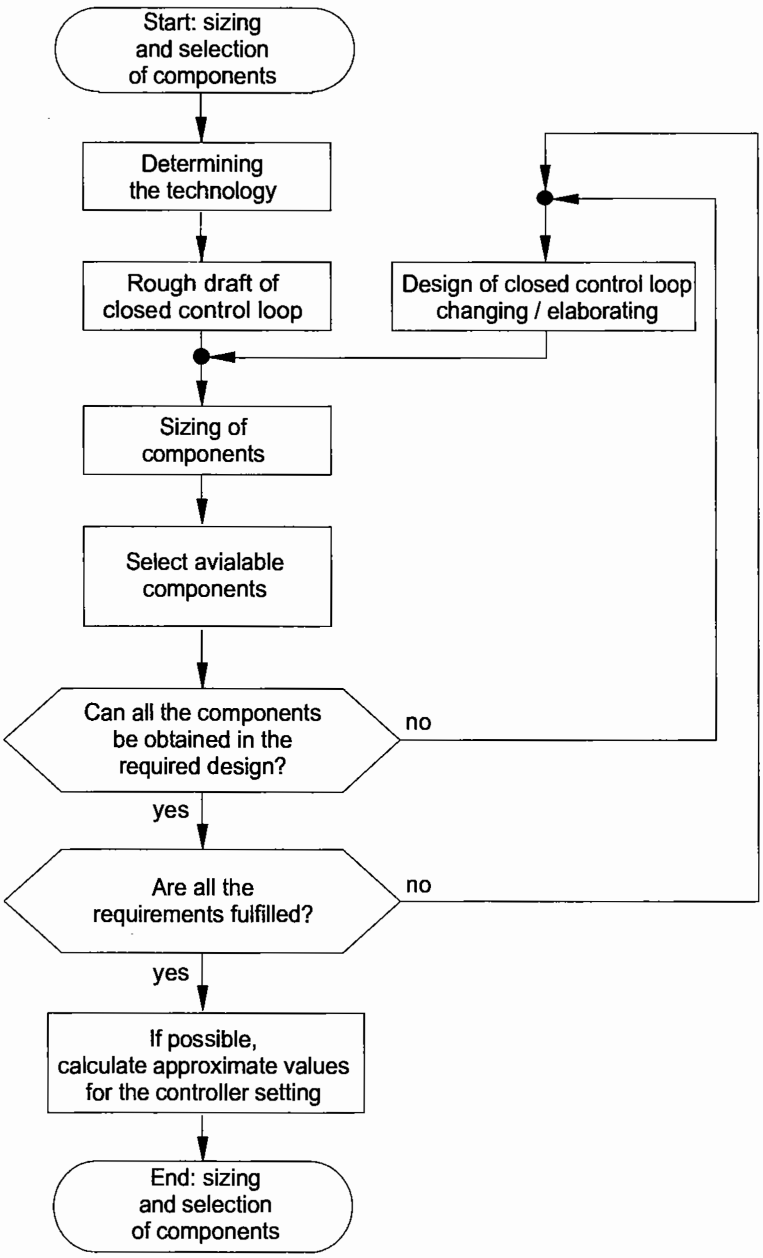


Fig. B8.5:
Flow diagram for drafting, selection and sizing

It is first necessary to select the technology to be used for the closed-loop control circuit.

- A closed-loop pressure control circuit can, for example, be produced using a pressure regulator or a directional control valve.
- An analogue or digital controller can be used.

A first draft of the closed-loop control circuit is then produced.

The next step is sizing the components of the closed-loop control circuit. This means:

- The characteristic data for the actuators are determined (cylinder diameters, strokes, swept volume). If reservoirs are required, the required volumes for these are determined.
- The data for the actuators and/or reservoirs are then used to calculate the flow rates and nominal valve sizes.
- Finally, the power supply requirement can be calculated.

Suitable components are then selected from manufacturers' catalogues.

It must be determined

- whether components of the desired size and type are available
- whether the closed-loop control circuit will fulfil all the required specifications.

If the requirements are not fulfilled, the draft of the closed-loop control circuit must be modified and optimised. The component sizes of the closed-loop control circuit must then be re-calculated.

When all the steps have been successfully completed, a specification will have been created of all the major components of the closed-loop control circuit. If the characteristic data of the components are known with sufficient accuracy, a rough calculation of the controller settings can be made.

Production of written documentation

As the final step in planning, diagrams and parts lists should be produced in accordance with the relevant standards.

- First, a detailed signal flow diagram should be drawn.
- The electrical and hydraulic circuit diagrams should then be produced. Standard symbols should be used for these. The guidelines for the drafting of circuit diagrams should also be followed.
- The circuit diagrams should then be checked and corrected if necessary.
- The relevant numbers and technical data of the devices should be added to the circuit diagrams. The setting values should be entered into the circuit diagrams if known. It is also advisable to mark measuring points in the circuit diagrams.
- Finally, the parts list should be produced.

8.3 Assembly

Proceed systematically during the practical assembly of a closed-loop control circuit in order to keep errors to a minimum. Observe the following:

- The relevant safety regulations
- The basic rules for the fitting and connection of the individual components.

It is advisable to work through the individual steps in a defined order (Fig. B8.6).

Configuration of devices and tubing

Signals are propagated in air at the speed of sound. This is approx. 330 m/s at 20°C. A piece of tubing 1m long will produce a signal delay of approx. 3ms.

Long signal transit times will considerably impair control quality. The following rules must therefore be observed when fitting tubing:

- Fit valves and actuators as close to each other as possible
- Install tubing by the most direct route possible.

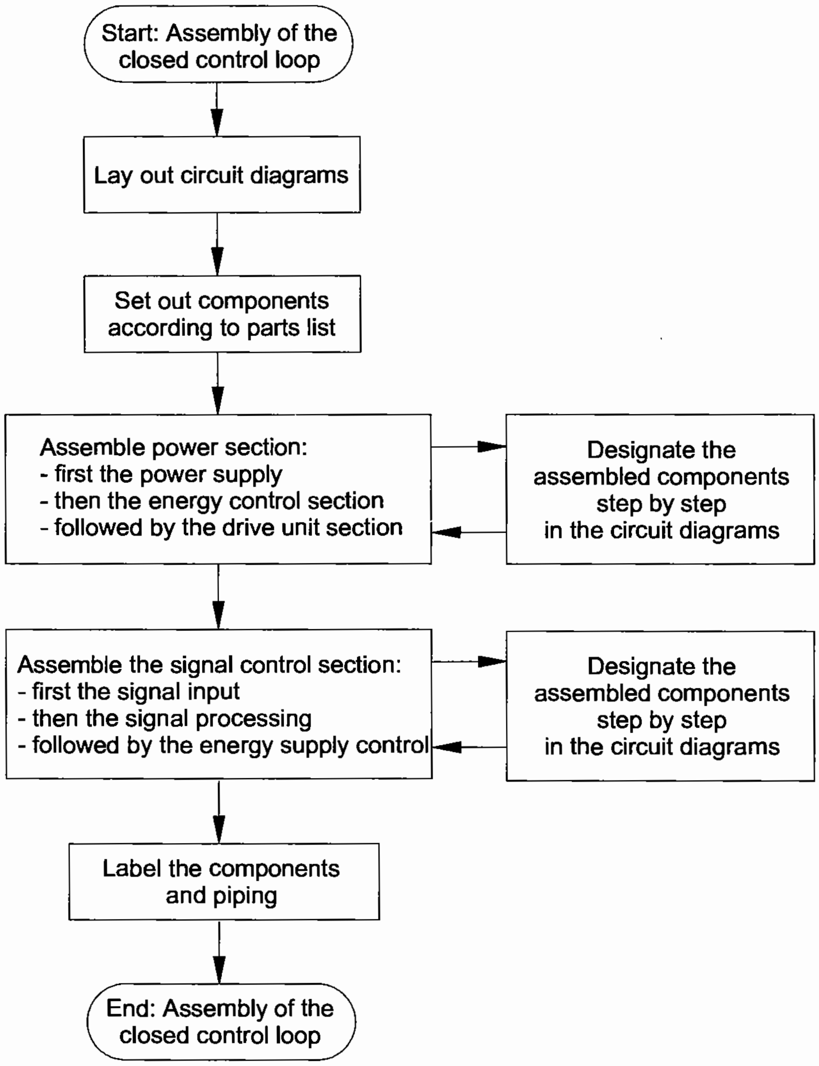


Fig. B8.6: Procedure for assembly of a closed-loop control circuit

Cables

Signals transmitted through electrical cables can be subject to distortion or interference. In the case of analogue signals, this will lead to a falsification of the signal and thus to a reduction in control quality. In order to achieve the maximum possible control quality, follow the instructions below when laying cables:

- Lay cables by the most direct route possible
- Avoid coiling the cables in order to prevent electrical stray effects
- Do not exceed the maximum permissible cable lengths
- Use screened cables if necessary.

8.4 Commissioning

Commissioning a closed control loop

The following flow diagram shows the procedure for the commissioning of a closed control loop.

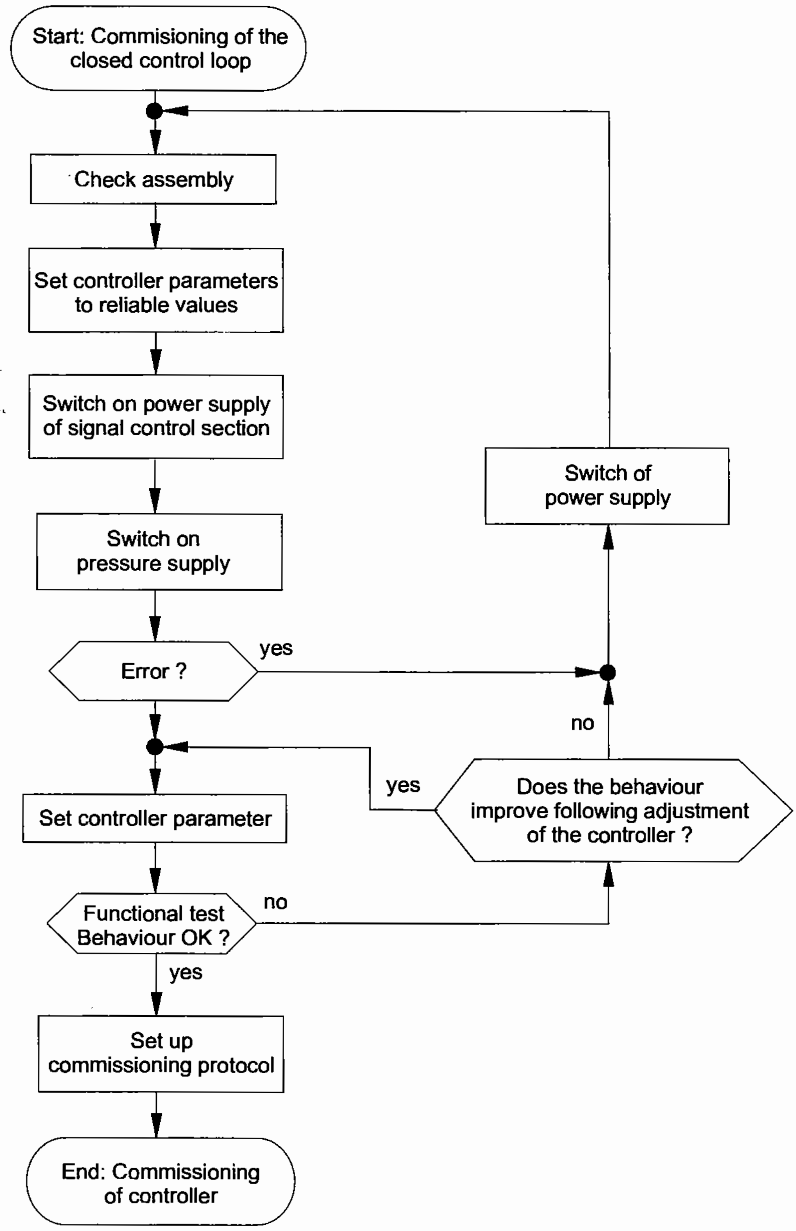


Fig. B8.6:
Flow diagram for commissioning of a closed control loop

The individual steps are explained in greater detail below.

Checking assembly

First, the complete assembly should be checked against the circuit diagrams. Do not under any circumstances switch on power supplies at this stage.

Initial controller settings

The controller coefficients must be set so that the closed-loop control circuit does not oscillate under any circumstances. It is generally advantageous to set the controller coefficients to very low values or even zero.

Switching on the power supplies

Be sure to observe the following sequence when switching on the power supplies:

- First switch on the power supply for the signal control section. In the case of an electrical controller, this will be the power supply for the controller.
- The hydraulic power pack i.e. power supply for the power section, must not be switched on before the power supply for the signal control section. If an undesirable operating state occurs (for example, oscillation of the closed-loop control circuit), immediately switch off the power supply again and locate the fault!

Controller settings

The controller parameters must be optimised until the closed-loop control circuit exhibits the desired behaviour.

Functional tests

Functional tests must cover all the operating conditions which may occur later during practical operation:

- Behaviour in response to interference variables (e.g. variation in supply pressure, load caused by an actuator),
- Behaviour with different reference variables
- Behaviour following an emergency stop.

Commissioning report

At the end of commissioning, an acceptance report should be produced. This should describe the results of the commissioning operation:

- The result of the functional tests
- The settings for pressure, controller parameters, etc.
- Special features of the closed-loop control circuit if applicable.

Commissioning of an installation with closed control loops

If a closed control loop forms part of a large installation, commissioning should be carried out in steps. The procedure is shown in the flow diagram in Fig. B8.7.

- The closed control loop should first be commissioned separately. It should be tested for correct operation under all the operating conditions which can be expected.
- Only after this should the closed control loop be connected step by step to the other parts of the installation and tested for correct operation.

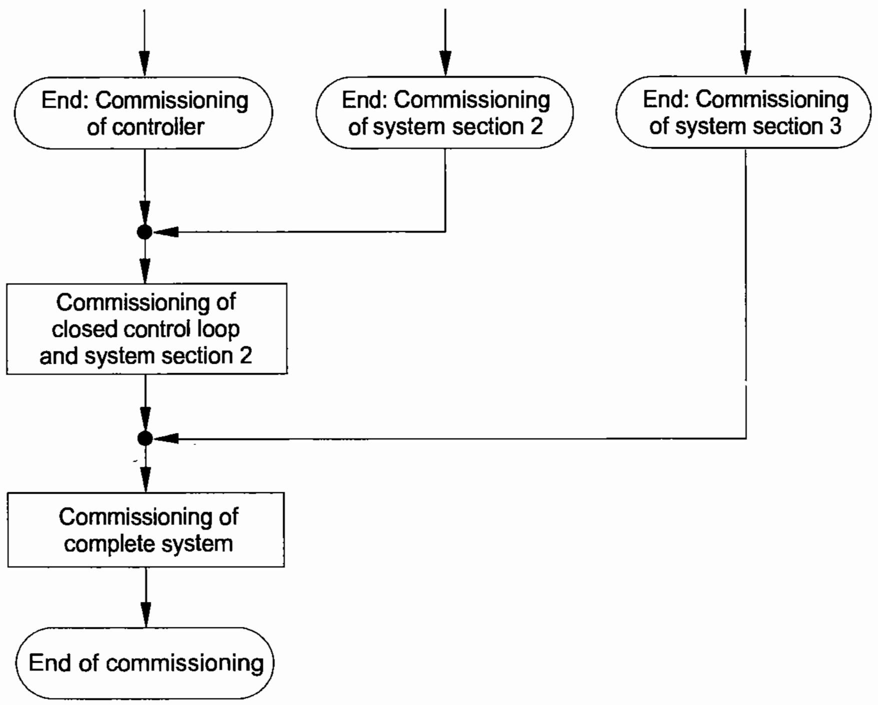


Fig. B8.7: Flow diagram for commissioning of an installation

8.5 Controller settings

Various methods are available for the setting of the controller gain values. These methods can be divided into three groups:

- Mathematical methods
- Standard methods
- Empirical methods, i.e. methods based on values determined by experience.

Mathematical methods

With mathematical methods, a model is created of the controlled system. This model uses mathematical formulae to describe the steady state and dynamic behaviour of the system. Suitable controller parameters are then calculated from this model. These calculations are often carried out on a computer, using a simulation program.

Standard methods

With standard methods, a small number of easily measurable characteristic variables are determined for the controlled system. These are then used to calculate the controller parameters by means of tables. Standard methods are very simple to use in practice.

Empirical methods

In the case of empirical methods, the controller gain values are set on the basis of experience with similar closed-loop control circuits.

The advantages and disadvantages of the various methods are compared in Table B8.1.

Table B8.1: Methods for controller setting

Methods	*Mathematical methods*	*Standard methods*	*Empirical methods*
Advantages	Particularly suitable for complex controlled systems	Easy to use Same setting method can be used for widely-differing controlled systems	Relative easy to use
Disadvantages	Considerable previous knowledge required	Optimum control behaviour generally not achieved	Different methods used for different controlled systems
Importance for industrial practice	Low	High	High
Example of application	Optimisation of a controller using modelling and computer simulation	Ziegler-Nichols method	Empirical controller setting with a hydraulic positioning actuator

Two standard methods of setting controllers often used in practice are the following:

- The Ziegler-Nichols method
- The Chien, Hrones and Reswick method.

Controller settings using the Ziegler-Nichols method

There are two ways of setting controllers using the Ziegler-Nichols method:

- Oscillation test using a P controller
- Determination of characteristic variables and time constants from the step response of the controlled system.

With the first alternative, the gain of a P controller is increased until the closed control loop oscillates. This critical controller setting is designated as K_{Pcrit}. The periodic duration T_{crit} of the oscillation is also measured. These two characteristic variables can then be used to calculate the controller gain settings for optimised P, PI and PID controllers in accordance with Table B8.2a.

If the closed control loop must not be brought into oscillation, then the step response of the controlled system should first be plotted (Fig. B8.9). The step response can be used to read the characteristic variables dead time Tt, time constant Ts and controlled-system gain Ks. The controller parameters are calculated from these using Table B8.2b.

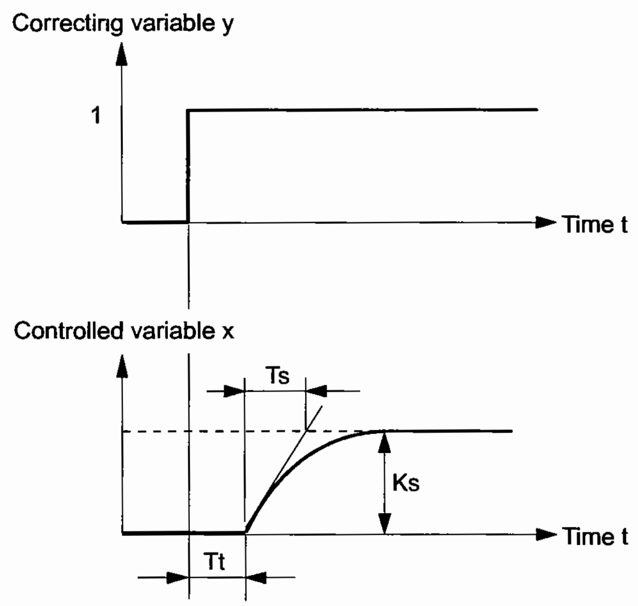


Fig. B8.9: Controlled-system characteristics for the Ziegler-Nichols method

The Ziegler-Nichols method allows optimisation of the response of a closed control loop to interference. When the reference variable is made to execute a step change, controller settings produced using the Ziegler-Nichols method will result in a pronounced overshoot of the controlled variable.

Table B8.2:
Controller setting using the Ziegler-Nichols method

	Controller	*KR*	*Tn*	*Tv*
a)	P	0.5 K_{Rkrit}	--	--
	PI	0.45 K_{Rkrit}	0.83 T_{krit}	--
	PID	0.6 K_{Rkrit}	0.5 T_{krit}	0.125 T_{krit}
	Controller	*KR*	*Tn*	*Tv*
b)	P	$\frac{TS}{Ks \cdot Tt}$	--	--
	PI	$0.9\frac{TS}{Ks \cdot Tt}$	3.3 Tt	--
	PID	$1.2\frac{TS}{Ks \cdot Tt}$	2 Tt	0.5 Tt

Closed loop control settings according to Chien, Hrones and Reswick

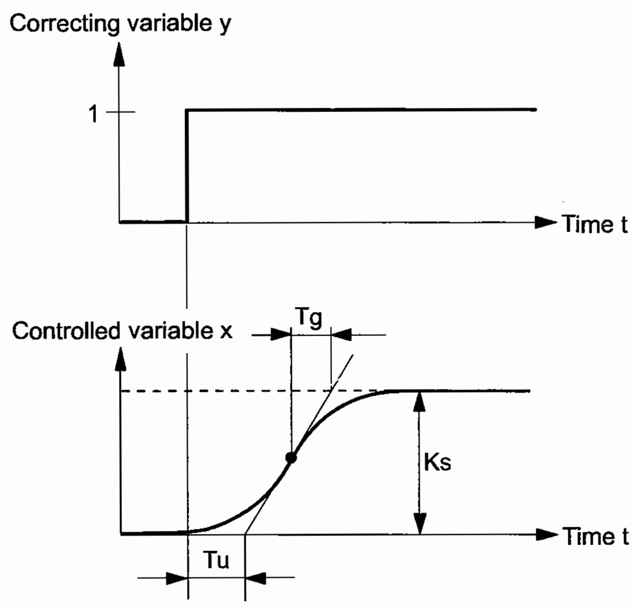


Fig. B8.10: Delay time Tu and compensation time Tg

The Chien, Hrones and Reswick method is suitable only for compensated controlled systems. The following steps are required in order to set a controller:

- First, the step response of the controlled system is measured.
- The delay time Tu and compensation time Tg are determined from this step response in accordance with Fig. B8.10.
- If the following applies: $\frac{Tg}{Tu}$ greater than 3,
  optimised controller parameters can be set on a PID controller in accordance with Table B8.3.

Table B8.3: Controller setting using the Chien, Hrones and Reswick method

Controller		A periodic control curve		Control curve with 20% overshoot	
		Interference variable	Reference variable	Interference variable	Reference variable,
P	K_R	$0.3\frac{Tg}{Tu \cdot Ks}$	$0.3\frac{Tg}{Tu \cdot Ks}$	$0.7\frac{Tg}{Tu \cdot Ks}$	$0.7\frac{Tg}{Tu \cdot Ks}$
PI	K_R	$0.6\frac{Tg}{Tu \cdot Ks}$	$0.35\frac{Tg}{Tu \cdot Ks}$	$0.7\frac{Tg}{Tu \cdot Ks}$	$0.6\frac{Tg}{Tu \cdot Ks}$
	T_n	4 Tu	1.2 Tg	2.3 Tu	Tg
PID	K_R	$0.95\frac{Tg}{Tu \cdot Ks}$	$0.6\frac{Tg}{Tu \cdot Ks}$	$1.2\frac{Tg}{Tu \cdot Ks}$	$0.95\frac{Tg}{Tu \cdot Ks}$
	T_n	2.4 Tu	Tg	2 Tu	1.35 Tg
	T_v	0.42 Tu	0.5 Tu	0.43 Tu	0.47 Tu

Setting the zero point

Apart from the setting of the closed loop controller parameters, most controllers permit setting of the zero point. This zero-point setting is also referred to as offset adjustment.

Offset adjustment can be used to compensate for the following effects:

- A shift in the controller zero point
- A shift in the valve zero point.

8.6 Fault-finding

Faults in a closed control loop may manifest themselves in a variety of symptoms. These symptoms are listed in table B8.4.

Table B8.4: Effects of faults in a closed control loop

Effects of faults	*Cause of fault see Table*
Inaccurate or slow control behaviour	Table B8.5
Steady-state oscillations	Table B8.6
Controlled variable runs against stop	Table B8.7
No reaction to changes in reference variables	Table B8.8

Possible causes are listed in Tables B8.5 to B8.8.

Table B8.5: Possible causes of control behaviour which is too slow or inaccurate.

Controller parameters incorrectly set
Offsets incorrectly set
Steady-state oscillations
Supply pressure too low
Tubing or hose cross-sections too small
Hoses blocked

Table B8.6: Possible causes of steady- state oscillations

Controller parameters incorrectly set
Electrical interferences
Sensor defective

Table B8.7: Possible causes of error if controlled variable runs against a stop.

Control direction incorrect (e.g. cable or hoses crossed over)
Sensor defective or sensor cable broken
Actuator defective or blocked
Controller defective

Table B8.8: Possible causes of error, if closed control loop does not react.

Sensor defective or connected incorrectly
Controller defective or connected incorrectly
Final control element defective or connected incorrectly
Emergency stop activated
Energy supply for signal control section switched off
Energy supply for power section switched off

Part C – Solutions

Closed loop hydraulics — *Subject*

Pipe bending machine — *Title*

Characteristic curve of a pressure sensor — *Exercise*

1. Designing and constructing the measuring circuit
2. Recording the characteristic curve of the pressure sensor
3. Deriving the characteristics of the pressure sensor from the measuring results

Solution description

1. Measuring circuit

The characteristics of a pressure sensor are:

Input range: 0bar to 100bar

Output range: 0V to 10V

Supply voltage: 15V

The characteristics of the pressure gauge are:

Measuring range: 0bar to 100bar

Measuring accuracy: ± 1.6bar (corresponding to ± 1.6% of final value, see data sheet)

The measuring circuit is to be constructed in accordance with the circuit diagrams.

2. Characteristic curve

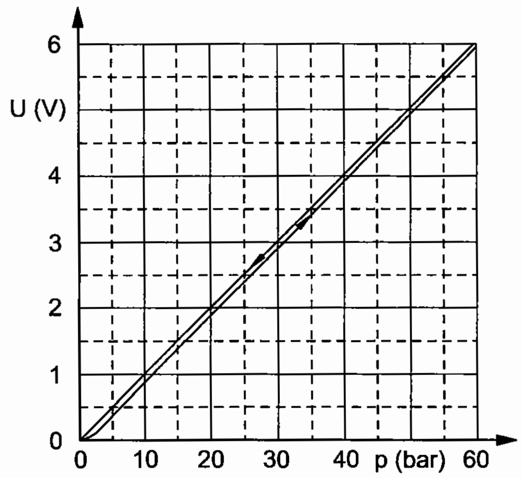
The series of measurements for the pressure sensor are set out in the following value table:

Value table

Measured variable and unit	*Measured values*									*Direction of measurement*
Pressure p in bar	0	10	20	30	40	50	60	70	80	
Voltage V in V	0.0	0.8	1.8	2.8	3.8	4.8	5.9	-	-	rising
Voltage V in V	0.0	0.9	1.9	2.9	3.9	4.9	6.0	-	-	falling

The following diagram is obtained from the value table:

Diagram



3. Characteristics

The diagram produces the following characteristics:

Input range:	0bar to 60bar
Output range:	0V to 6V
Measuring range:	60bar in total
Linear range:	overall range
Transfer coefficient:	K = 1V/10bar = 0.1V/bar
Hysteresis:	cannot be established from the series of measurements, (according to data sheet: 0.1%)

Evaluation of measuring results:

- The comparison with the data sheet shows that the measuring range of the sensor is greater than that required for this test set-up.
- Also, it is very helpful that the linear range extends across the entire characteristic curve.
- The evaluation of the transfer coefficient must be made in conjunction with the controller and all the other elements in the closed control loop and can therefore not be carried out at this point. At this stage, only the advantage of the transfer coefficient remaining constant across the entire range is clear.
- The extremely low hysteresis too, is a favourable characteristic feature of the pressure sensor.

Overall, it can be observed that the pressure sensor has an adequate measuring range and that it is more accurate than the other devices. Consequently, this sensor may be used as a suitable measuring system in this instance.

Closed loop hydraulics — *Subject*

Forming plastic products — *Title*

Pressure/signal characteristic curve of a dynamic 4/3-way valve — *Exercise*

1. Constructing a measuring circuit to plot the characteristic curve
2. Plotting and recording the pressure/signal characteristic curve
3. Establishing the characteristics from a characteristic curve

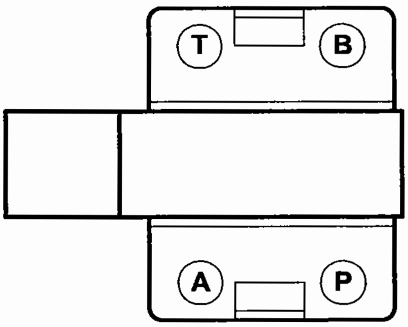
1. Measuring circuit

Solution description

The hydraulic connections of the 4/3-way valve are:
P, T, A, B.

The configuration of the sub-base is:

The sub-base



The electrical connections are:
Voltage supply: 0V (blue), 24V (red),
Signal voltage: ± 10V (yellow and green).

The hydraulic and electrical circuits are to be constructed in accordance with the circuit diagrams.

2. Pressure/signal characteristic curve

During the course of the series of measurements, the pressure will lie between 0bar and the pump pressure, i.e. approx. 60bar. Accordingly, between 0Vand approx. 6V are to be measured at the pressure sensor.

The pressure display provides information regarding the position of the valve spool when the power pack is switched on:

- If pressure is practically zero, the output is closed.
- If pressure is close to pump pressure, the output is open.
- If the pressure is in between, the valve is in mid-position.

The pressure display changes if the control voltage is changed. This applies for voltage values between approx. - 1V and + 1V.

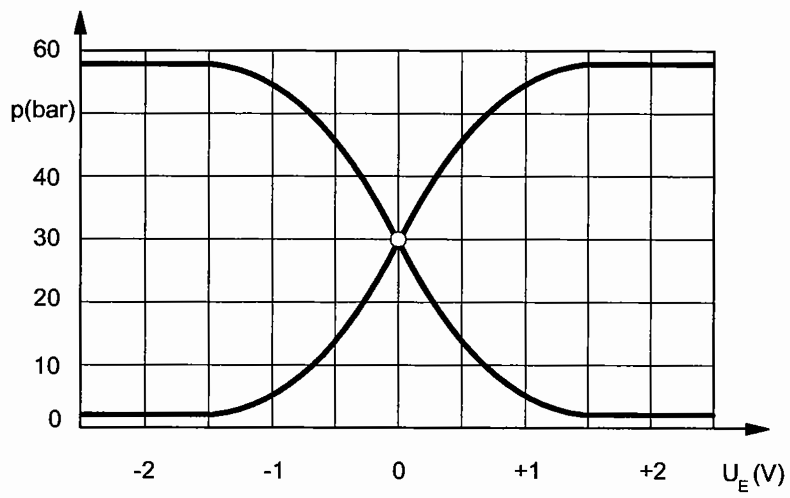
The following value table is obtained by systemically traversing this voltage range:

Value table

Measured variable and unit	*Measured values*									*Direction of measurement (rising/falling)*
Voltage V in V	-1.0	-0.5	-0.3	-0.1	0.0	0.1	0.3	0.5	1.0	
Pressure p_A in bar	0	0	2	18	43	56	60	60	60	rising
Pressure p_A in bar	0	0	2	14	38	54	58	60	60	falling
Pressure p_B in bar	60	60	60	56	43	20	2	0	0	rising
Pressure p_B in bar	60	60	59	54	38	15	2	0	0	falling

The following diagram is obtained from the measured values:

Diagram



3. Characteristics

Deviations in measured values may occur as a result of production tolerances. These will in turn produce variations from the values specified in the solutions.

The first example describes a solution for an ideal case (see previous illustration). The characteristics are:

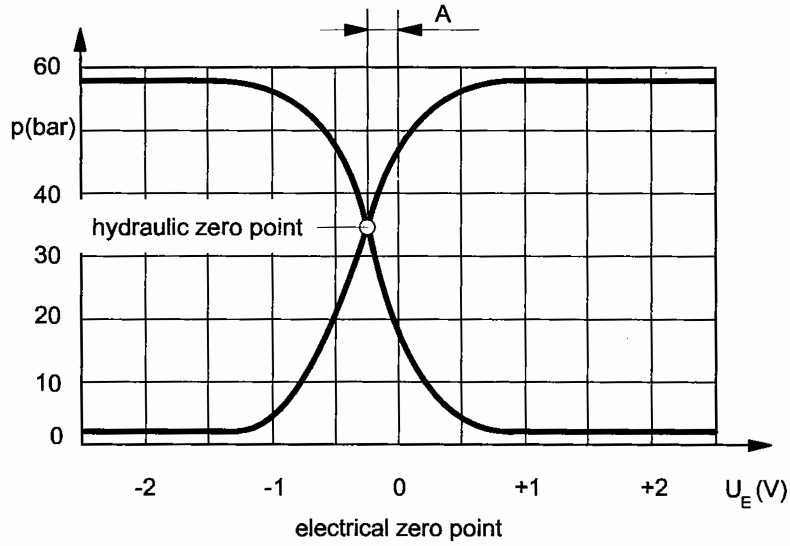
Linear range:	across a large section of the pressure range
Hydraulic zero point:	approx.0V
Electrical zero point:	at approx. 31bar
Asymmetry:	0V, hence no
Overlap:	Zero overlap with tendency to negative
Hysteresis:	<1%, or not detectable
Pressure gain:	K_A = 38 - 14bar / 0,1V= 240 bar/V K_B = 45 - 18bar / 0,1V= 270 bar/V
Signal range of pressure gain:	Output A: 2.6% Output B: 2.3%

Another example refers to a case with the deviations to be expected. The deviations may occur in various degrees and in different combinations.

- Asymmetry, i.e. hydraulic zero point not equal to electrical zero point.
- Pressure at hydraulic zero point not equal to half pump pressure. For clarification, please refer to the electrical substitute model shown in Fig. C2.1.
- Pressure gain at outputs A and B vary.

The following diagram illustrates a measuring result with potential deviations.

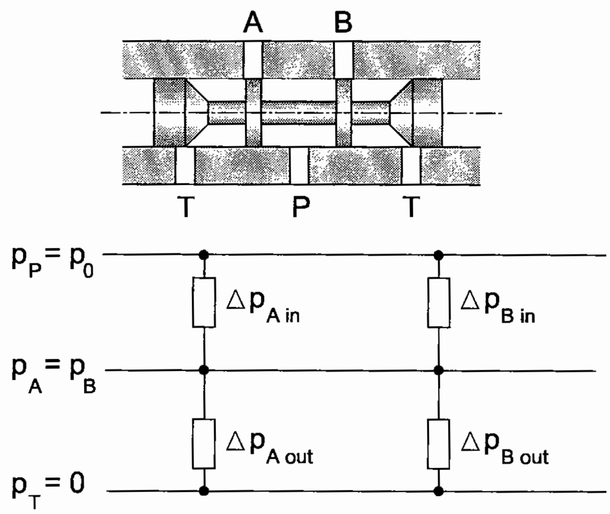
Diagram



Explanation regarding pressure at hydraulic zero point (fig. C2.1)

- The differential pressures occuring at a restricted point may be regarded as a resistance.
- The total pressure to the tank drops via one connection each, A and B.
- The pressure drop at a connection is divided between the inlet and outlet sections of the control edges.
- Only when the overlap is identical on all four control edges, do you obtain the above described ideal case. Even with the slightest differences, the intersection changes.

Fig. C2.1: Resistances at control edges of a 4/3-way valve



Evaluation of the valve

- The linear range cannot be defined clearly, although it extends across a large section of the characteristic curve.
- The hysteresis is extremely small (<1%) and therefore barely measurable.
- The pressure gain is very high and the signal range for the reversal correspondingly small (<5%).

Hence, this valve permits a very quick and reliable reversal of pressure.

Closed loop hydraulics — *Subject*

Cold extrusion — *Title*

Transition function of a pressure controlled system — *Exercise*

1. Constructing a measuring circuit
2. Recording the transition function
3. Describing the controlled system type and determining the time constant

Solution description

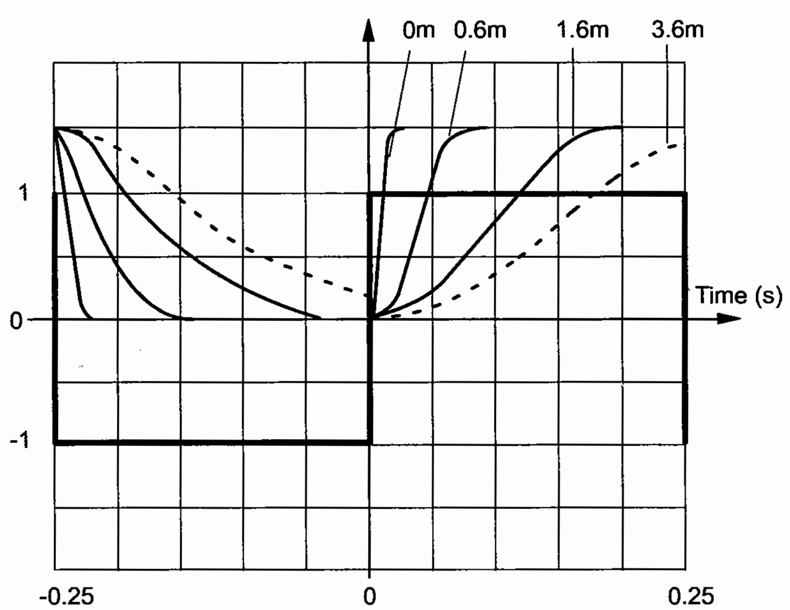
1. Measuring circuit

The measuring circuit is to be constructed in accordance with the circuit diagrams.

2. Transition function

Different tubing lengths used as a reservoir produce the following transition functions:

Diagram



3. System type and time constan

We are dealing with a controlled system

- with compensation, since a final value is reached,
- with delay, since the output variable (pressure) follows the input variable (signal step) with a delay.

The following time constants are obtained:

Value table

Variable	*Values*				*Tendency*
Hose length L	0	0.6m	1.6m	3.6m	increasing
Volume V	~ 0	0.02l	0.05l	0.1l	increasing
Time constant T_S	8ms	38ms	90ms	200ms	increasing

Closed loop hydraulics — *Subject*

Thread rolling machine — *Title*

PID controller card — *Exercise*

1. Constructing the measuring circuit
2. Establishing the range of the input variables
3. Checking the function of the summation point
4. Setting different output variables

1. Measuring circuit

Solution description

The designation for the characteristics on the card are

Input signals: w and x

Summation point: e

Elements of the controller: P, I and D

Output signal: y

Three green LED's are illuminated as voltage display in the initial position.

2. Input variables

Value table

Characteristic	*max. value*	*min. value*	*Comment*
Reference variable w	+ 9.8V	- 9.9V	within tolerance
Controlled variable x	+ 9.9V	- 9.9V	within tolerance

3. Summation point

Value table

Reference variable w	*Controlled variable x*	*Summation point e*	*Comment*
1	0	1	1 - 0 = 1 (= w)
1	1	0	1 - 1 = 0
1	-1	2	1 - (-1) = 2
0	-1	1	0 - (-1) = 1 (= - x)
0	1	-1	0 - 1 = - 1 (= - x)
-1	0	-1	-1 - 0 = -1 (= w)

4. Output variable

Value table

Range	*max. offset*	*min. offset*	*Comment*
0V to + 10V	+ 8.6V	+ 1.5V	within tolerance
- 10V to + 10V	+ 7V	- 7V	within tolerance

Subject

Closed loop hydraulics

Title

Stamping machine

Exercise

P controller

1. Constructing and commissioning the measuring circuit
2. Plotting the characteristic curve of the P controller
3. Recording the transition function of the P controller
4. Using other test signals

Solution description

1. Measuring circuit

- The circuit is to be constructed in accordance with the circuit diagram.
- The controller card is to be put in the initial position.
- In order to examine the P controller, the other two controller elements of the PID controller must be set at zero.

2. Characteristic curve of the P controller

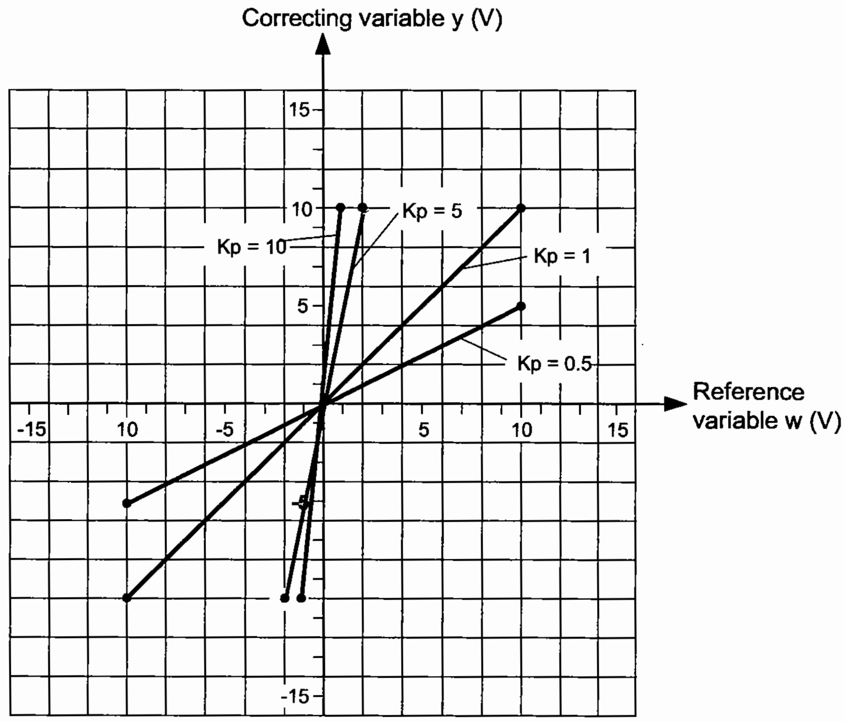
Value table

Input: Reference variable w in V	*Output: Correcting variable y in V with proportional coefficient K_P =*			
	1	*5*	*10*	*0.5*
+10	10	> 10	> 10	5
+5	5	> 10	> 10	2.5
+1	1	5	10	0.5
+0.5	0.5	2.5	5	0.25
0	0	0	0	0
-0.5	-0.5	-2.5	-5	-0.25
-1	-1	-5	-10	-0.5
-5	-5	< -10	< -10	-2.5
-10	-10	< -10	< -10	-5

In the case of values greater than 10V or smaller than -10V the limitation of the P controller is reached. Therefore, these measured values cannot be used for the characteristic curve.

Solution 5

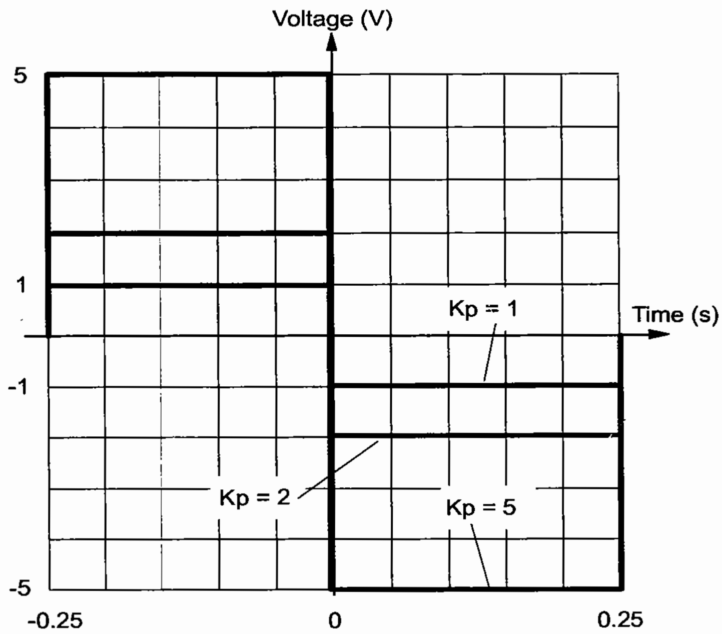
Diagram



The proportional coefficient K_P describes the slope of the characteristic curve.

3. Transition function of the P controller

Diagram



The equation for the P controller is:

$$y_P = K_P \cdot e$$

- This equation does not contain a time factor. There is no time shift of the output relative to the input.
- There is however a change in the step height:

  with $K_P = 1$ output and input are identical,

  with $K_P = 2$ the magnitude of the step is twice that of the input

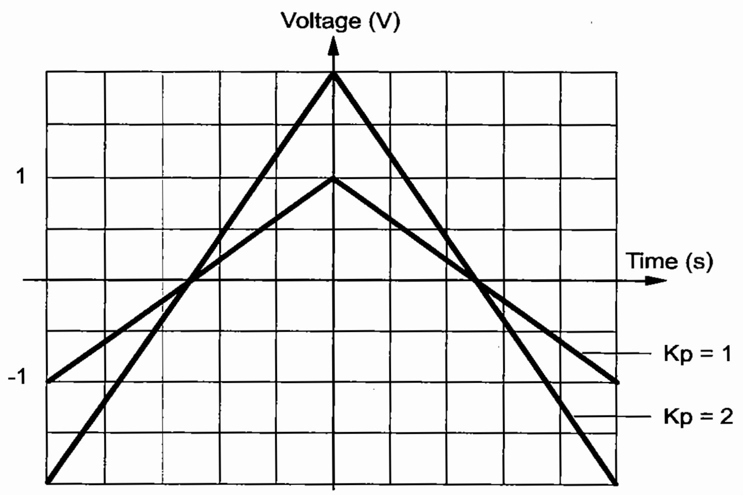
  with $K_P = 5$ the magnitude of the step is five times that of the input

4. Other test signals

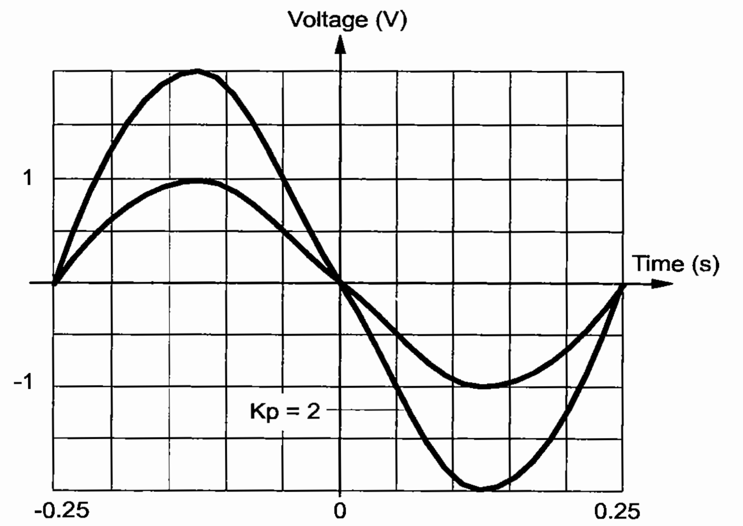
Other test signals show

- the change in amplitude is proportional to the controller coefficient K_P, hence this is also known as gain.
- no shift in the time characteristics. All zero crossings and extreme values occur at the same time as the input signal.

Diagram



Diagram



Subject

Closed loop hydraulics

Title

Clamping device

Exercise

Pressure control loop

1. Constructing a pressure control loop
2. Checking the control direction
3. Closing the control loop
4. Setting optimum control quality
5. Determining the limit of stability

Solution description

1. Pressure control loop

The pressure control loop is to be constructed in accordance with the circuit diagrams and the PID controller card put in the initial position.

2. Control direction

The control direction is set correctly once the above points have been carried out.

3. Closed control loop

The typical effects of reverse polarity protection can be seen as follows:

Solution 6

Value table

Reverse polarity	*Change in controlled variable x with increasing reference variable w*
Reference variable w	Controlled variable x = 6V as long as w = 0V. The controlled variable x decreases until x = 0V is reached (when w = 6V). A reverse behaviour of reference and controlled variable.
Correcting variable y	Controlled variable x = 6V. When w = 6V, x = 0V changes The controlled variable remains constant at an extreme value and always changes, when w = x.
Feedback r	Controlled variable x = 0V. When w = 0V, x = 6V changes The controlled variable remains constant at an extreme value and always changes, when w = x. Additionally, the pressure is indicated with the wrong sing.

With correct polarity of all the signals, the controlled variable ex follows the reference variable w in the same direction.

4. Control quality

A reference variable of $w = 3V \pm 2V$ produces the following characteristics for the control quality:

- Overshoot amplitude x_m,
- stead-state system deviation e_{stat},
- Settling time T_a.

Value table

K_P	x_m (V)	e_{stat} (V)	T_a (s)	Oscillations	Evaluation
1	0	0	0.25	none	too slow
3	0	0.1	0.10	none	too slow
5	0	0	0.04	none	good
8	0.2	0	0.05	Overshoot	Oscillation acceptable
10	0.4	0	0.05	Forward swing	too much oscillation
12	0.5	0	0.05	Stead-state oscillation	unstable

The optimum controller setting obtained are:

from the table: $5 < K_{Popt} < 10$,

through re-adjustment: $K_{Popt} = 7$.

For $K_{Popt} = 7$ the characteristic curves for control quality are:

overshoot amplitude $x_{m,opt} = 0$

steady-state system deviation $e_{stat,opt} = 0$

settling time $T_{a,opt} = 0.04s$.

Moreover, this promotes a stable closed control loop setting.

The evaluation of the control quality is subject to the user's judgement. Therefore, this solution can only be regarded as a reference.

5. Limit of stability

With K_{Pkrit} = 12, the limit of stability is reached at w = 3V ± 2V.

The following applies for a reference variable jump of ± 0.5V:

Value table

Reference variable w	*Limit of stability K_{Pkrit}*	*Evaluation*
1V ± 0.5V	8.3	
2V ± 0.5V	7.8	minimum
3V ± 0.5V	8.0	
4V ± 0.5V	8.5	
5V ± 0.5V	1.1	maximum

The lowest value for the limit of stability is the decisive factor for the evaluation of the closed control loop, i.e. K_{Pcrit} = 7.8.

The limit of stability already changes with minor deviations from the specified test setup. Hence the values quoted here only apply for a tubing length of 3m and not, for example, the serial connection of three 1m long tubing sections!

Closed loop hydraulics — *Subject*

Injection moulding machine — *Title*

I controller — *Exercise*

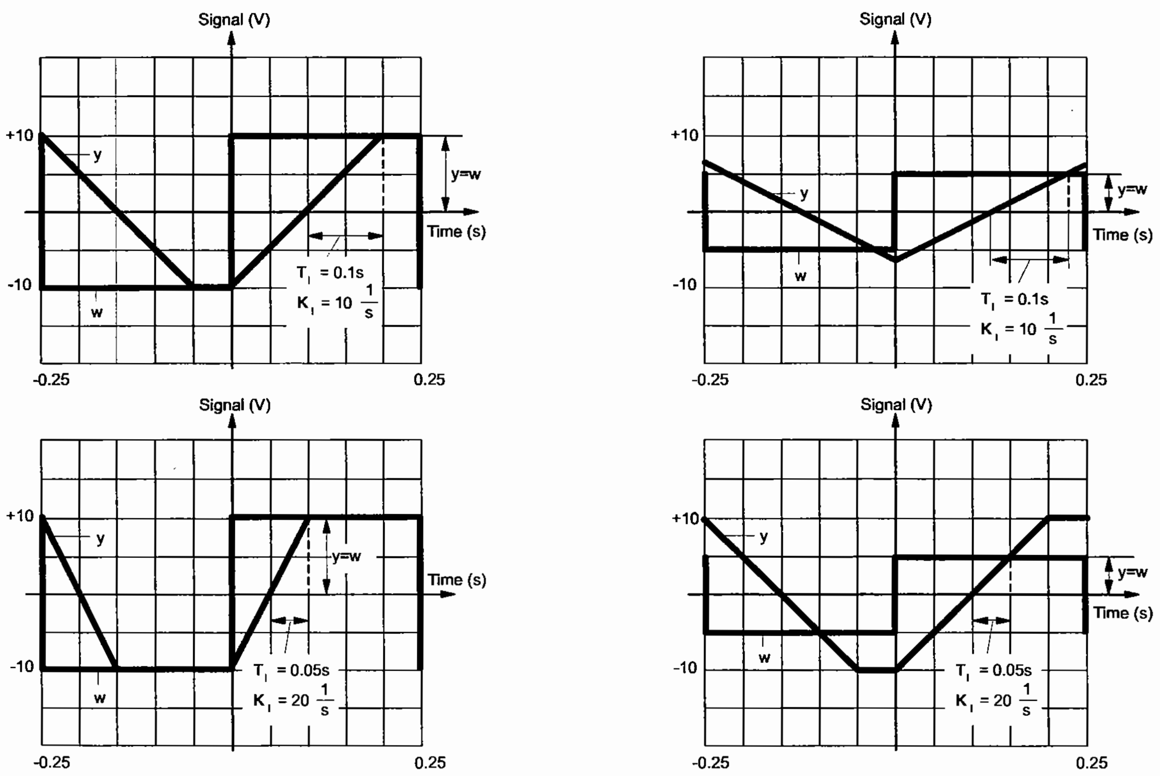
1. Constructing and commmissioning a measuring circuit
2. Recording the transition function and characteristics of the I controller
3. Determining the tansition function and characteristics of the PI controller
4. Comparing the use of the P, I and PI controllers

1. Measuring circuit — *Solution description*

The circuit is to be constructed in accordance with the circuit diagram. When commissioning the circuit, the zero of the controller card, generator and oscilloscope must be carefully balanced.

2. I controller

Diagram



The integration time T_I is reduced with an increasing integration coefficient K_I.

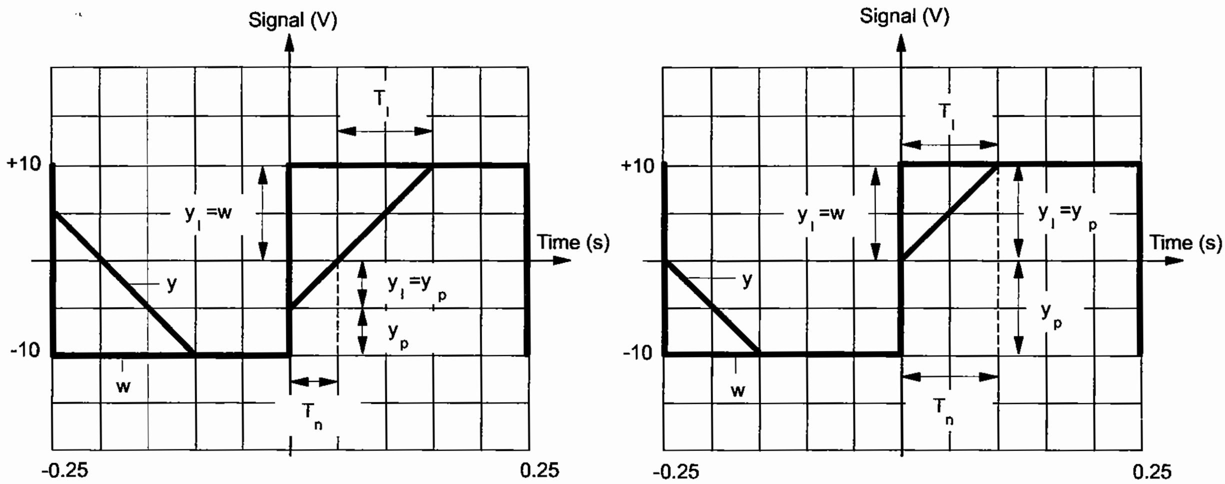
Reason
The greater the rate of change of the correcting variable y, the faster the magnitude of the step change reference variable w is reached.

Integration time T_I and integration coefficient K_I do not change with the reference variable w.

Reason
The characteristics of the transition function are dependent on the magnitude of the step change reference variable w, whereas the characteristics of the controller are not (see diagrams).

3. PI-Regler

Fig. A7.6: Measurement of integral-action time T_n



The representations of the diagram cannot be reproduced in this way, since the limitation of the I element is greater than 10V.

4. P, I and PI controller

Table

Property	*Controller types*		
	P	*I*	*PI*
Velocity	Fast	slow	fast
Steady-state system deviation	Yes	No	no

Closed loop hydraulics — *Subject*

Pressing-in of bearings — *Title*

D, PD and PID controller — *Exercise*

1. Constructing and commissioning the measuring circuit
2. Recording the transition function and ramp response of the D controller
3. Determining the time constant of the PD controller
4. Establishing the construction of the PID controller from the transition function

Solution description

1. Measuring circuit

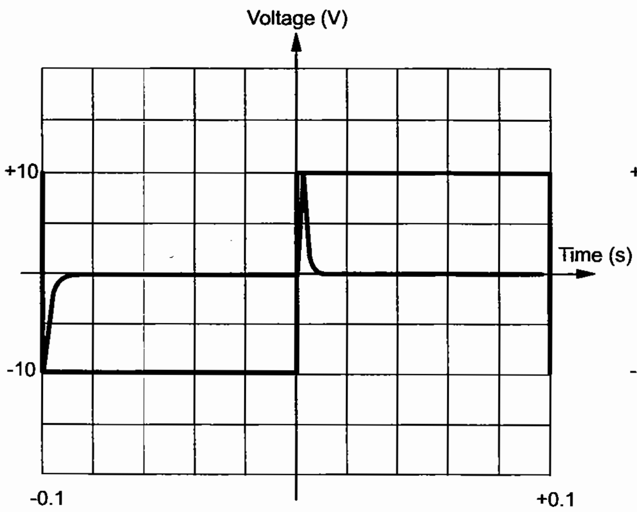
The circuit corresponds to the basic circuit in A5 and A7 for the PID controller card.

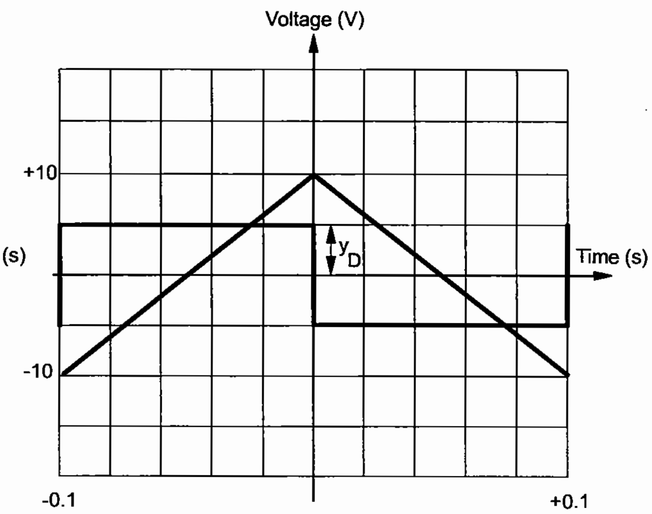
2. D controller

Transition function and ramp response of D controller with

w = 0V ± 10V, f = 5 Hz, square wave K_D = 25ms

Diagram





The slope of the reference variable is

$$\frac{\Delta w}{\Delta t} = 4 \cdot A \cdot f = 4 \cdot 10V \cdot 5\frac{1}{s} = 200\frac{V}{s}$$

The results in the correcting variable y:

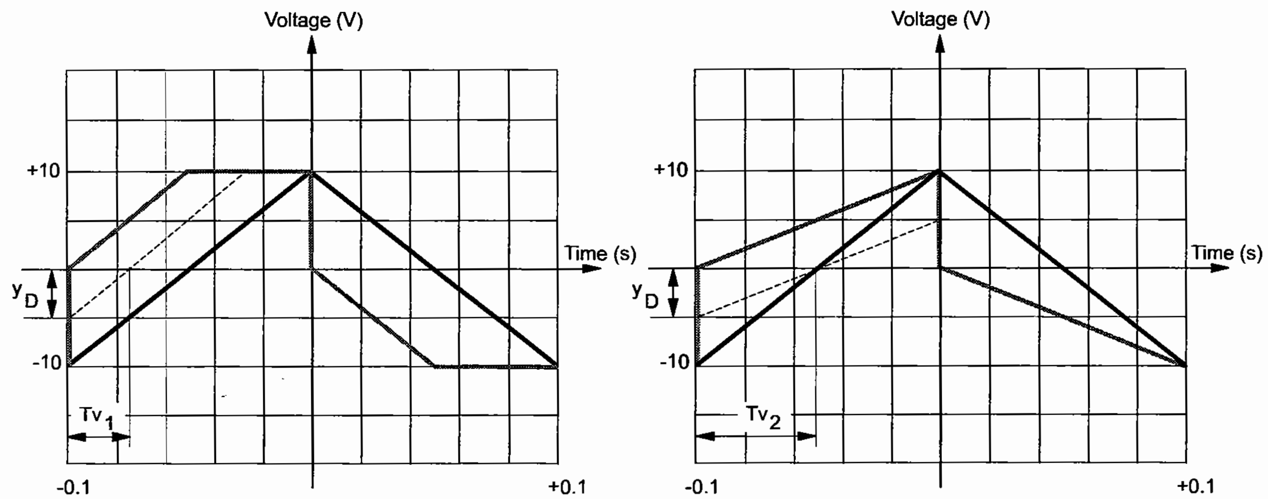
$$y = K_D \cdot \frac{\Delta w}{\Delta t} = 0.025s \cdot 200\frac{V}{s} = 5V$$

The accordance with the measuring result is dependent on the accuracy of the reference variable w: slight deviations of the reference variable w from the specified setpoint value change the correcting variable y.

3. PD controller

- $w = 0V \pm 10V$, f = 5 Hz, triangular form
- 1. $K_P = 1$, $K_D = 25ms$
  2. $K_P = 0.5$, $K_D = 25ms$

Diagram



The rate times are:

$$T_{v1} = \frac{K_D}{K_P} = \frac{0.025s}{1} = 0.025s = 25ms$$

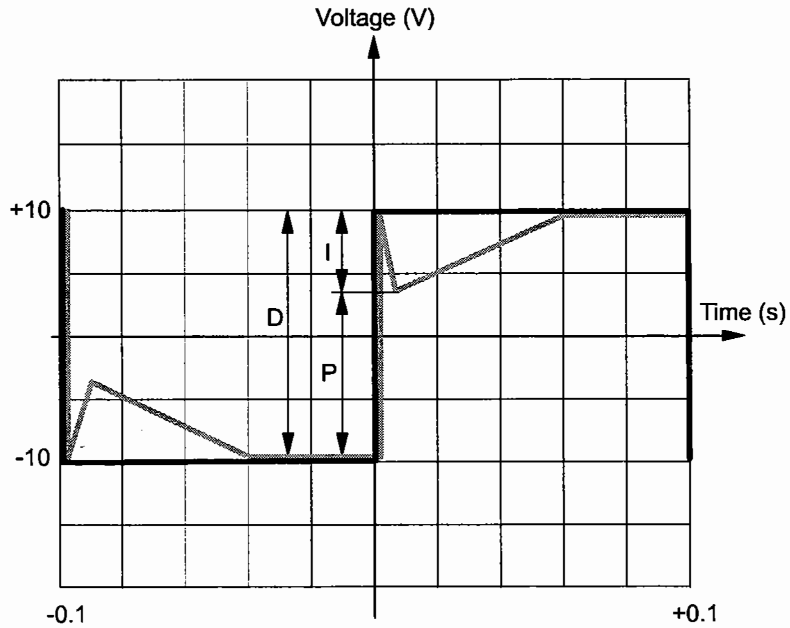
$$T_{v2} = \frac{K_D}{K_P} = \frac{0.025s}{0.5} = 0.05s = 50ms$$

The measurement generally agrees with the calculation. You should, however, make sure that the magnitude of the step change y_D of the D element is not calculated twice.

4. PID controller

The transition function of the PID controller shows

- the jump of the P element,
- the ramp of the I element and
- the spike pulse of the D element.



Value table

Subject: *Closed loop hydraulics*

Title: ***Welding tongs of a robot***

Exercise:

Pressure control loop with PID controller

1. Constructing a pressure control loop
2. Commissioning a pressure control loop
3. Setting the parameters of a PID controller using an empirical method

Solution description

1. Pressure control loop

The pressure control loop is to be constructed in accordance with the circuit diagrams and the PID controller card put in the initial position.

2. Commissioning

2.1 Control direction

The control direction is set correctly when the reference variable w and controlled variable x change in the same direction.

2.2 Limit of stability

The limit of stability is determined with the P controller and is reached when steady-state oscillations occur. Since the oscillation gradient depends on various influences, there are deviations in the result.

$$K_{Pcrit} = 8.1$$

3. Empirical parameterisation

The value table sets out examples of possible influences. The settings of optimum parameters is dependent both on the individual evaluation and the special test set-up. Hence, there are also large deviations with this exercise.

Value table

Controller coefficient			Control quality			Stability	Comment
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)		
4	0	0	0	0	40	stable	e_{stat} becomes even at zero
5	0	0	0.2	0	40	stable	small overshoot
7	0	0	0.5	0	60	stable	with forward swing
8.1	0	0	0.6	-	-	unstable	steady-state oscillation through P element
1	0	0	0	0.1	-	stable	e_{stat} exists
1	1	0	0	0	0.5	stable	e_{stat} eliminated through I element
1	9	0	0.6	0	0.5	stable	overshoot
1	24	0	1	0	0.5	stable	with forward swing
1	450	0	2	-	-	unstable	steady-state oscillation through I element
4	10	0	0.8	0	0.2	stable	large overshoot
4	10	405	0.8	0	0.2	stable	superimposed small steady-state oscillation.
4	10	5	-	-	-	unstable	steady-state oscillation through D element
7	80	0	1	0	0.3	stable	large overshoot
7	80	2	1	0	0.3	stable	with forward swing
7	80	3	-	-	-	unstable	steady-state oscillation through D element

In this instance, the I and D elements do not lead to any improvement in control quality. The optimum parameterisation obtained is:

Value table

Optimum controller coefficients			Best possible control quality			Stability
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)	
5	0	0	0.2	0	40	stable

Subject

Closed loop hydraulics

Title

Pressure roller of a rolling machine

Exercise

Ziegler-Nichols method

1. Constructing and commissioning the pressure control loop
2. Setting the PID controller in accordance with the Ziegler-Nichols method
3. Changing the controlled system and re-setting it at its optimum level

Solution description

1. Pressure control loop

The pressure control loop is to be constructed, the PID controller put into the initial position and the control direction checked.

2. Ziegler-Nichols method

A reference variable of $w = 3V \pm 2V$ results in a limit of stability with:

- $K_{Pcrit} = 10.6$
- $T_{crit} = 12ms$

From this, the coefficients of the PID controller are calculated:

- $K_P = 0.6 \cdot K_{Pcrit} = 0.6 \cdot 10.6 = 6.36$
- $T_n = 0.5 \cdot T_{crit} = 0.5 \cdot 12ms = 6ms$
- $T_v = 0.12 \cdot T_{crit} = 0.12 \cdot 12ms = 1.44ms$
- $K_I = \frac{K_P}{T_n} = \frac{6.36}{0.006s} = 1060 \frac{1}{s}$
- $K_D = K_P \cdot T_v = 6.36 \cdot 1.44ms = 7.8ms$

The transition function initially exhibits small continuous oscillations after some initial overshoots, which gradually decay. The closed control loop is therefore at the limit of stability and thus not stable!

The following control quality is obtained with the calculated coefficients:

- overshoot amplitude x_m = 1.4V
- steady-state system deviation e_{stat} = 0
- settling time T_a = approx. 80ms, after which small continuous oscillations are maintained!

A very high integration coefficient K_I can be seen in comparison with the empirically determined coefficients (see solution to exercise 9). This results in the extremely high overshoot amplitude x_m. Also, the closed control loop becomes unstable as a result of this.

The settling time may also deteriorate.

Conclusion: An empirical readjustment of the controller parameters is essential for this closed control loop.

3. Modified closed control loop

The following characteristics are obtained for pressure control without reservoir:

Limit of stability:

- $K_{Pcrit} = 2.1$
- $T_{crit} = 10ms$

The coefficients of the PID controller are calculated from this:

- $K_P = 0.6 \cdot K_{Pcrit} = 0.6 \cdot 2.1 = 1.26$
- $T_n = 0.5 \cdot T_{crit} = 0.5 \cdot 10ms = 5ms$
- $T_v = 0.12 \cdot T_{crit} = 0.12 \cdot 10ms = 1.2ms$
- $K_I = \frac{K_P}{T_n} = \frac{1.26}{0.005s} = 252\frac{1}{s}$
- $K_D = K_P \cdot T_v = 1.26 \cdot 1.2ms = 1.5ms$

The control quality is then:

Value table

Controller coefficients to Z.-N.			*Control quality*			*Stability*
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)	
1.26	252	1.5	1.2	0	25	stable

The empirical parameterisation produces the following:

Value table

Controller coefficients empirical			*Control quality*			*Stability*
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)	
1	16.5	1.75	0.2	0	10	stable

The empirical setting of the optimum parameters depends on the user's interpretation. The results should therefore be regarded purely as e-xamples of specimen solutions.

A comparison with the achieved control quality shows that the empirical coefficients are more appropriate than those calculated in accordance with the Ziegler-Nichols method.

Subject: *Closed loop hydraulics*

Title: ***Edge-folding press with feeding device***

Exercise: **Pressure control loop with interference**

1. Constructing a pressure control loop
2. Commissioning a pressure control loop
3. Optimum setting of a PID controller
4. Examining the effect of interference

Solution description

1. Pressure control loop

The pressure control loop is to be constructed in accordance with the circuit diagrams.

2. Commissioning

The following are required for commissioning:

- putting the electrical and hydraulic circuits into the initial position
- connecting the power supply
- setting the control direction correctly

3. PID controller

The limit of stability is free of interference for a reference variable $w = 3V \pm 1V$:

- $K_{Pcrit} = 9$
- $T_{crit} = 14ms$

The coefficients according to Ziegler-Nichols are:

- $K_P = 0.6 \cdot K_{Pcrit} = 0.6 \cdot 9 = 5.4$
- $T_n = 0.5 \cdot T_{crit} = 0.5 \cdot 14ms = 7ms$
- $T_v = 0.12 \cdot T_{crit} = 0.12 \cdot 14ms = 1.7ms$
- $K_I = \frac{K_P}{T_n} = \frac{5.4}{0.007s} = 771 \frac{1}{s}$
- $K_D = K_P \cdot T_v = 5.4 \cdot 1.7ms = 9.2ms$

The control quality for the calculated coefficients is:

Value table

Controller coefficients to Z.-N.			*Control quality without interference*			*Stability*
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)	
5,4	771	9,2	0,7	-	-	instabil
(5,4	771	3	1	0	100	stabil)

The calculated coefficients for the I and D element are so high as to render the closed control loop unstable!

With empirically established coefficients, the control quality is as follows:

Value table

Controller coefficients empirical			*Control quality without interference*			*Stability*
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)	
6	25	3	0	0	50	stabil

Here, the empirical setting appears to be conclusively better.

4. Effect of interferences

The settings for leakage can produce widely varying results. Hence, we shall merely quote a result by way of an example. In this instance, the leakage has been increased until a good transition function can still just be obtained for computational coefficients.

The following characteristics are thus obtained with leakage:

– $K_{PcritL} = 12$

Value table

Controller coefficients to Z.-N.			*Control quality with leakage*			*Stability*
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)	
5.4	771	9.2	0.6	0	100	stable

Value table

Controller coefficients empirical			*Control quality with leakage*			*Stability*
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)	
6	25	3	0	0.1	-	stable

In this case, the setting according to Ziegler-Nichols appear to be more favourable since, due to the high I element, a permanent deviation can be avoided.

A supply pressure of 45bar produces the following characteristics:

– K_{PcritD} = 17

Value table

Controller coefficients to Z.-N.			Control quality with pressure drop			Stability
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)	
5.4	771	9.2	0.5	0	150	stable

Value table

Controller coefficients empirical			Control quality with pressure drop			Stability
K_P	K_I (1/s)	K_D (ms)	x_m (V)	e_{stat} (v)	T_a (ms)	
6	25	3	0	0	60	stable

The closed control loop becomes considerably slower as a result of the pressure drop: K_{PcritD} is greater than K_{Pcrit0}. However, a slight pressure drop is still relatively well compensated owing to the empirically determined coefficients. With the calculated coefficients the closed control loop is only just stable. The advantages of the Ziegler-Nichols method would also still be apparent with a larger pressure drop: because of the high I element of the calculated coefficients, a sufficient control quality is more likely to be achieved with these than with those empirically determined.

Overall, the series of measurements demonstrates that the parameters determined according to the Ziegler-Nichols are better for compensating interferences. Since this was the inventors' intention, the Ziegler-Nichols method may be regarded as perfectly acceptable, even if it does not appear to be particularly suitable for the case in question. However, in practice, interferences to the extent simulated in this instance, are eliminated by way of exchanging components and not through the controller!

Subject

Closed loop hydraulics

Title

Table feed of a milling machine

Exercise

Displacement sensor

1. Constructing a measuring circuit with hydraulic linear unit
2. Recording the characteristic curve of the displacement sensor
3. Deriving the characteristics of the displacement sensor from themea-sured values

Solution description

1. Measuring circuit

The circuit is to be constructed in accordance with the circuit diagrams.

2. Characteristic curve

The characteristic curve may be plotted after the signal flow in the circuit has been checked to be correct.

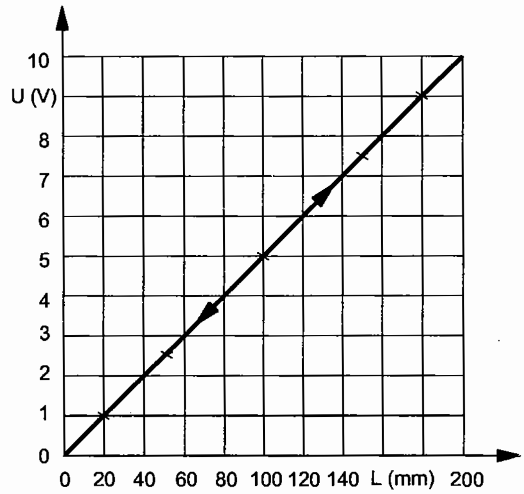
Value table

Measured variable and unit	*Measured values*							*Direction of measurement (rising/falling)*
Length L in mm	(0)	10	50	100	150	190	(200)	
Voltage V in V	0.1	0.5	2.5	5.0	7.5	9.5	10.0	rising
Voltage V in V	0.1	0.5	2.5	5.0	7.5	9.5	10.0	falling

Significant measurement errors may occur due to the complex setting. This is to be taken into consideration.

The following diagram is obtained:

Diagram



3. Characteristics

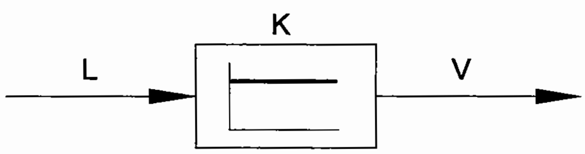
The transfer coefficient of the displacement sensor is:

$$K = \frac{10V}{200mm} = \frac{0.05V}{mm} = 50\frac{V}{mm}$$

The representation of the displacement sensor in a closed control loop depends of the respective application. Two possibilities are quoted here as examples:

Verbal description

Symbolic description



Evaluation of the measuring results:

- The measuring range is adequate.
- The linear range extends across the entire measuring range.
- No hysteresis can be detected.
- The transfer coefficient is constant.

Overall the sensor appears to be suitable within the framework of the available equipment.

Subject

Closed loop hydraulics

Title

X/Y-axis table of a drilling machine

Exercise

Flow characteristic curves of a dynamic 4/3-way valve

1. Constructing and commissioning the measuring circuit
2. Recording the flow/signal characteristic curve
3. Deriving the flow/pressure characteristic curve
4. Comparison with the nominal data

Solution description

1. Measuring circuit

The measuring circuit is to be constructed in accordance with the circuit diagrams.

2. Flow/signal characteristic curve

The preparations for the commissioning of the measuring circuit are described in great detail in order to make clear the correlations between the various measured variables.

Zero position

If the pressure relief valve is completely open, the entire volumetric flow returns to the tank via the by-pass. The sensor displays are therefore all practically zero

p_P = 0bar
p_A = 0bar
Δp_1 = 0bar
q_A = 0 l/min

Setting the pressure

By closing the pressure relief valve, the pressure p_P at port P of the directional control valve rises. As the directional control valve is closed in its mid-position, no flow condition q_A is created. The working pressure p_A at port A rises only slightly. Thus, the differential pressure Δp_1 increases between ports P and A.

p_P = 53bar
p_A = 0bar
Δp_1 = 53bar
q_A = 0 l/min

Setting the activating signal

The flow q_A increases with a rising activating signal V_E, whereby the supply pressure p_P decreases slighly and the pressure at the working port p_A rises. The following measured values are obtain with V_E = 1V:

p_P = 54.3bar
p_A = 0.2bar
Δp_1 = 54.1bar
q_A = 0.5 l/min

Checking the signal direction

If the flow q_A does not increase with the activating signal, the signal direction in the circuit is wrong. Either the polarity of the activating signal is incorrect or the wrong output of the valve has been used.

Determining the measuring range

In order to establish the limits of the measuring circuit, the maximum supply pressure p_P of the activating signal V_E is increased until the flow rate no longer changes.

U_{Elimit} = 9V

q_{Amax} = 3.8 l/min.

Δp_1 = 28.5bar – 2.5bar = 26bar

The values specified apply for a higher pump performance (4l). In the case of a standard pump of only 2 l/min, the limit of the correcting range is already reached at V_E = 4V.

Flow/signal characteristic curve for output A

Value table

Differential pressure Δp_1 = 5bar

V_E in volts	0	1	3	5	7	9	10
q_A in l/min	0	0	0.5	0.9	1.27	1.6	1.8
p_P in bar	5	5	5.2	5.4	5.6	5.8	5.9
p_A in bar	0	0	0.2	0.4	0.6	0.8	0.9

Differential pressure Δp_1 = 10bar

V_E in volts	0	1	3	5	7	9	10
q_A in l/min	0	0.19	0.78	1.33	1.83	2.33	2.6
p_P in bar	10	10	10.3	10.5	10.9	11.2	11.3
p_A in bar	0	0	0.3	0.5	0.9	1.2	1.3

Differential pressure Δp_1 = 20bar

V_E in volts	0	1	3	5	7	9	10
q_A in l/min	0	0.28	1.1	1.86	2.6	3.4	3.7
p_P in bar	20	20.1	20.5	20.9	21.3	21.8	22.1
p_A in bar	0	0.1	0.5	0.9	1.3	1.8	2.1

Differential pressure Δp_1 = 35bar

V_E in volts	0	1	3	5	7	9	10
q_A in l/min	0	0.4	1.4	2.4	3.5	*3.8*	*3.8*
p_P in bar	35	35.1	35.6	36.1	36.8	*28.8*	*23.4*
p_A in bar	0	0.1	0.6	1.1	1.8	*2.1*	*2.1*

Characteristic curve for output B

Value table

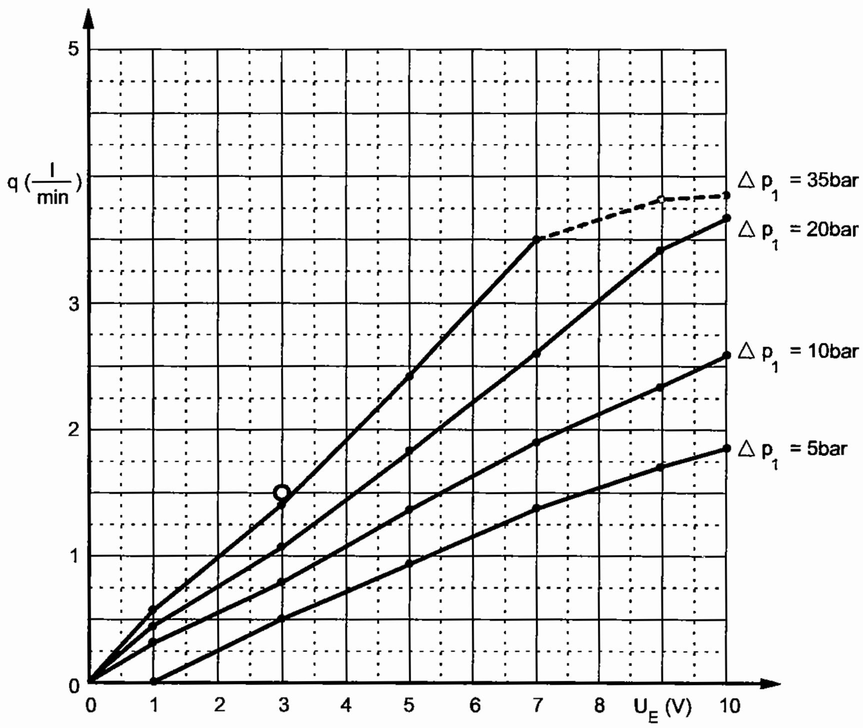
Differential pressure Δp_1 = 20bar

V_E in volts	0	- 1	- 3	- 5	- 7	- 9	- 10
q_B in l/min	0	0.23	1.0	1.8	2.5	3.2	3.5
p_P in bar	20	20	20.1	20.4	20.8	21.3	21.6
p_B in bar	0	0	0.1	0.4	0.8	1.3	1.6

The difference between flow values q_A and q_B are within a permissible range of ± 10%. The pattern of the characteristic curve for output B is thus symmetrical to output A.

Flow/signal characteristics for output A

Diagram



The evaluation of the characteristic curves produces:

Linear range

The pattern of the flow characteristic curves is largely linear. With activating signals below $V_E = 1V$, the flow drops to zero. With high differential pressures Δp_1, the flow no longer increases evenly since the pump performance has been reached.

Hysteresis

No hysteresis can be detected.

Volumetric flow gain and differential pressure

The volumetric flow gain represents the gradient in the linear range. This rises with increasing differential pressure Δp_1.

Flow/signal gain

at $\Delta p_1 = 35bar$:

$$K_V = \frac{\Delta q}{\Delta V_E} = \frac{2.4\frac{l}{min} - 1.4\frac{l}{min}}{2V}$$

$$K_V = \frac{1\frac{l}{min}}{2V} = 0.5\frac{\frac{l}{min}}{V}$$

3. Flow/pressure characteristic curve

Conversion of the values table produces the following:

Value table

Activating signal V% = 100%, i.e. V_E = 10 V

Δp_1 in bar	5	10	20	35
q_A in l/min	1.8	2.6	3.7	*3.8*

Activating signal V% = 90%, i.e. V_E = 9V

Δp_1 in bar	5	10	20	35
q_A in l/min	1.6	2.33	3.4	*3.8*

Activating signal V% = 70%, i.e. V_E = 7V

Δp_1 in bar	5	10	20	35
q_A in l/min	1.27	1.83	2.6	3.5

Activating signal V% = 50%, i.e. V_E = 5V

Δp_1 in bar	5	10	20	35
q_A in l/min	0.9	1.33	1.86	2.4

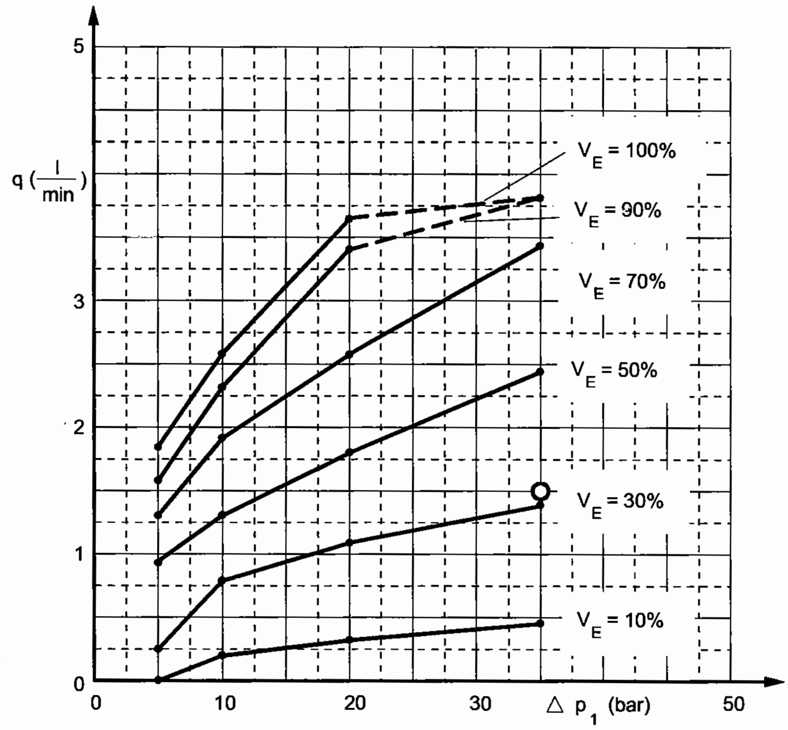
Activating signal V% = 30%, i.e. V_E = 3V

Δp_1 in bar	5	10	20	35
q_A in l/min	0.5	0.78	1.1	1.4

Activating signal V% = 10%, i.e. V_E = 1V

Δp_1 in bar	5	10	20	35
q_A in l/min	0	0.19	0.28	0.4

Diagram



4. Comparison with the nominal data

The following nominal values are specified by the manufacturer:

Nominal flow rate:	q_N = 5 l/min
Differential pressure:	Δp_2 = 70bar
Number of control edges:	two
Activating signal:	V_{Emax} = 10V

The measuring point described by the characteristic data lies at the top edge of the diagram. It cannot be measured with the equipment available. A conversion of the characteristics is necessary.

With Δp_1 = 35bar and V_E = 30% the computational flow flow q_r is:

$$q_r = 5\frac{l}{min} \cdot \frac{3V}{10V} = 1.5\frac{l}{min}$$

This value is drawn into the diagrams.

The measurement amounted q_m = 1.4 l/min.

The following deviations are obtained:

$$q_f = \frac{1.4 - 1.5}{1.5} \cdot 100\% = -6.7\%$$

The measured values lie within the tolerance of ± 10%.

Subject

Closed loop hydraulics

Title

Feed unit of an assembly station

Exercise

Linear unit as controlled system

1. Constructing the hydraulic and electrical measuring circuit
2. Recording the step response of the controlled system
3. Calculating the velocity and system gain
4. Recording the pressure characteristics and flow rate

Solution description

1. Measuring circuit

The hydraulic and electrical circuit are to be constructed in accordance with the circuit diagrams.

2. Step response of controlled system

In the initial position, i.e. after the hydraulic and electrical power have been switched on at activating signal $V_E = 0$, the following measured values are obtained:

p_A = approx. 30bar

p_B = approx. 48bar $\left(\frac{p_a \cdot A_K}{A_{KR}}\right)$

p_P = approx. 60bar (= maximum pump pressure)

q is practically zero

x is desired

It is possible that the slide may drift, in which case different working pressures p_A and p_B will be obtained. In addition, the pressure ratios of p_A and p_B required to stop the slide are generally not obtained with V_E = 0V (for explanation see solution to exercise 2).

The correct polarity of the circuit is checked by re-adjusting the activating signal V_E:

- with an increasing activating signal V_E
- the slide moves in the positive x-direction.

The traversing motion finishes at the end stop of the cylinder. The same applies for negate activating signals. The positioning of the slide by means of adjusting the activating signals requires a certain amount of practice.

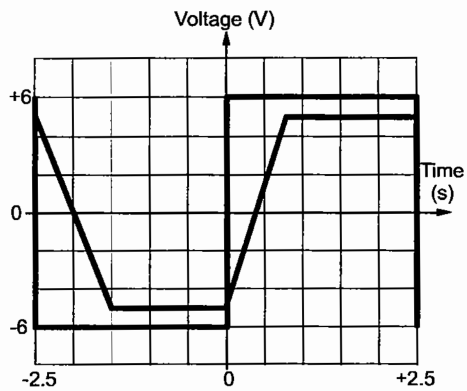
In order to maintain the slide drift-free in its mid-position, it is necessary to give an offset to the activating signal.

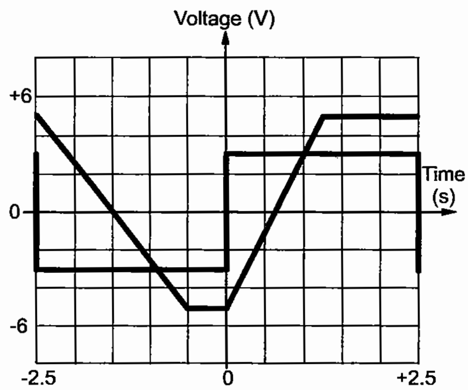
The transition function of the controlled system shows that this is a system without compensation:

- with constant activating signal V_E
- the output variable x continually increases with the time t.

The following tansition functions are obtained for
$V_E = \pm 6V$ and $V_E = \pm 3V$:

Diagram





3. Velocity and system gain

The diagrams enable you to calculate the velocity v and system gain K_S as follows:

$V_E = \pm 6V$ and $x = 200mm = 0.2m$

Value table

	Time t	Velocity v	Gain K_S
Advancing	0.7s	0.29 m/s	0.048 (m/s)/V
Retracting	1.0s	0.2 m/s	0.033 (m/s)/V

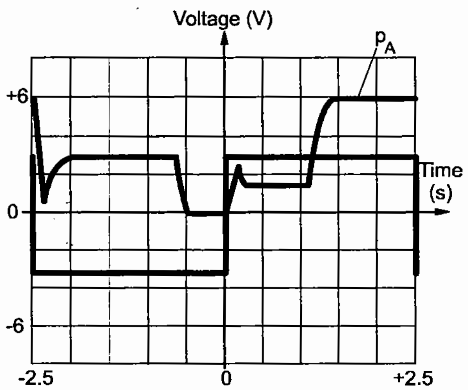
$V_E = \pm 3V$ and $x = 200mm = 0.2m$

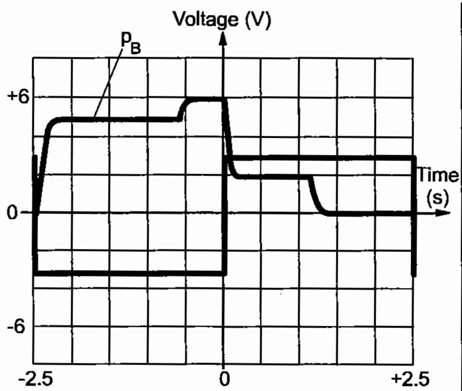
Value table

	Time t	Velocity v	Gain K_S
Advancing	1.25s	0.16 m/s	0.053 (m/s)/V
Retracting	2.0s	0.1 m/s	0.033 (m/s)/V

4. Characteristics of pressure and flow

Diagram





The following value table is obtained from the diagrams:

Value table

	Pressure p_A	Pressure p_B	Pressure p_P	Flow q
Advancing	14bar	20bar	61bar	1.72l/min
Advancing	30bar	50bar	63bar	0.75l/min

The differential pressures at the inlet control edges are calculated from the value table:

Advancing: $\Delta p_{out} = p_{Pout} - p_{Aout} = 61bar - 14bar = 47bar$

Advancing: $\Delta p_{in} = p_{Pin} - p_{Bin} = 63bar - 50bar = 13bar$

Here too, the correlation between differential pressure and flow can be seen: A high flow requires a high differential pressure.

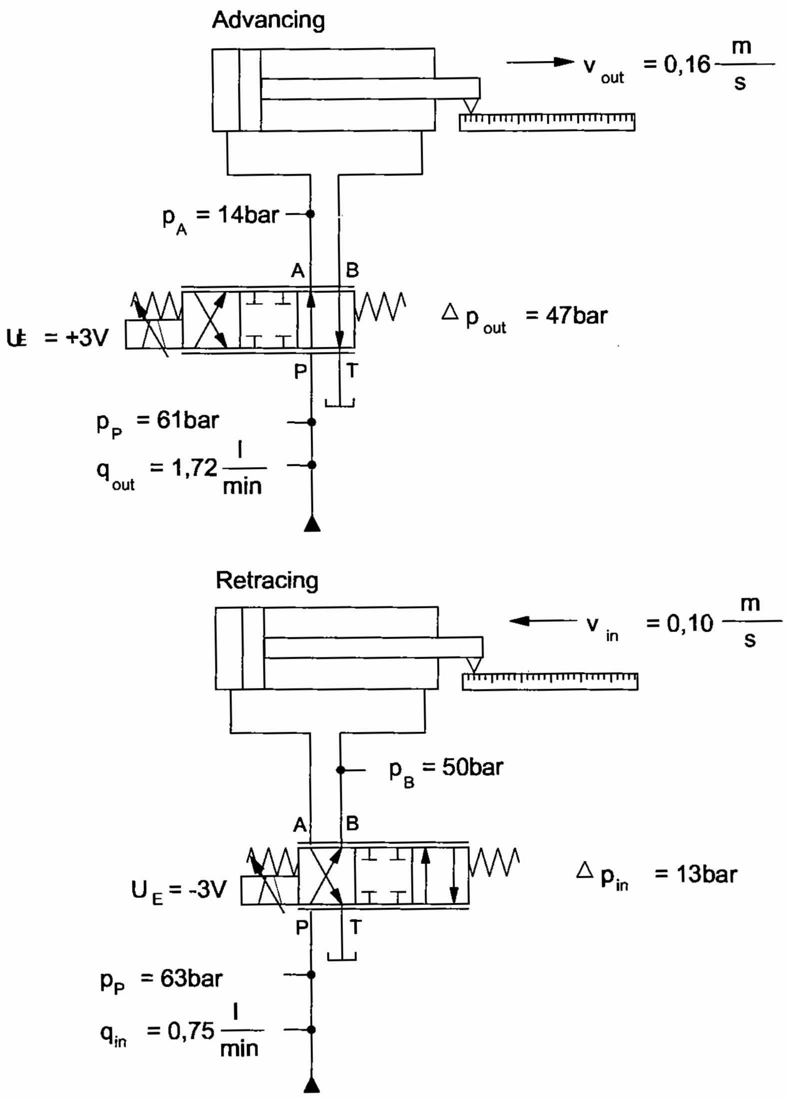


Fig. A14.2: Hydraulic circuit diagram of the controlled system

The operating points can be drawn in the flow characteristic curves (C13).

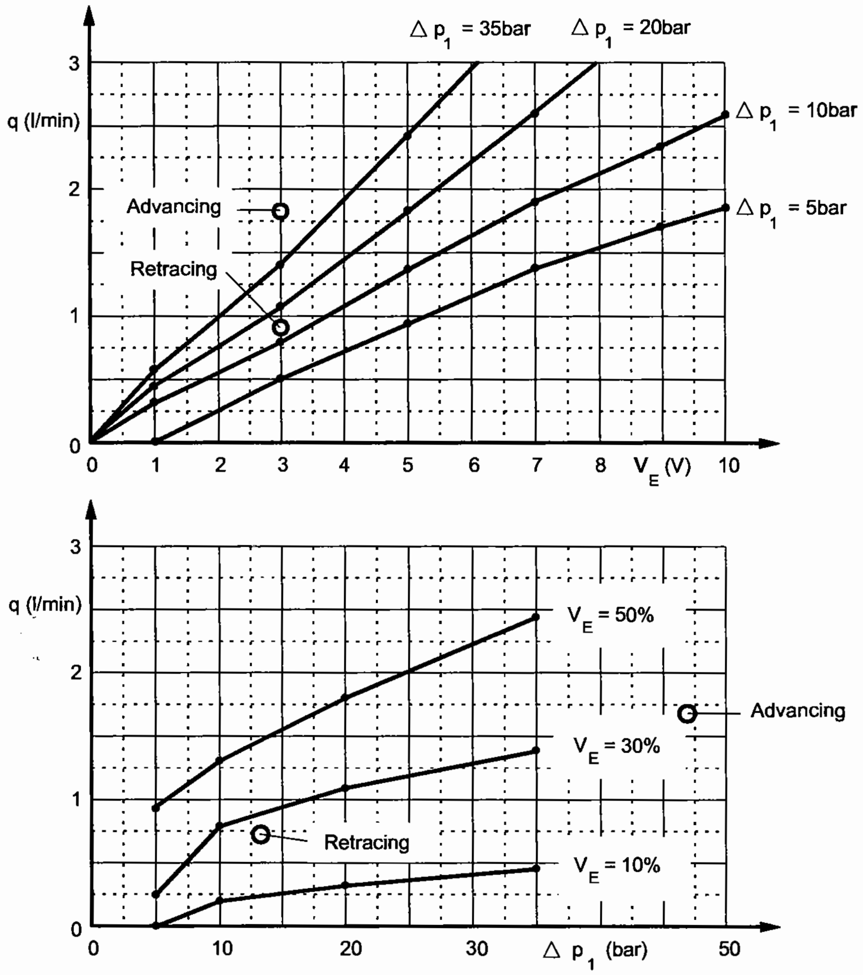


Fig. A14.3:
Flow characteristic curves of the controlled system

The flow/signal gain is greater during advancing.

Both operating points are close to the chacteristic curve for V_E = 30%.

The ideal result has been demonstrated in this instance. With practical measurements, considerable deviations may occur, e.g. with varying equipment sets..

Subject: *Closed loop hydraulics*

Title: ***Automobile simulator***

Exercise

Position control loop

1. Constructing a position control loop electrically and hydraulically
2. Checking the control direction and setting the offset
3. Recording the transition function and setting parameters using theempirical method
4. Calculating the closed-loop gain
5. Verifying the positional dependence of the limit of stability
6. Testing other closed-loop controllers

Solution description

1. Constructing the position control loop

The position control loop is to be constructed in accordance with the circuit diagrams.

2. Control direction and offset

The slide will only move into zero position after the power supply has been switched off, if the control direction is correct.

The mid-position is reached with a reference variable of w = 5V, if the control direction is correct.

In order to set the correct control direction, the closed control loop is divided and the reference variable w = 5V set. This is now the correcting variable y for the valve. The valve opens and the slide advances up to the end stop. The valve is influence by changing the reference variable w between + 10V and - 10V. The valve is closed with w = 0V: The slide remains stationary at the position. Hence, the following applies: + w produces + x, and the control direction is direct. If this is not the case, the polarity of the signal connection of w and y is to be checked and corrected.

If the closed control loop is closed, then the system deviation e = w - x is the control signal for the valve. With a reference variable of w = 0V, the slide moves

- to position x = 0 (end stop retracted) with correct polarity
- to position $x = x_{max}$ (end stop extended) with incorrect polarity

The typical effects of polarity in the closed control loop manifest themselves as follows:

Table

Reverse polarity	*Change in controlled variable x with increasing reference variable w*
Reference variable w	Controlled variable $x = x_{max}$ (end position advanced) From w = - 10V, x slowly decreases until x = 0V is reached From w = 0V, x no longer changes. The behaviour of w and x is the reverse.
Correcting variable y	Controlled variable $x = x_{max}$ (end position advanced) With w = + 10V, the slide moves into the opposite end position. Intermediate positions are not possible.
Feedback r	Controlled variable x = 0 (end position retracted) With w = 0V, the slide moves into the opposite end position. Intermediate positions are not possible.

The following examples with feedback of incorrect polarity serve as an explanation:

- The system deviation remains negative for as long as a negative reference variable w exists. The valve opens to output B. The slide remains retracted.
- If the reference variable w is greater than the controlled variable x, the sign of the system deviation and the control signal y changes. The valve opens towards output A and the slide advances. The feedback of incorrect polarity signals a negative voltage. Because of this, the system deviation becomes increasingly greater, the valve opens further and the slide advances further. The process ends once the other end stop is reached.

If the closed control loop is set correctly, the offset setting shows a drift in the position of the slide.

3. Transition function and empirical parameterisation

The following characteristics of the transition function are obtained with a setpoint step-change of w = 5V ± 3V with different controller gains K_P:

- overshoot amplitude x_m
- settling time T_a
- system deviation e_{stat}
- stability

Value table

K_P	x_m	T_a	e_{stat}	*Stable/unstable*	*Evaluation*
1	0	3s	0	stable	too slow
5	0	0.6s	0	stable	
10	0	0.44s	0	stable	
20	0	0.40s	0	stable	good
30	0	0.38s	0	stable	
40	0	0.38s	0	stable	very good
50	0	0.38s	0	stable	
55	> 0	0.38s	0	stable	minor oscillations, decaying
63	> 0	--	--	unstable	steady-state oscillation limit of stability

The optimum parameterisation obtained is:

$K_{Popt} = 40$.

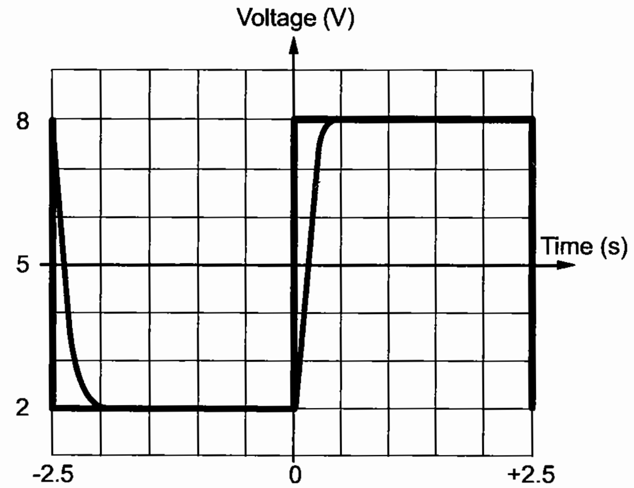
The settling time Ta is not reduced any further with greater gains. However, there are already small oscillations. The limit of stability is reached at:

$K_{Pcrit} = 63$.

The setting of K_{Popt} greatly depends on personal judgement. Depending on the evaluation of the criteria "setting time" and "avoidance of oscillations", different results may be obtained regarding K_{Popt}. The value specified applies to a relatively low settling time and absolutely no oscillations. If minor oscillations are permitted during traversing of the slide, this results in a higher value for K_{Popt}.

The transition function with $K_{Popt} = 40$ is as follows:

Diagram



The limit of stability determined here serves as a comparison variable in the following exercises. The limit of stability may greatly vary from the result given here as an example. It is a characteristic which very clearly reflects, how smooth or erratic the movement of the linear drive is. Influences such as bearing clearance, distorted guide, long tubing sections or restricted cross sections in the hydraulic section become noticeable here.

4. Closed-loop gain

The maximum closed-loop gain V_{0max} and the closed-loop gain V_{0opt} with optimum parameterisation are:

$V_0 = K_P \cdot K_S \cdot K_R$

$K_{Pcrit} = 63$ — Critical gain of the P controller

$K_{Popt} = 40$ — Optimum gain of the P controller

$K_S = 0.05 \frac{(m/s)}{V}$ — System gain

$K_R = 50 \frac{V}{m}$ — Transfer coefficient of feedback

$$V_{0max} = 63 \cdot 0.05 \frac{(m/s)}{V} \cdot 50 \frac{V}{m} = 157.5 \frac{1}{s}$$

$$V_{0opt} = 40 \cdot 0.05 \frac{(m/s)}{V} \cdot 50 \frac{V}{m} = 100 \frac{1}{s}$$

5. Positional dependence of limit of stability

The limit of stability changes depending on the position of the slide. However, the specified measurement procedure shows only one tendency, because it is not very accurate.

Value table

w ± 0,5V	K_{Pcrit}	*Evaluation*
1.5V	84	Maximum
2.5V	81	
3.5V	79	
4.5V	77	
5.5V	71	
6.5V	68	
7.5V	66	
8.5V	65	Minimum

In this case the stability decreases with increasing slide positions. It is, however, possible for the stability to decrease towards the centre and to increase at the edges. Typically. the stability is reduced when the piston rod is extended.

6. Other controllers

PI controller

An I controller is not suitable for a system without compensation as this is confirmed empirically:
Initially, there is no effect.
From K_I = 90 1/s produces a small overshoot.
From K_I = 900 1/s onwards, there is a large overshoot.
The closed control loop remains stable, however the I element does not achieve any improvement.

PD controller

A PD controller presents a useful combination for an uncompensated system.
The closed control loop becomes unstable from K_D = 160ms. Other than that, there is no change. Thus, the PD controller does not offer any improvements compared to the P controller.

PID controller

Although the overshoot amplitude of the I element does become smaller as a result of the D element, it is not reduced to zero. Therefore the PID controller is also unsuitable for this position control loop.

The empirical investigation confirms the recommendation:
A non-compensated system is to be combined with a P controller.

Subject *Closed loop hydraulics*

Title ***Contour milling***

Exercise **Lag error**

1. Constructing and commissioning a position control loop
2. Specifying a constant feed speed as reference variable
3. Calculating and measuring the lag error
4. Determining the positional dependence of the lag error

Solution description

1. Constructing and commissioning a position control loop

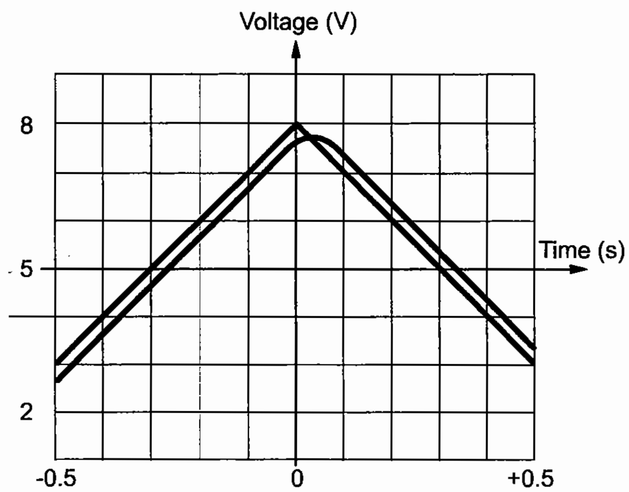
The same position control loop is used here as in exercise 15, where the circuit diagram and commissioning have already been described. Please note the comment regarding the limit of stability.

2. Constant feed speed as reference variable

In this instance, it is particularly important for the time characteristics of the reference variable to be set accurately.

The following diagram ($v = 0.2$ m/s and $K_P = 20$) is obtained as a ramp response to the reference variable:

Diagram



A change in the velocity v and controller gain K_P shows:

Value table

Velocity v	*Controller gain K_P*	*Lag error e_x*
constant	greater	smaller
constant	smaller	greater
greater	constant	greater
smaller	constant	smaller

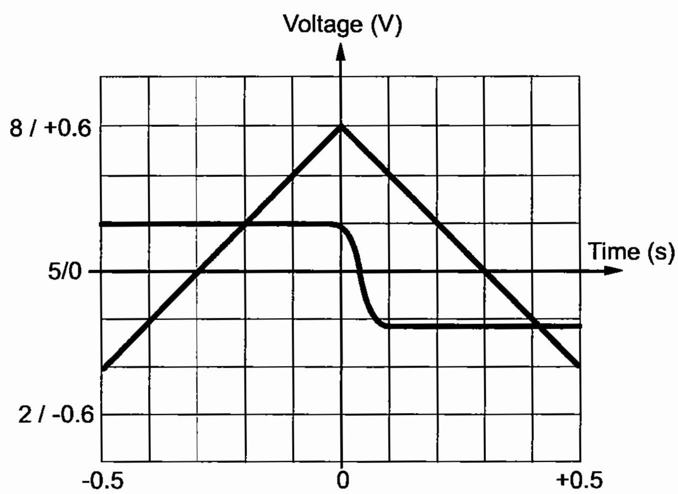
The lag error decreases with increasing controller gain.
If the controller gain is to great, the closed control loop becomes unstable.

The lag error increases with increasing velocity.

If the lag error is recorded directly, a different type of scaling may be selected. The same tendencies will occur as those mentioned above.

The diagram will thus be as follows (for v = 0.2 m/s and K_P = 20):

Diagram



3. Lag error

Calculating the lag error e_{xth} for

- velocity v = 0.2 m/s and
- controller gain K_P = 40:

Closed-loop gain

$$V_0 = K_P \cdot K_S \cdot K_R = 40 \cdot 0.05 \frac{(m/s)}{V} \cdot 50 \frac{V}{m} = 100 \frac{1}{s}$$

Lag error

$$e_{xth} = \frac{v}{V_0} = \frac{0.2 \frac{m}{s}}{100 \frac{1}{s}} = 0.002m = 2mm$$

System deviation

$$e_{th} = e_{xth} \cdot K_R = 0.002m \cdot 50 \frac{V}{m} = 0.1V$$

The following result is produced for different controller gains with v = 0.2 m/s:

Value table

K_P	e	e_{xmess}	e_{xth}	Measuring error $= e_{xth} - e_{xmeas}$
20	0.2V	4mm	4mm	0mm
40	0.1V	2mm	2mm	0mm

Since all other characteristics remain the same and the setpoint velocity remains constant, the lag error in this instance depends only on the controller gain K_P.

The lag error is greater in the return stroke than the forward stroke, since the system gain in the return stroke (K_{Sin}) is smaller than that in the forward stroke (K_{Sout}) (see exercise 14).

4. Positional dependence of lag error

Identical setpoint velocity and identical controller gain produce the same lag error as mentioned under point 3.:

$e_x = 2mm$ and $e = 0.1V$

$v = 0.2$ m/s and $K_P = 40$ produce the following value table:

Value table

Range of operating path	*Reference variable w*	*System deviation e*	*Lag error e_x*
Edge	1.5V ± 0.5V	0.1V	2mm
Centre	5V ± 0.5V	0.1V	2mm
Edge	8V ± 0.5V	0.1V	2mm

The lag error remains constant across the entire travel path.

Subject: *Closed loop hydraulics*

Title: ***Machining centre***

Exercise

Modified controlled system

1. Constructing and commissioning the closed control loop
2. Changing the controlled system by means of load and reservoir
3. Measuring lag error with modified system

Solution description

1. Constructing and commissioning the position control loop

The same position control loop is used here as that used in exercise 15. The circuit diagram and commissioning are described in that exercise.

2. Modifying the controlled system

The following characteristics are obtained in respect of the controlled system:

$K_{Pcrit0} = 66$

$K_{Popt0} = 41$

$T_{a0} = 80ms$

The increasing load m and tubing volume V produce the following changes in the controlled system:

Value table

$\frac{m}{V} =$	$\frac{0kg}{0l}$	$\frac{10kg}{0l}$	$\frac{0kg}{0.1l}$	$\frac{10kg}{0.1l}$	Tendency
K_{Pcrit}	66	39	30	21	decreases
K_{Popt}	41	15	18	5	decreases
T_a with K_{Popt}	80ms	160ms	160ms	1s	increases

3. Measuring lag error with modified system

Value table

$\frac{m}{V}=$	$\frac{0kg}{0l}$	$\frac{10kg}{0l}$	$\frac{0kg}{0.1l}$	$\frac{10kg}{0.1l}$	Tendenz
e	0.1V	0.1V	Unstable	Unstable	constant
e_x	2mm	2mm	--	--	constant

The same lag error is produced as in exercise 16.

Reason: Identical setpoint velocity v as reference variable w and identical controller gain K_P produce the same closed-loop gain
$V_0 = K_P \cdot K_S \cdot K_R$
and hence the same lag error $e_x = v/V_0$.

However, the specified controller gain for the system with load and tubing volume lies above the limit of stablity and this setting is therefore not appropriate in practice.

An optimum controller setting with increasing change of the controlled system results in

- a reduced controlled gain,
- a reduced closed-loop gain,
- a greater lag error.

Correspondingly, the same applies with higher velocities: Higher velocities can be travelled with unmodified systems.

Subject

Closed loop hydraulics

Title

Drilling of bearing surfaces

Exercise

Interferences in the hydraulic position control loop

1. Constructing a hydraulic position control loop
2. Commissioning a closed control loop
3. Investigating interferences in the closed control loop

Solution description

1. Constructing a position control loop

The position control loop is to be constructed in accordance with the circuit diagrams.

2. Commissioning

The position control loop is systematically commissioned by working through all the points in the check list.

Note

Deviations in the numeric values may occur due to the individual configurations possible. The list is to be regarded as a exemplary solution.

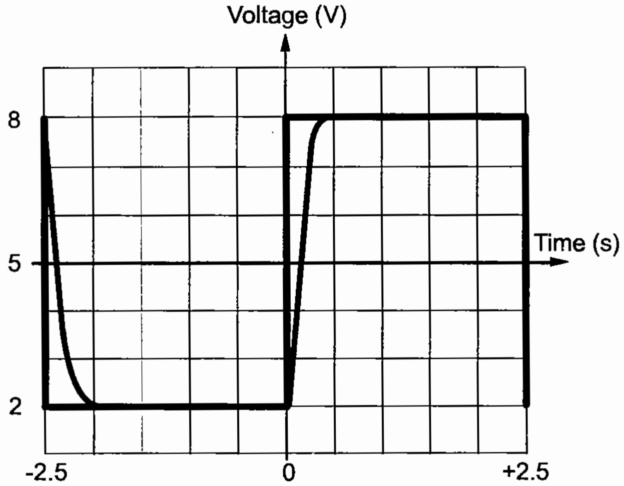
- Safety-related presettings

Reference variable	*Controller gain*	*Other parameters*			
w	K_P	K_I	K_D	Offset	Limiter
5V = 100mm	10	0	0	0	± 10V

- Switch on power supply
- Check control direction correct
- Set offset correct

■ Transition function

Diagram



■ Limit of stability

Reference variable w	*Crit. controller gain K_{Pcrit}*
1.5V ± 0.5V Square-wave	48

■ Quality criteria

Priority	*1*	*2*	*3*	*4*
Characteristic	Stability	Overshoot amplitude x_m	Steady-state system dev. e_{stat}	Settling time T_a
Tolerance	no oscillations during positioning	0	± 0.1mm	< 0.2s

■ Reglerparameter optimieren

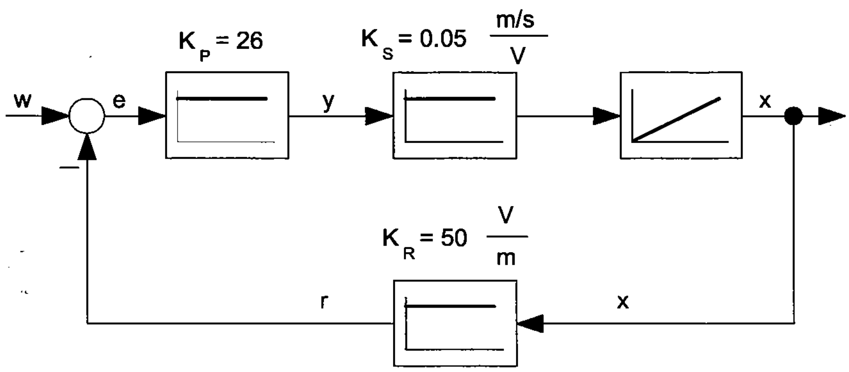
Reference variable w	*Controller gain K_{Popt}*	*Overshoot amplitude x_m*	*Steady-state system deviation e_{stat}*	*Settling time T_a*
1.5V ± 0.5V Square-wave	26	0	0	0.1s

- Lag error and closed-loop gain (for K_{Popt})

Setpoint velocity $v_{setpoint}$	*Reference variable* w	*System deviation* e	*Lag error* e_x	*Closed-loop gain* V_0
0.2m/s = 0.2V / 20ms	1.5V ± 0.5V 5Hz, Ramp	0.15V	3.1mm	65 1/s

- Block diagram with gain factors

Block diagram



3. Interferences in a closed control loop

The characteristics in an interference-free closed control loop are as follows:

$K_{Pcrit0} = 48$

$K_{Popt0} = 26$

$T_{out0} = 0.1s$

$T_{in0} = 0.11$

3.1 Pressure drop

The drop in supply pressure has the following effects:

Value table

Characteristic	*Values*					*Tendency*
p_P	50	40	30	20	10bar	decreases
p_A	26	22	18	12	7bar	decreases
K_{Pcrit}	49	55	72	110	290	increases
T_{out} with K_{Popt0}	0.1	0.11	0.14	0.17	0.27s	increases

An increase in K_P shows:

Value table

Characteristic	*Values*					*Tendency*
p_P	50	40	30	20	10bar	decreases
K_{Popt0}	32	34	44	20	70	increases
T_{out} with K_{Popt}	0.09	0.09	0.12	0.13	0.2s	increases

The interference can no longer be effectively compensated if the supply pressure is below p_P = 40bar (= 30% loss).

3.2 Leakage

The following changes occur with leakage:

Value table

Characteristic	*Values*					*Tendency*
q_L	1/8	1/4	1/8	1/2	Rot.	increasing
K_{Pcrit}	120	160	180	220		increasing
T_{out} with K_{Popt0}	0.07	0.07	0.07	0.07	s	constant
T_{in} with K_{Popt0}	0.14	0.16	0.18	0.22	s	increasing
e_{stat}	0.08	0.12	0.16	0.2	V	increasing

Rectifying faults:

Value table

Characteristic	*Values*					*Tendency*
q_L	1/8	1/4	1/8	1/2	Rot.	increasing
K_{Popt}	39	42	44	50		increasing
T_{out} with K_{Popt}	0.07	0.07	0.07	0.07	s	constant
T_{in} with K_{Popt}	0.12	0.14	0.16	0.21	s	increasing

Only small leakages can be compensated. In principle, there is no point in correcting disturbances by changing the parameters, since it is the components which need to be changed.

In the case of larger leakage, the piston drifts towards the extended position and no longer returns.

Reason: Due to the differential pressure, leakage oil flows from the rod side to the piston side; as a result of this the necessary pressure can no longer be built up on the rod side.

Note

A comparison with exercise 17 shows:

- *Leakage and insufficient supply pressure result in a loss of energy in the closed control loop. The controller gain can be set at a higher level.*
- *Larger tubing will provide additional energy, thereby reducing the stability range.*

Subject: *Closed loop hydraulics*

Title: ***Feed on a shaping machine***

Exercise

Status controller

1. Constructing the measuring circuit
2. Determining the characteristics of the status controller
3. Recording the transition and ramp function

Solution description

1. Measuring circuit

The circuit is to be constructed in accordance with the circuit diagram. Only one voltage supply is required. First of all, it is important to set all parameters to zero.

2. Characteristics of a status controller

The characteristics of the status controller are checked with the multimeter. These fluctuate within production tolerances. However, by and large, they should lie within the range of values specified in the data sheet.

3. Transition and ramp function

First of all, the status controller is to be put in the initial position.

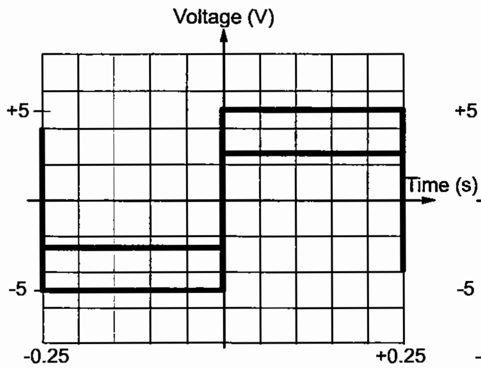
During the measurements, ensure that those parameters not required in the control loop are always at zero. Only in this way is it possible to test a loop specifically.

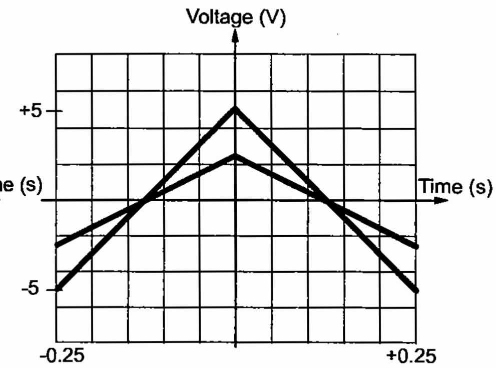
With differentiating controller loops, the sign reversal can be seen at the summation point. An additional measurement may be carried out here before the summation point. The result of the velocity loop then corresponds to the differentiator in exercise 8.

3.1 Position controller

The following transition and ramp functions are obtained in respect of the position controller:

Diagram



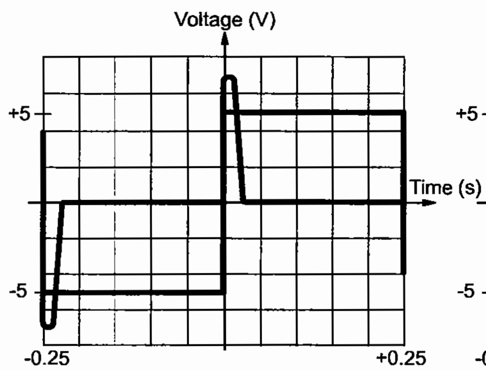


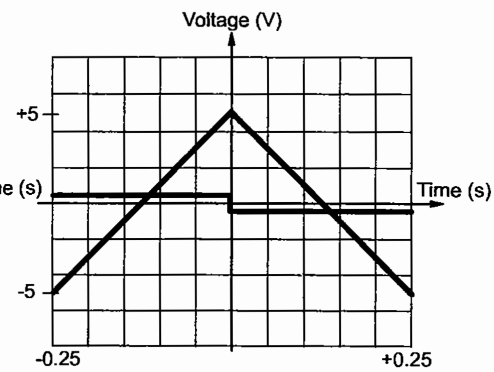
The position controller corresponds to a P element (see exercise 5).

3.2 Velocity controller

The following transition and ramp functions are obtained in respect of the velocity controller:

Diagram



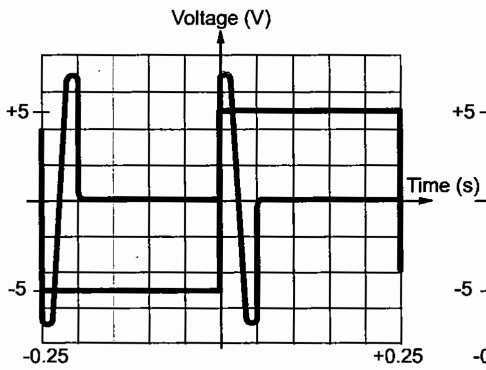


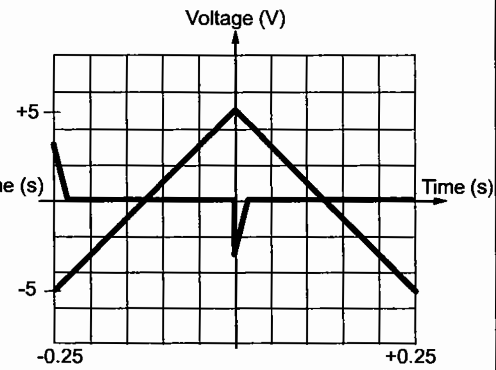
The velocity controller corresponds to a D element with sign reversal (see exercise 8).

3.3 Acceleration controller

The following transition and ramp functions are obtained in respect of the acceleration controller:

Diagram





The acceleration controller corresponds to the serial connection of two D elements. This can be detected on the second spike of the step response and on the single spike of the ramp response when compared with the velocity controller.

Closed loop hydraulics — *Subject*

Paper feed of a printing machine — *Title*

Position control loop with status controller — *Exercise*

1. Constructing a position control loop with status controller
2. Establishing the stability range
3. Setting the parameters of a status controller
4. Measuring and calculating lag errors
5. Adapting the status controller to a modified controlled system

Solution description

1. Constructing the position control loop

The position control loop is to be constructed in accordance with the circuit diagrams.

2. Establishing the stability range

The following steps must be carried out for commissioning:

- Safety-related presettings

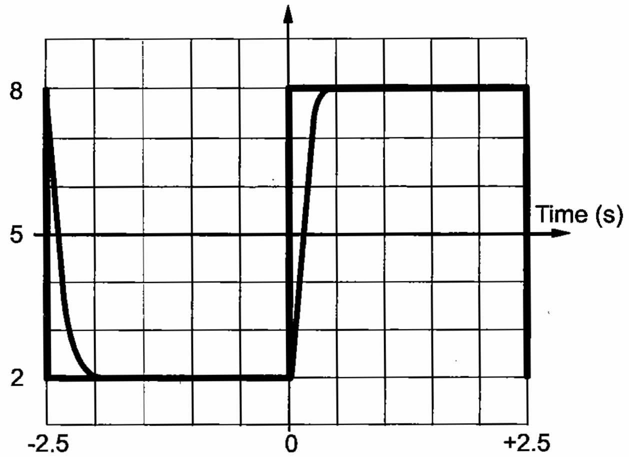
Value table

Reference variable	*Controller parameters*				*Other*	
w	P	Kx	Kẋ	Kẍ	Offset	Limiter
5V constant	1	1	0	0	0	± 10V

- Check the control direction — correct, if the slide
  – advances the in positive direction
  – with increasing setpoint value.
- Set the offset — correctly, if the slide
  – remains at the position
  – with a constant setpoint value.
- Transition function

  The transition function shows the same characteristics as that of the P controller. (See solution for exercise 15 or 18)

Diagram



- Limit of stability

  $K_{Pcrit} = Kx \cdot P = 6.7 \cdot 10 = 67$

  This also corresponds to the result in exercises 15 and 17. (Deviations may occur as a result of tolerances in the circuit components.)

3. Setting the parameters of the status controller

The following effects can be seen during the parameterisation of the status controller:

- K_P can be left at K_{Pcrit}. Steady-state oscillations occur.
- The oscillations are reduced to a large overshoot through $K\ddot{x}$.
- The overshoot is attenuated through $K\dot{x}$.

Should this procedure fail to fully meet the quality criteria, then it is possible to start again with a slightly reduced K_P.

Values set too high for $K\ddot{x}$ or $K\dot{x}$ also lead to oscillations.

Optimum controller parameters obtained are:

Value table

Reference variable	*optimum controller parameters*				*Settling time*
	P	Kx	$K\dot{x}$	$K\ddot{x}$	T_a
5V ± 3V Square-wave	10	5.6	0ms	0.7ms²	60ms

Overall it can be seen that the setting time is slightly lower than that for a pure P controller (80ms). This can be explained by higher proportional gain: $K_P = 56$ instead of $K_P = 41$.

Again, the same applies in that the limit of stability K_{Pcrit} can only be used as a comparison variable. The absolute value may clearly deviate from the result given in this instance. What is important with the comparison is that the same components (linear unit, tubing sections, valves etc.) are being used as in the previous exercises.

Note

In the case of an erratic linear unit (higher K_{Pcrit}), the advantage of a status controller can be less clearly seen, since the differential elements can easily lead to oscillations. Here the advantage of a status controller only becomes apparent in the following test using additional load.

4. Measuring and calculating lag error

At a velocity of 0.2 m/s, a system deviation is measured of

$$e = 0.07\text{V}$$

Dies ist ein Schleppfehler von

$$e_x = \frac{e}{K_R} = \frac{0.07\text{V}}{50\frac{\text{V}}{\text{m}}} = 1.4\text{mm}$$

As a mathematical check, the closed-loop gain V_0 is to be calculated first of all:

$$V_0 = Kx \cdot P \cdot K_S \cdot K_R$$

$$V_0 = 5.6 \cdot 10 \cdot 0.05\frac{\text{s}}{\text{V}} \cdot 50\frac{\text{V}}{\text{m}} = 140\frac{1}{\text{s}}$$

The lag error is then:

$$e_x = v \cdot \left(\frac{1}{V_0} + \frac{K\dot{x}}{Kx}\right)$$

$$e_x = 0.2\frac{\text{m}}{\text{s}} \cdot \left(\frac{1}{140\frac{1}{\text{s}}} + \frac{0\text{s}}{5.6}\right) = 0.00143\text{m} = 1.4\text{mm}$$

The lag error is greater on the P controller than on the status controller:

- The solution in exercise 16 produced a lag error of 2mm.

Reason: A higher closed-loop gain V_0 can be set with the status controller, whereby the lag error can be reduced to such an extent that a minimal increase through the $K\dot{x}$-element still does not produce a larger lag error than the P controller.

5. Status controller with modified controlled system

The following characteristics of the controlled system are obtained as a result of load m and tubing volume V:

Value table

$\frac{m}{V} =$	$\frac{0kg}{0l}$	$\frac{10kg}{0l}$	$\frac{0kg}{0.1l}$	$\frac{10kg}{0.1l}$	*Tendency*
P	10	10	10	10	constant
Kx_{crit}	6.7	4.5	3.2	2.1	decreases
Kx_{opt}	5.6	3.9	3.2	2.1	decreases
$K\dot{x}_{opt}$	0	0.3	1.8	1.6ms	decreases
$K\ddot{x}_{opt}$	0.7	1.9	2.8	5.1ms²	increases
T_a	60	80	80	100ms	increases

Looking at the setting time, this illustrates the advantage of the status controller: the settling time is considerably less than with a pure P controller.

Moreover, it can be seen that the influence of the load can be very effectively compensated, i.e. in particular with $K\dot{x}$, which influences the acceleration of the load.

The tubing volume cannot be compensated quite as effectively. However, thanks to the very high proportional gain, this nevertheless results in a shorter settling time than with a P controller.

Both system modifications, load and tubing volume, overlap in a similar way to the P controller.

Subject: *Closed loop hydraulics*

Title: ***Horizontal grinding machine***

Exercise

Interferences in the position control loop

1. Constructing and commissioning the position control loop
2. Investigating interferences in the hydraulic circuit
3. Constructing a position control loop with braking load
4. Examining the interference behaviour with braking load

Solution description

1. Position control loop

The position control loop is to be constructed in accordance with the circuit diagrams and commissioned with the help of the checklist.

The safety-related presettings are:

Value table

Reference variable	*Controller parameters*				*Other parameters*	
w	P	K_x	$K_{\dot{x}}$	$K_{\ddot{x}}$	Offset	Limiter
5V = 100mm	10	1	0	0	0	± 10V

Die Reglerparameter lauten:

Value table

Reference variable	*Controller parameters*				
w	K_{Pcrit}	K_{Popt}	P	$K_{\dot{x}}$	$K_{\ddot{x}}$
1,5V ± 0,5V Square-wave	45	4.0	10	0.3ms	0.8ms²

Note

Deviations from the specified numeric values may occur due to the individual configurations possible. The sample solution is therefore purely intended as an example. K_{Pcrit} is merely intended to serve as comparison variable for the results in the other exercises.

2. Interferences in the hydraulic closed control loop

The characteristics in the interference-free circuit are:

$K_{P\wedge crit0}$ = 45 K_{Popt0} = 40

$K\dot{x}_0$ = 0.3ms $K\ddot{x}_0$ = 0.8ms²

T_{out0} = 70ms T_{in0} = 85ms

2.1 Pressure drop

The following value table is obtained with constant controller gain K_{Popt}:

Value table

Characteristic	*Values*					*Tendency*
p_P	50	40	30	20	10bar	decreasing
K_{Pcrit}	48	52	66	100	270	increasing
T_{out} with K_{Popt0}	70	90	110	160	240ms	increasing

Optimisation of the controller parameters results in the following value table:

Value table

Characteristic	*Values*					*Tendency*
p_P	50	40	30	20	10bar	decreasing
K_{Popt}	46	52	65	*96*	*160*	increasing
$K\dot{x}_{opt}$	0	0.1	0.4	*0.3*	*0.4ms*	increasing
$K\ddot{x}_{opt}$	0.7	1.3	2.0	*0.3*	*0.5ms²*	increasing
T_{outopt}	70	80	80	100	180ms	increasing

At $p_P < 30$bar, compensation of the interference via the controller is no longer useful.

In comparison with the P controller, interference can be slightly better compensated via the status controller. Hence, even with pressure drop, the settling time with the status controller is slightly less than with the P controller:

- between 70ms and 180ms with the status controller
- between 90ms and 200ms with the P controller

2.2 Leakage

The following parameters are obtained with leakage:

Value table

Characteristic	*Values*					*Tendency*
q_L	1/8	1/4	3/8	1/2	Rot.	increasing
K_{Pcrit}	140	170	180	210		increasing
T_{out} with K_{Popt0}	70	70	70	70	ms	constant
T_{in} with K_{Popt0}	120	150	180	220	ms	increasing
e_{stat}	0.08	0.10	0.12	0.12	V	increasing

The leakage can be compensated as follows:

Value table

Characteristic	*Values*					*Tendency*
q_L	1/8	1/4	3/8	1/2	Rot.	increasing
K_{Pcrit}	80	110	130	140		increasing
$K\dot{x}_{opt}$	0.5	0.9	1.0	1.6	ms	increasing
$K\ddot{x}_{opt}$	0.2	0.3	0.3	1.3	ms^2	increasing
T_{outopt}	70	70	70	70	ms	constant
T_{inopt}	120	140	160	200	ms	increasing
e_{stat}	0	0	0	0	V	Compensated through offset

Interference as a result of leakage is compensated in the same way as with the P controller.

3. Position control loop with braking load

The position control loop is to be constructed in accordance with the circuit diagrams and commissioned with the help of the checklist.

4. Interference behaviour with braking load

4.1 Transition function

A reference variable of w = 2V and a controller gain K_P = 40, produces the following characteristics with a different load:

Value table

Characteristic	*Values*							*Tendency*
Last schalten	zu	ab	zu	ab	zu	ab		
p_L	20	20	30	30	40	40	bar	increasing
x	10	10	35	25	40	30	mV	increasing
x_m	0.2	0.2	0.7	0.5	0.8	0.6	mm	increasing
T_a	0.15	0.4	0.16	0.4	0.3	0.8	sec	increasing

A reference variable of w = 2V and load pressure p_L = 40bar produces the following characteristics with different controller gains:

Value table

Characteristic	*Values*					*Tendency*
K_P	20	40	60	80		increasing
x	45	35	25	20	mV	decreasing
x_m	0.9	0.7	0.5	0.4	mm	decreasing
T_a	0.3	0.16	0.1	0.06	sec	decreasing
e_{stat}	0	0	0	0		constant

A steady-state system deviation estat is only clearly smaller than K_{Popt} if the load is removed.

4.2 Lag error

A setpoint velocity of $v_{setpoint}$ = 0.2 m/s and a controller gain of K_P = 40 result in the following lag errors with different loads:

Value table

Characteristic	*Values*					*Tendency*
p_L	0	10	20	30	bar	increasing
e	0.1	0.12	0.16	0.2	V	increasing
e_x	2.0	2.4	3.2	4.0	mm	increasing

With a constant load of e.g. p_L = 30bar, the lag error can be minimised through optimisation of the controller parameters:

Value table

Characteristic	*Values*					*Tendency*
K_P	20	40	60	80		increasing
e	0.4	0.2	0.15	0.1	V	decreasing
e_x	8	4	3	2	mm	decreasing

A load of p_L = 30bar and a controller gain of K_P = 40 produce the following lag errors with different velocities:

Value table

Characteristic	*Values*			*Tendency*
v_{set}	0.1	0.2	m/s	increasing
w	0.1/20	0.2/20	V/ms	increasing
e	0.1	0.2	V	increasing
e_x	2	4	mm	increasing

Part D – Appendix

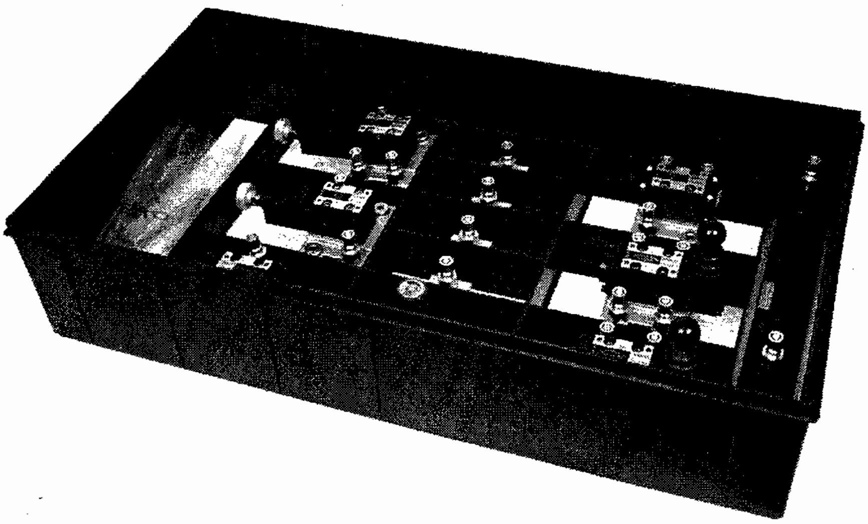
Data sheets

Operating notes

The following notes must be observed in order to ensure trouble-free operation.

- Observe all regulations in force regarding accident prevention throughout the operating procedures.
- All valves, devices and connecting hoses are fitted with quick connection couplings. Maximum pressure may not exceed 120bar (12MPa). The maximum working pressure is 60bar (6MPa).
- Please check that all return lines are connected and the connecting hoses are securely attached prior to commissioning the hydraulic circuit.
- The pressure relief valve incorporated into the power pack, Pt. No. 152962, is limited to approx. 60bar (6MPa).
- Prior to disassembly, please make sure that the assembled circuit is unpressurised. If connections are released under pressure, pressure is fed into the component via the non-return valve of the self-sealing coupling. This pressure can be reduced by means of the pressure relief valve, Pt. No. 152971.

Storage tray



Equipment set TP511 in storage tray

All the components of the equipment set for technology package TP511 are stored in a storage tray.

This storage tray serves both as a means of packaging for despatch purposes and as a drawer insert for the Didactic furniture rage.

Mounting technology

The components of the equipment set are mounted on the Festo Didactic profile plate. The profile plate has 14 parallel T-grooves equally spaced 50 mm apart.

There are four alternatives for mounting the components on the profile plate:

Alternative A Detent system (also referred to as snap-lock system),
without additional facilities,
clamping mechanism with lever and spring,
which can be moved in the direction of the groove,
for light, non load-bearing components

Alternative B: Rotational system, without additional facilities,
triple grip nut with locking disc and T-head bolt,
vertical or horizontal alignment,
for medium-weight load-bearing components

Alternative C: Screw-in system, with additional facilities,
cheese head screw with T-head nut,
vertical and horizontal alignment,
for heavy load-bearing components or
components which are rarely removed from the profile plate

Alternative D: Plug-in system, with adapter
Components on plug-in assembly board with locating pins,
movable in the direction of the groove,
for light, non load-bearing components

The signal input, indicator and relay plates can also be mounted to the holding frame for ER units.

With **alternative A**, a slide engages in the T-groove of the profile plate. This slide is pre-tensioned by a spring. By pressing the blue lever, the slide is retracted and the component can either be removed from or attached to the profile plate. The components are aligned with the groove and can be moved in the direction of the groove.

With **alternative B**, the component is secured to the profile plate by means of a T-head bolt and a blue triple grip nut. A locking disc is used for positional attachment, which can be attached in all four 90° directions. In this way, the components can be secured on the profile plate either parallel or across the groove.

When the locking disc has been adjusted to the required setting, the component is positioned on the profile plate. By turning the triple grip nut clockwise, the T-head nut is rotated by 90° in the T-groove by means of thread friction. Further turning of the triple grip nut clamps the component against the profile plate.

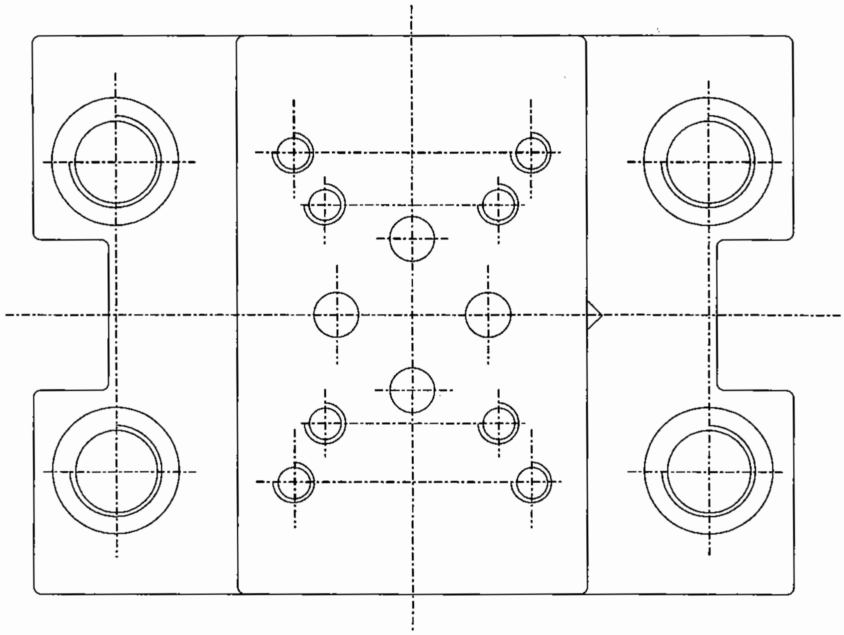
Alternative C is used for heavy components or components which are screwed on to the profile plate only once or seldom removed. Such components are secured by means of cheese head screws with hexagon socket and T-head nuts.

With **alternative D**, the tried and tested ER-units for plug-in assembly boards which have locating pins on a 50 mm grid, can be attached to the profile plate by means of adapters. One black, plastic adapter is required for each locating pin. The adapters are inserted in the T-groove, positioned at intervals of 50 mm and secured by a rotation of 90°. The locating pins of the ER-unit are inserted in the adapter holes.

Sub-base

This sub-base for valves with nominal size 4 (NG4) has a hole pattern in accordance with ISO 228, size 2. Because of the similarity of the port pattern with size 03, a slight dimensional change and additional mounting holes have been introduced to facilitate the optional use of valves of nominal size 6 (NG6).

Sub-base

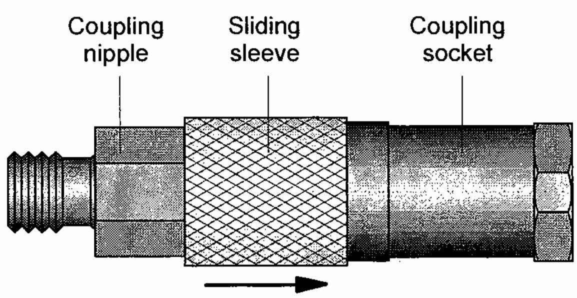


Coupling system

All hydraulic components are equipped with self-closing couplings. These have been designed in particular enabling circuits to be assembled and dismantled with nearly no oil leakage, while at the same time allowing connections to be made with very little effort.

A coupling consists of a nipple and socket. Connections are made by pushing a socket onto a nipple. The sliding sleeve then engages to provide a secure connection. This sleeve is pushed back to detach a connection. A spring then pushes the socket away from the nipple.

Coupling nipples can be screwed into the sub-bases. All valves mounted on sub-bases can thus be connected up via nipples. All other components should preferably also be equipped with nipples, and hoses lines should therefore be fitted with two sockets. Components such as shut-off valves or non-return valves which are connected on one side to hoses and on the other to components are equipped with coupling nipples and coupling sockets respectively.



Self-closing coupling

Since the couplings close to create a leakproof seal, it may occur that pressure is trapped inside a component. If this happens, the force required to operate the coupling will increase to such an extent that the component cannot subsequently be coupled up again. The remedy in cases of this kind is to use a pressure relieving device. This is of similar design to a coupling socket but incorporates an adjustment spindle. The spindle should initially be rotated fully out and the device then pushed onto a nipple until the sliding sleeve engages. The spindle can be rotated inward to push back the sealing pin of the nipple and open the seal. The pressure behind the nipple will then be relieved; a drop of oil may escape during this operation. The pressure relieving device can be removed again by pushing back the sliding sleeve.

Guidelines and standards

DIN ISO1219	Fluid power systems and components: Symbols
DIN 1319 Part 1	Basic terminology of measuring technology: Measuring, counting, testing
DIN 1319 Part 2	Basic terminology of measuring technology: Use of measuring equipment
DIN 19221	Measuring, controlling, regulating: Symbols used in formulae in control technology
DIN 19222	Measuring, controlling, regulating: Instrumentation and Control: Terminology
DIN 19225	Measuring, controlling, regulating: Designation and classification of controllers
DIN 19226	Closed-loop and open-loop control technology, Terminology and designations
DIN 19227	Measuring, controlling, regulating; Graphic symbols and code letters for process instrumentation and control
DIN 19231	Measuring, controlling, regulating: Pressure range for pneumatic signal transmission
DIN 19233	Automatic machines, automation: Terminology
DIN 19236	Measuring, controlling, regulating: Optimisation, terminology
DIN 19237	Measuring, controlling, regulating: Control technology: terminology
DIN 19239	Measuring, controlling, regulating: Open-loop control technology; programmable logic controllers; programming
DIN 24311	Hydraulic dynamic valves
DIN 40719 Part 60	Circuit documentation; Production of function charts for measuring, controlling, regulating
DIN 44300	Data processing: Terminology
DIN 66025	Industrial automation: Program structure for alphanumerically- controlled machines
DIN 66201 Part 1	Process computer system: Terminology
ZH 1/74	Safety rules for hydraulic hoses lines
DIN 66217	Coordinate axes and directions of motion for numerically-controlled machines
DIN 66257	Numerically-controlled machines: Terminology
IEC 27-2A	Letter symbols to be used in electrical technology. Part 2: Telecommunications and electronics. First supplement
IEC 50 (351)	International Electrotechnical Vocabulary Automatic control
DIN IEC 381 Part 1	Analogue signals for closed-loop and open-loop control systems; Analogue DC signals; identical to IEC 381-1, 1982 edition

Guidelines and standards (continued)

ISO 3511-3	1984 Process measurement control functions and instrumentations –Symbolic representation –
ISO 3511-3 Part 3:	Detailed symbols for instrument interconnection Diagramms
VDI/VDE 3844	Drives for actuation of final control elements Characteristic data for pneumatic and electro-hydraulic drives
VDI/VDE 3685	Adaptive controllers: Terminology, properties, notes and examples
VDI 2860	Assembly

List of literature

Europa Lehrmittel	Steuern und Regeln im Maschinenbau Europa Lehrmittel Verlag
Europa Lehrmittel	Fachkunde Elektronik Europa Lehrmittel Verlag
Karg, Eduad	Regelungstechnik Vogel Buchverlag Würzburg
Merz, Ludwig	Grundkurs der Regelungstechnik Oldenbourg
Schmäing, Eduard	Regelungstechnik in Bildern Vogel Verlag
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Zerbe, Günther	Regelungstechnik Formeln, Beispiele, Lösungswege, Tabellen Te-Ma-Verlag
Weck, Manfred	Werkzeugmaschinen Band 3 Automatisierung und Steuerungstechnik VDI Verlag
A. Feuser, M. Piechnick	Antriebsdimensionierung unter Berücksichtigung von Zylinderflächen- und Steuerkantenverhältnissen O+P 37 (1993) Nr.6

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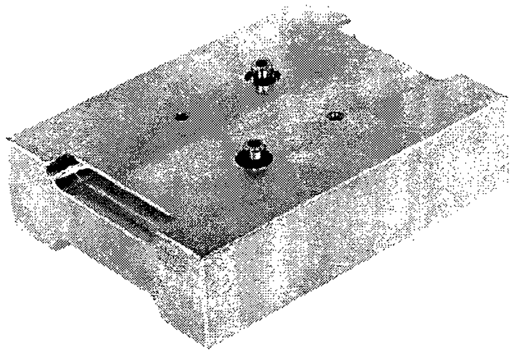
034065

Loading weight

m



Design

Metal weight with two cheese-head screws and four recessed grips to facilitate handling.

Function

The weight is used for load experiments with linear actuators.

Mounting

To secure the weight, the following variants are possible:

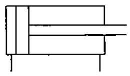
1. The weight is mounted directly onto the slide of the linear drives of Festo Didactic. To secure, both of the enclosed socket head screws are inserted into the drop bores of the weight and tightened together with the slide.
2. To compensate for different hole patterns, Festo Didactic supplies an intermediate plate (Order no. 019500). To secure, both of the enclosed socket head screws are inserted into the drop bores of the weight and tightened together with the slide

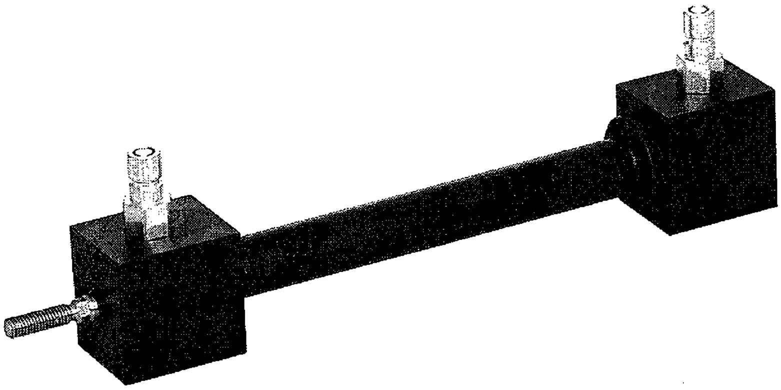
Several weights can be stacked together by laying one upside-down on top of the other and securing them together using the cheese-head bolts.

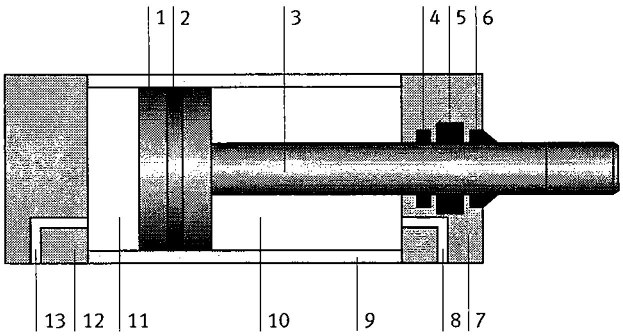
⚠ We recommend that you wear safety shoes whilst attaching the weight, as it may cause serious injury if dropped onto your feet.

Technical data

Mechanical	
Mass	5 kg
Dimensions	Length 150 mm Width 110 mm Height 40 mm
Mounting method	2 Cheese-head screws M5







Construction	The cylinder consists of:	piston (1), piston seal and piston guide (2), piston rod (3), piston rod bearing (4), piston rod seal (5), scrape ring (6), cylinder cap (7), connections (8, 13), cylinder barrel (9), piston rod area (10), piston area (11), cylinder base (12)

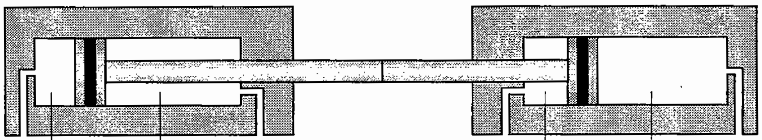
Function

The piston area (11) is put under pressure via connection (13). A force is produced from the pressure and the piston surface which leads to movement of the piston. At the same time oil is released from the piston rod area which drains off at the connection (8). To retract the piston again, pressure is admitted to the piston rod area (10) at connection (8). The oil discharged then drains off at connection (13). The piston seal (2) seals both chambers against each other and the piston guide supports the piston. The piston rod seal (5) seals the outward piston rod area (10). The scrape ring (6) protects the piston rod seal (5) from soiling. The piston rod bearing (4) guides and supports the piston rod.

Load cylinder

If the cylinder is used as a load cylinder for the linear unit (Order No. 167089), two cylinders will be placed in opposing positions.

Different options are available to load working cylinders:
1. The oil displaced in the load cylinder is restricted (passive load)
2. The oil displaced in the load cylinder is directed to the tank via a pressure relief valve (passive load)
3. A chamber is connected to a hydraulic accumulator (increasing passive load)
4. A chamber of the load cylinder is pressurised (active load)



Further circuitry options:
1. The two full piston surfaces or the two annular surfaces serve as working cylinders (tandem cylinder).
2. The "load cylinder" is connected in addition to support the working cylinder, whereby the full piston surface of the working cylinder operates jointly with the annular surface of the load cylinders at pressures p1.1 and p2.1 respectively, against the annular surface of the working cylinder and the full piston surface of the load cylinder.

Note

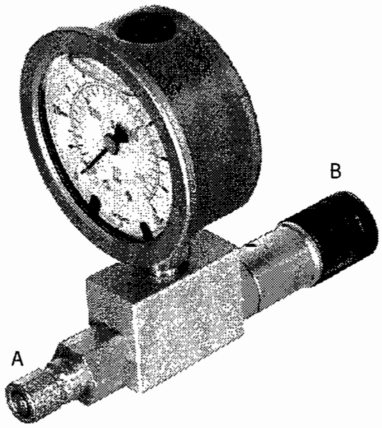
Assembly of cylinder on linear unit (Order No. 167089):
- The cylinder housing is screwed to the yoke of the linear unit via the front surface.
- The piston rod is screwed into the slide and locked with a nut.

Technical data

Hydraulic	
Medium	Mineral oil, recommended viscosity 22 cSt (mm^2/s)
Piston diameter	16 mm
Piston rod diameter	10 mm, mit M 8
Stroke	200 mm
Operating pressure p	6 MPa (60 bar)
Max. permissible high pressure p_{max}	12 MPa (120 bar)
Connections	For two coupling socket

152841

Pressure gauge



Design

Pressure gauge, branch tee, 2 connections (A = nipple, B = socket)

Function

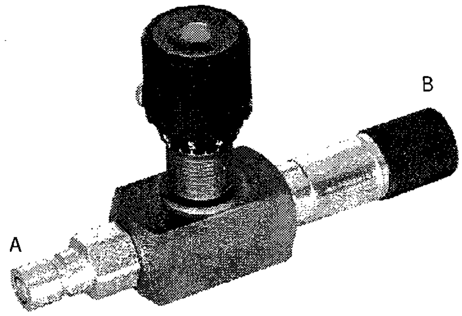
The branch tee can be interposed at any desired point or connected close to a measuring point to allow pressure measurement. The pressure causes a spiral Bourdon tube to open out. This motion is applied to the pointer of the pressure gauge. The position of the pointer is therefore proportional to the pressure applied.

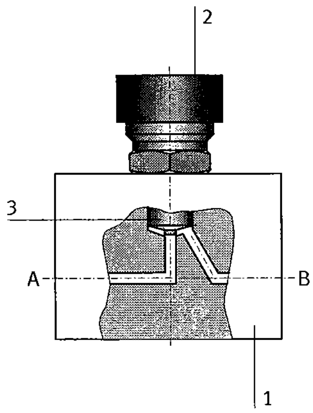
Note

The pressure gauge has a glycerine filled to protect it against impacts, condensation and the entry of water during cleaning.

Technical data

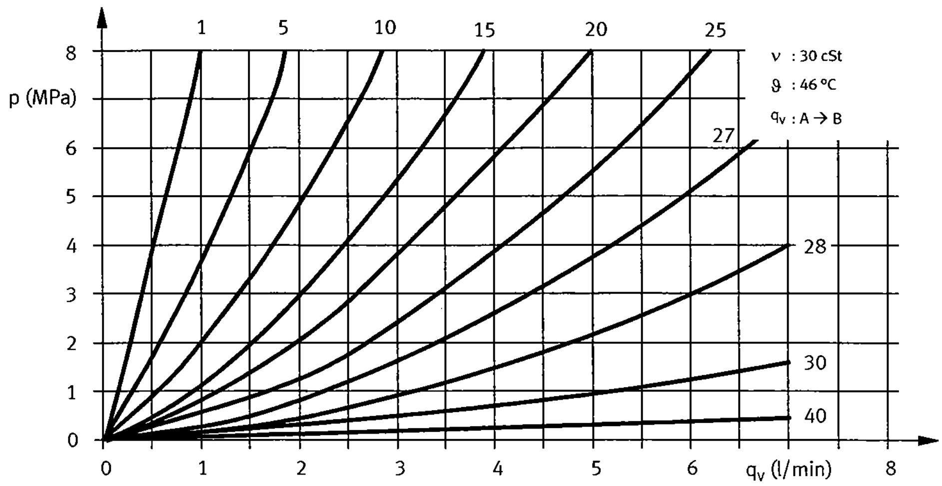
Hydraulic	
Medium	Mineral oil, recommended viscosity 22 cSt (mm^2/s)
Accuracy	1,6 % of full-scale value
Indicating range	10 MPa (100 bar)
Operating pressure	Static: 3/4 of full-scale value Dynamic: 2/3 of full-scale value
Damping fluid	Glycerine
Actuation	Hydraulic via a spiral Bourdon tube
Connections	For coupling nipple/socket





Design — Valve housing (1), rotary knob (2), throttle point (3), nipple (A), socket (B).

Function — In both directions, from A to B and B to A, hydraulic fluid flows through the throttle point (3), the size of which can be adjusted by means of the rotary knob.



Pressure-drop/flow-rate characteristic for various rotary-knob settings (division lines)

152842

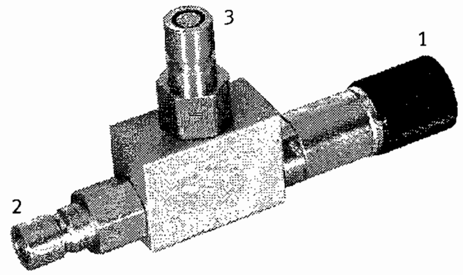
Flow control valve

Technical data

Hydraulic	
Medium	Mineral oil, recommended viscosity 22 cSt (mm^2/s)
Operating pressure	6 MPa (60 bar)
Max. permissible pressure p_{max}	12 MPa (120 bar)
Nominal flow rate	9 l/min
Actuation	Manual
Connections	For coupling nipple/socket

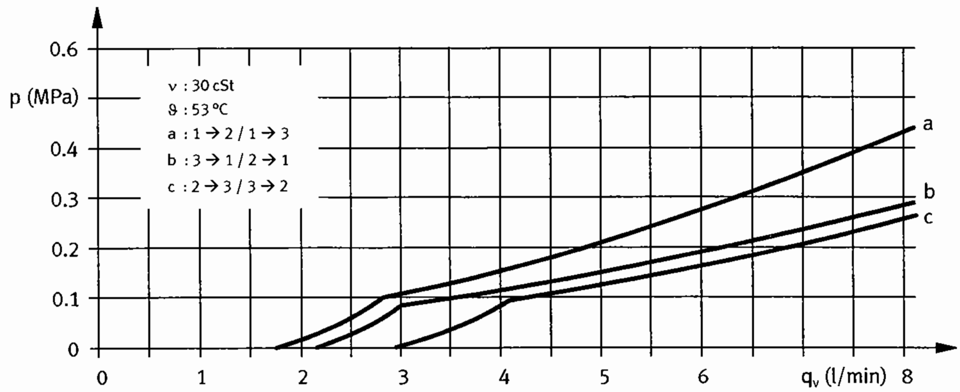
152847

Branch tee



Design — Branch tee with 3 connections (1 = socket, 2 and 3 = nipples).

Function — This component can be fitted at any desired point to create a branch.

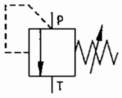


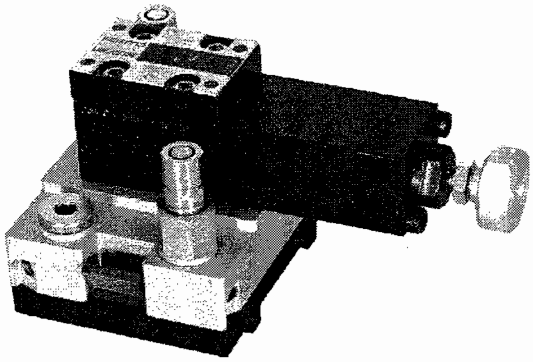
Pressure-drop/flow-rate characteristic

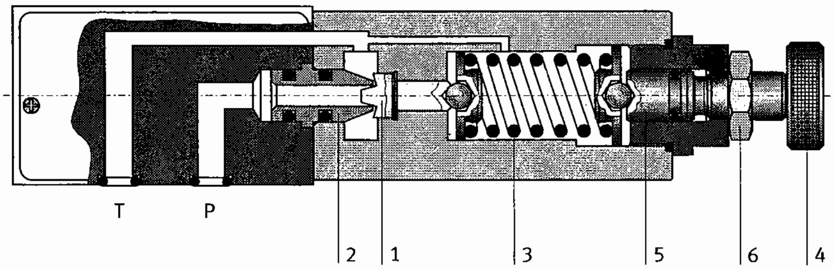
Technical data

Hydraulic	
Medium	Mineral oil, recommended viscosity 22 cSt (mm^2/s)
Operating pressure p	6 MPa (60 bar)
Max. permissible pressure p_{max}	12 MPa (120 bar)
Connections	For coupling nipple/socket

Pressure relief valve, Pressure sequence valve







Design

The pressure relief valve is mounted on a function plate equipped with two coupling nipples. The component is fitted to the grid system of the profile plate by means of the two blue levers (mounting variant "A").

The valve consists of: Sealing cone (1), valve seat (2), spring (3), rotary knob (4), threaded spindle (5), lock nut (6).

Function

The valve is closed in the normal position. When the opening pressure is reached at port P, the sealing cone (1) lifts away from the valve seat (2) against the force of the spring (3) and hydraulic fluid is discharged via the return line port T. When the pressure falls below the preset value, the valve closes again.

The valve is used as a pressure relief valve with port T connected to the tank and as a pressure sequence valve with port T connected to a further power component (such as a cylinder).

Note

The valve ports are identified by letters.

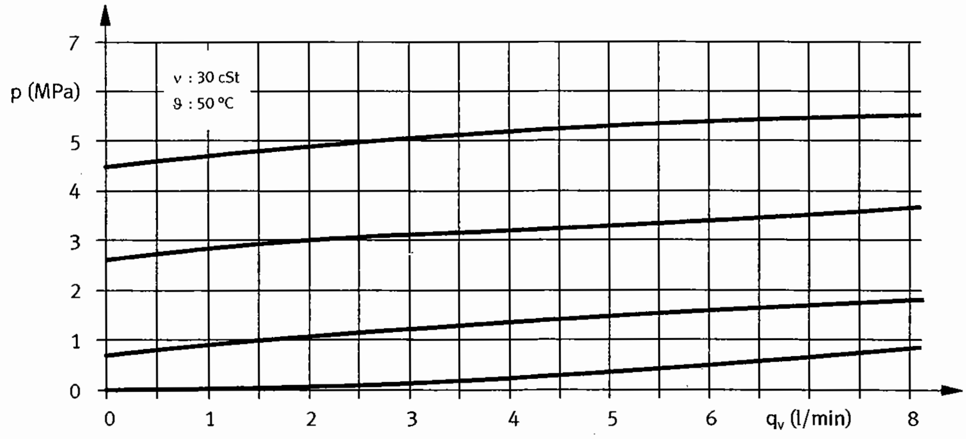
P Supply port

T Return-line port (tank connection)

The valve has an internal leakage-oil line to the tank.

152848

Pressure relief valve, Pressure sequence valve



Pressure/flow-rate characteristic for various rotary-knob settings

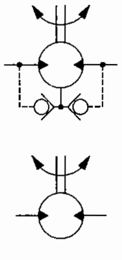
Technical data

Hydraulic	
Medium	Mineral oil, recommended viscosity 22 cSt (mm^2/s)
Operating pressure p	6 MPa (60 bar)
Max. permissible pressure p_{max}	12 MPa (120 bar)
Adjustment	Manual
Actuation	Hydraulic
Connections	For 2 coupling sockets

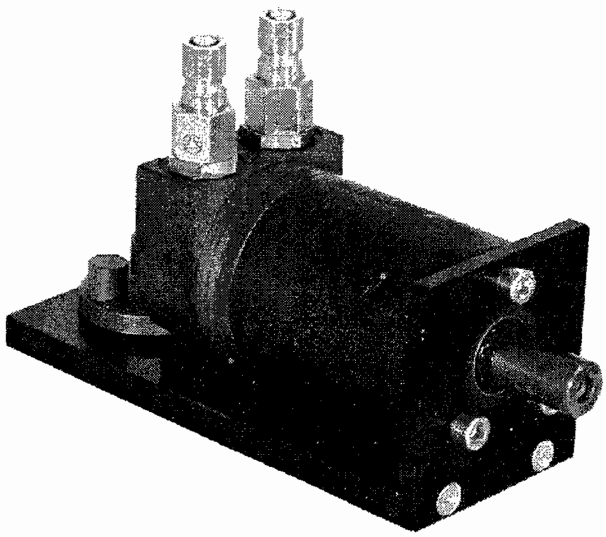
Subject to change

152858

Hydraulic motor

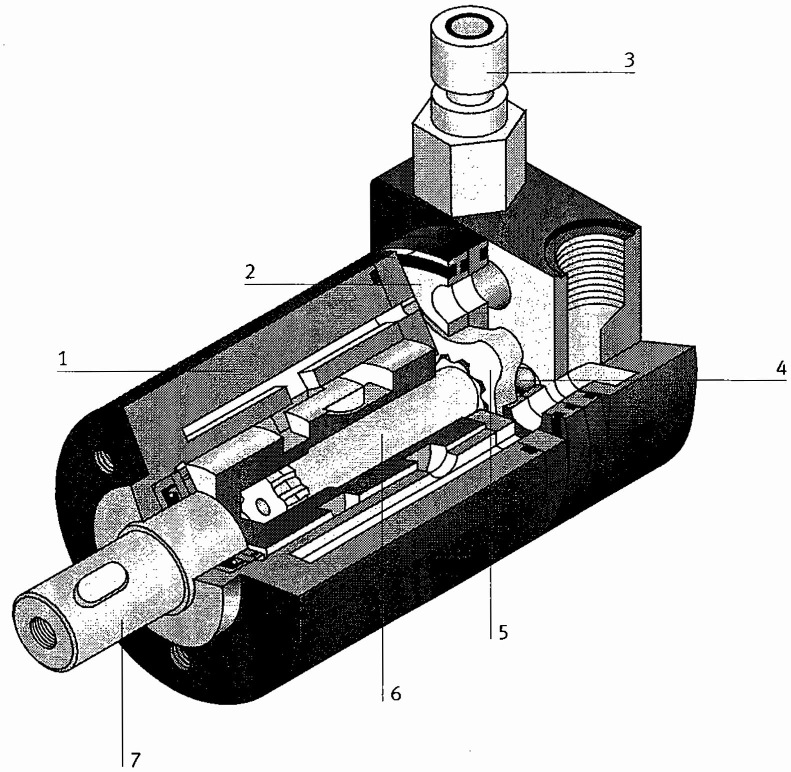


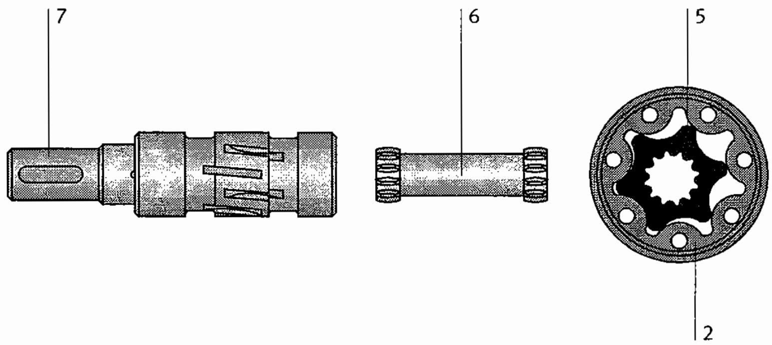
simplified symbol



Design

This hydraulic motor is mounted on a mounting plate. The component is fitted to the profile plate using the rotary system by means of two blue grip nuts (mounting variant “B”).





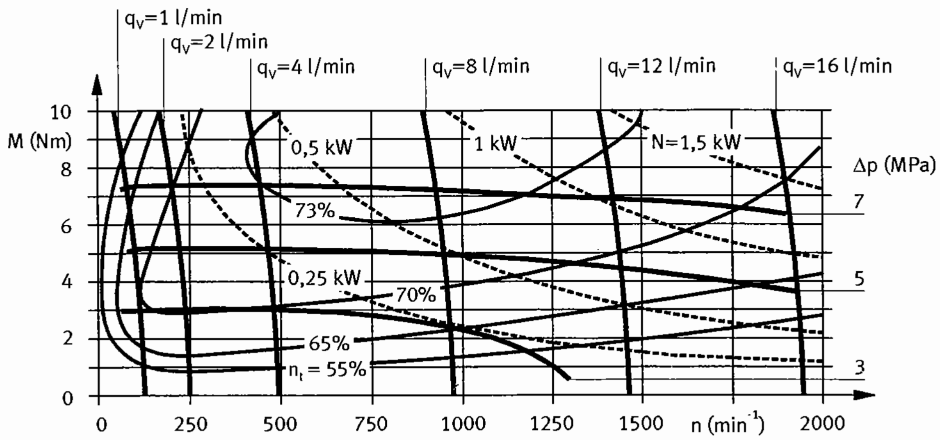
The motor consists of: Housing with control ducts (1), fixed, internal gear (2), connections (3), shuttle valve (4), external gear (5), cardan shaft (6), shaft with collector part (7).

Function

The direction of rotation changes with the flow direction. The hydraulic fluid is supplied at one of the connections. The external gear (5) is hereby placed into rotation and drives the shaft (7) via the cardan shaft (6). The alternate supply and discharge of the volumetric flow rate is controlled via the collector and the control ducts of the housing. The leakage in the motor is fed to the low pressure connection (3) via the shuttle valve (4).

Note

The flow-rate/rotary-speed indicator PN 183736 can be attached using the top cheese-head bolt. Before doing this, however, screw the coupling adapter into the end of the shaft.



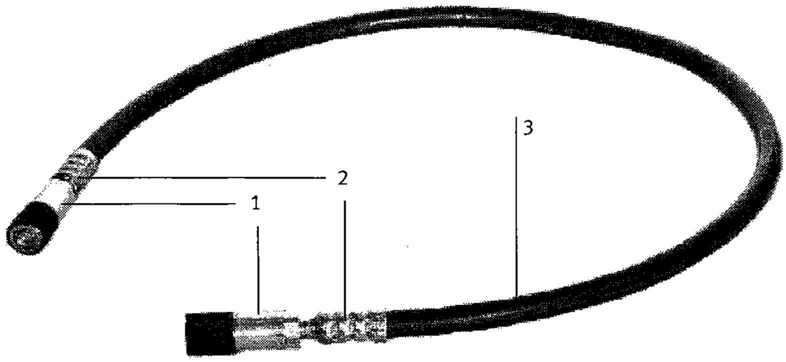
Torque/rotary-speed characteristic

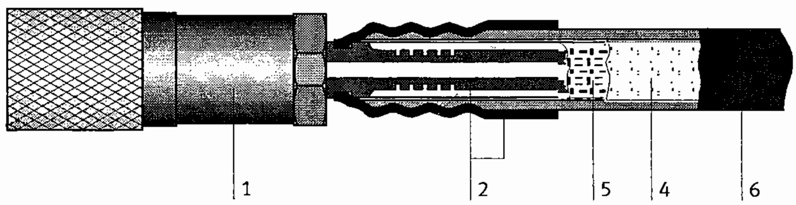
Technical data

Hydraulic	
Medium	Mineral oil, recommended viscosity 22 cSt (mm²/s)
Design	Orbital
Geometric displacement	8.2 cm³
Operating pressure p	6 MPa (60 bar)
Max. permissible pressure p_{max}	12 MPa (120 bar)
Max. permissible pressure in return line $p_{R\,max}$	5 MPa (50 bar)
Max. rotary speed n_{max}	1950 min^{-1}
Output shaft with spring	Ø 16 x 28, A5 x 5 DIN 6885
Max. permissible shaft load	radial: 1600 N axial: 800 N
Connections	For 2 coupling sockets

152960, 152970, 159386, 158352

Hose line with quick release coupling (600, 1000, 1500, 3000 mm)



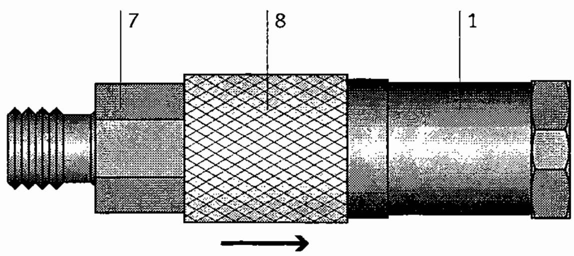


Design

Coupling socket (1), fitting (2), high-pressure hose (3), braided wire (4), inner hose (5), cover sheath (6).
The high-pressure hose (3) is of 3-ply design. The inner hose (5) is made of synthetic rubber, the 2nd ply of braided wire (4) and the cover sheath (6) of abrasion-resistant synthetic rubber.

Function

The two coupling sockets (1) are self-closing when uncoupled. These sockets provide a leakproof hydraulic connection in conjunction with the coupling nipple (7). To make a connection, the coupling socket (1) is pushed onto the nipple until the sliding sleeve (8) snaps forward. This sleeve is pulled back to separate the connection. The coupling socket will then spring away from the nipple. Only the front faces of the couplings come into contact with hydraulic fluid during the coupling operation.

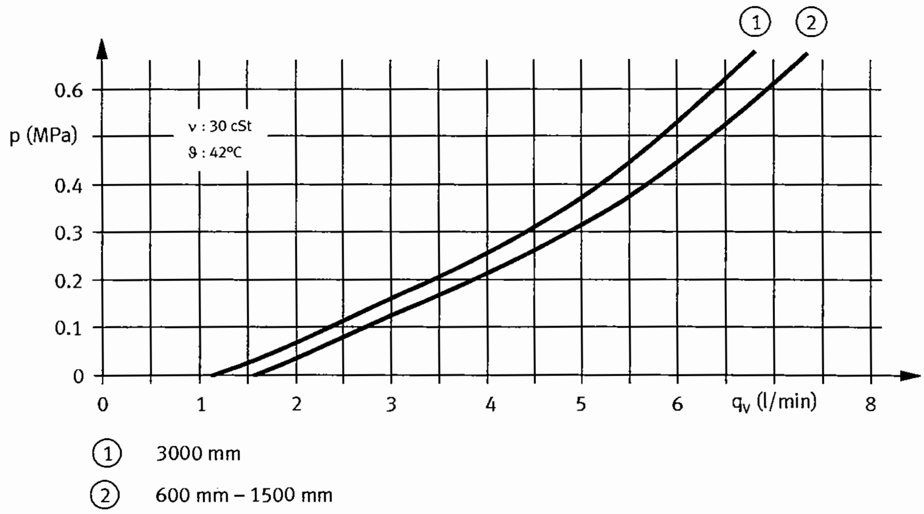


152960, 152970, 159386, 158352

Hose line with quick release coupling (600, 1000, 1500, 3000 mm)

Notes

- Carry out coupling and decoupling only at zero pressure.
- In order to obtain a long service life with the hose lines, ensure that they are not twisted while assembling circuits and observe the specified minimum bending radius and operating temperature.
- The storage and use of hose lines are governed by the following safety regulations:
  - The maximum storage time is 4 years for hoses without fittings and 2 years for hoses with fittings.
  - Hose lines should not be used for longer than 6 years, including a storage period of a maximum of 2 years.
  - Hoses are marked with their date of production (quarter and year) e.g.: 1 Q 92.
  - Hose line fittings are marked with their date of production (month and year) e.g.: 10 93.
  - Fittings (2) are stamped with their maximum operating pressure.



Pressure/flow-rate characteristic

152960, 152970, 159386, 158352

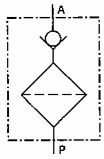
Hose line with quick release coupling (600, 1000, 1500, 3000 mm)

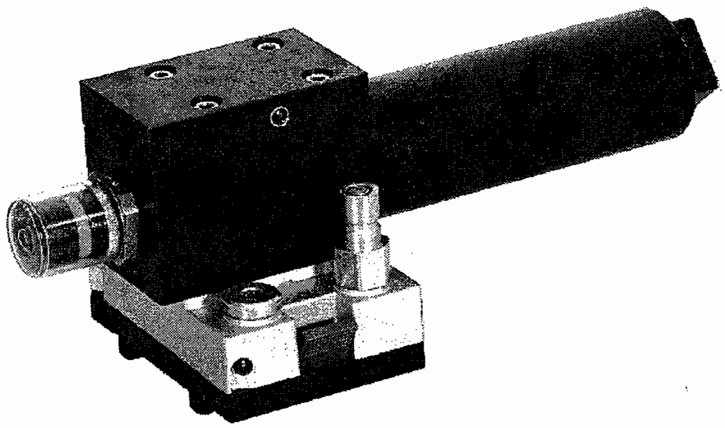
Technical data

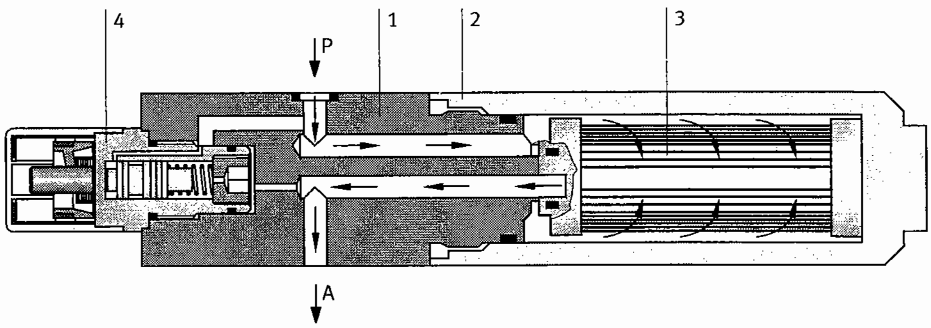
Type of Hose (Order No.)	152960	152970	159386	158352
Medium	Mineral oil, recommended viscosity 22 cSt (mm^2/s)			
Hose length	600 mm	1000 mm	1500 mm	3000 mm
Nominal size	6 mm			
Operating pressure p	6 MPa (60 bar)			
Max. permissible pressure p_{max}	12 MPa (120 bar)			
Temperature range	-40 – +125 °C			
Bending radius, min.	100 mm			
Connections	For 2 coupling nipples			

152969

Pressure filter







Design

The pressure filter and two barbed fittings are mounted on a mounting plate. The unit is secured to the profile panel by the snap-lock system using two blue levers (mounting variant "A").

The filter consists of: Housing (1), Cap (2), Filter cartridge (3), Contamination indicator (4)

Function

Oil is fed from connection P through the housing (1) into the cap (2). The pressure gradient present results in the oil flowing through the filter cartridge (3) from the outside to the inside. The oil is then discharged via connection A. The pressure drop across the filter cartridge is used as a means of monitoring the degree of contamination of the filter by a visual indicator (4). The cover plate is equipped with a non-return valve to ensure that incorrect connection of tubing does not result in dirt absorbed by the filter being returned to the system.

The purpose of the filter is to remove suspended solid matter (abrasion particles, burrs, dust, etc.) and water from the hydraulic fluid.

The efficiency of the filter is measured by the ratio β of the concentration of particles upstream and downstream of the filter. Since the retentive capacity of the filter depends on the particle size, particles are classified and specified as an index (in µm) for the retention value b; for example, β_5 is the retention value for particle with a size of 5 µm.

152969

Pressure filter

Multipass filter cartridge performance data as per ISO 4572

	Beta values as a function of filter cartridge differential pressure				
	$\beta_x = \frac{\text{Number of particles of size > x µm upstream of filter}}{\text{Number of particles of size > x µm downstream of filter}}$				
Degree of filtration	**Δp (bar)**	β_2	β_3	β_5	β_{10}
5 µm	2	12	40	300	>2000
5 µm	5	11	35	200	>2000

Parameters

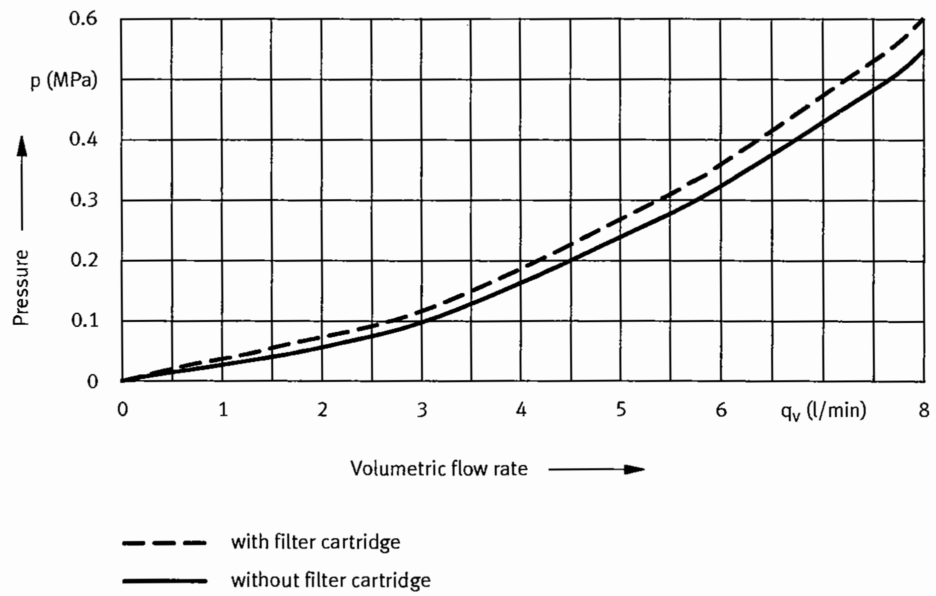
The efficiency of the filter also depends on the following factors:

a) Whether the full flow is filtered, or only part of this (flow through pressure relief valve is discharged unfiltered)

b) How often the entire contents of the tank passes through the filter

c) Whether all lines and components have been flushed

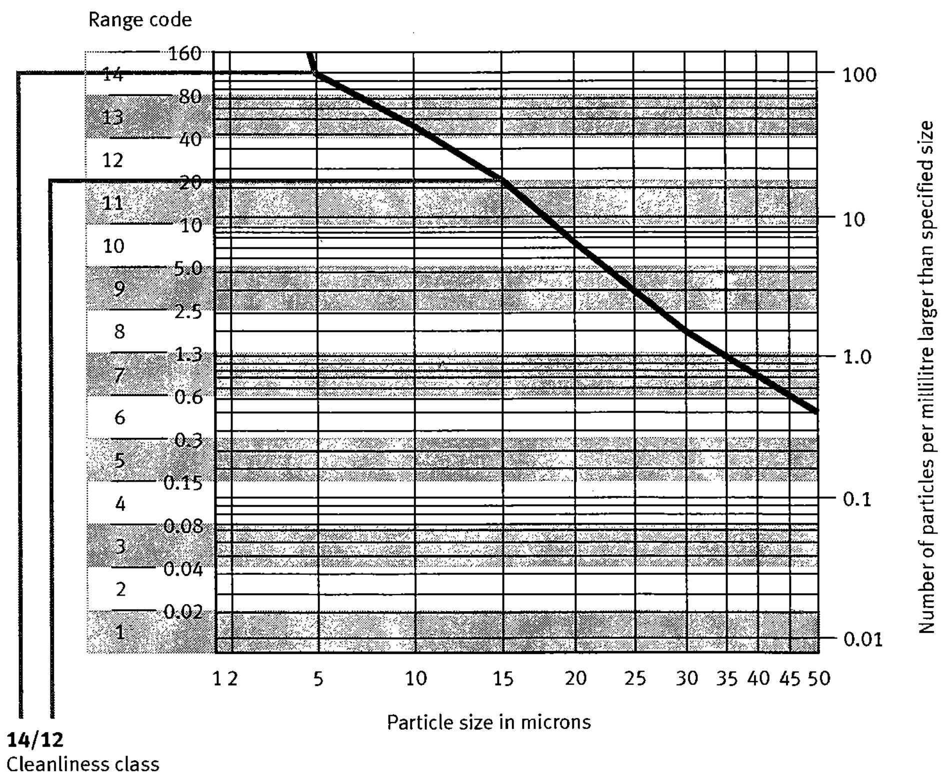
d) How high a contamination level the system generates during operation (dust, water condensation, results of refilling with fresh fluid)



Flow-rate characteristics with and without filter cartridge

Cleanliness class

If we count the number of particles in 1 ml of hydraulic fluid and classify these according to their size, we can plot a graph showing the level of contamination present for each particle size. The number of particles is divided into classes, the cleanliness classes.



Cleanliness class graph

The cleanliness class required is governed by the component within the system which is most sensitive to contamination (see table on next page).

152969

Pressure filter

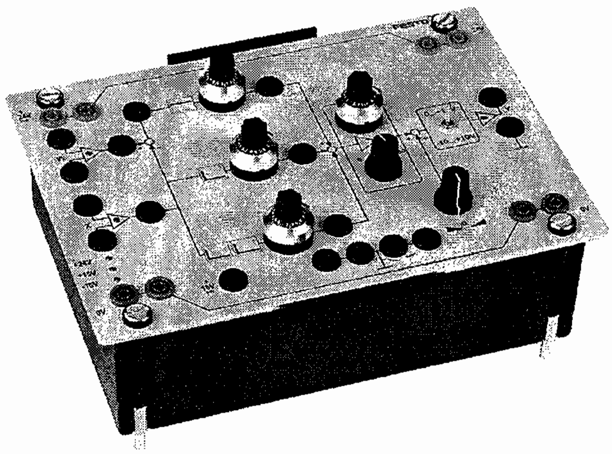
Recommendation

Component	**Cleanliness class as per ISO 4406 for particles of 5 µm/15 µm**
Gear pump	18/15
Piston-type variable pump	16/14
Solenoid-actuated directional control valve	18/15
Pressure valve (regulating function)	17/14
Flow control valve	17/14
Non-return valve	18/15
Proportional directional control and pressure valves	16/13
Regulator	16/13
Cylinder	18/15
Hydraulic motor	18/15

Technical data

Hydraulic	
Medium	Mineral oil, recommended viscosity 22 cSt (mm^2/s)
Max. permissible pressure p_{max}	12 MPa (120 bar)
Pore size	5 µm
Attainable cleanliness class	15/12 – 17/14
Differential pressure for contamination indicator Δp	5 bar -10 %
Connections	For 2 coupling sockets

Z



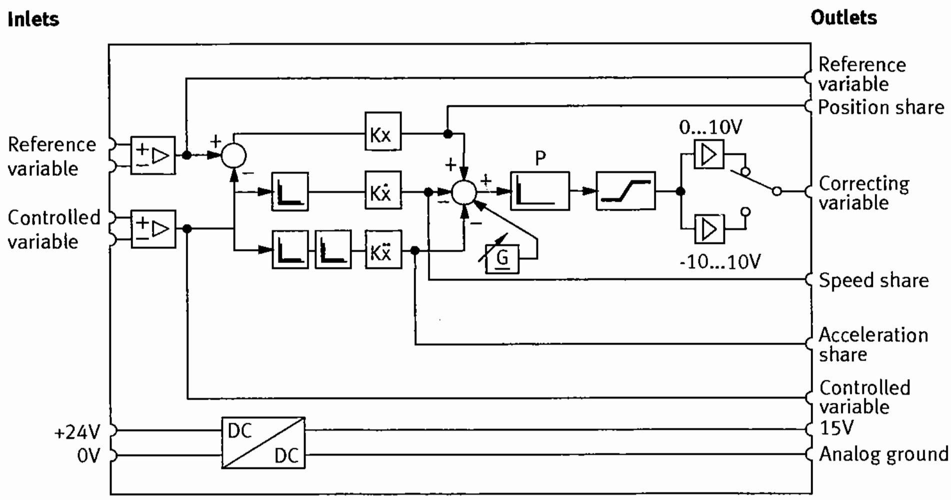
Design

The status controller is made up of the following function areas:

- Power supply
- Differential inputs
- Comparator
- Controller components: Position component, Speed component, Acceleration component
- Overall gain
- Correcting variable offset
- Summation point
- Limiter
- Output

Function

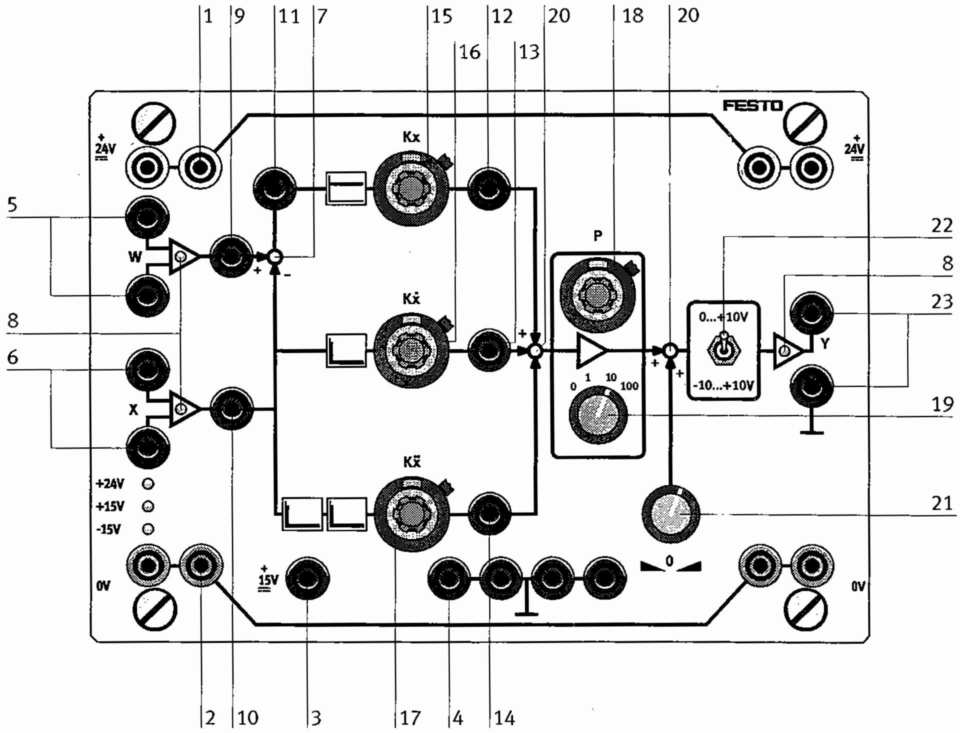
The status controller is used as a controller in pneumatic and hydraulic closed-loop positioning circuits.



Representation in circuit diagram

162253

Status controller



Key to operator facilities

1	Power supply + 24 V
2	Power supply ground 0 V
3	Sensor power supply + 15 V
4	Sensor ground or analogue ground
5	Differential setpoint input
6	Differential actual-value input
7	Comparator
8	Overmodulation indicator
9	Test socket Setpoint
10	Test socket Actual value
11	Test socket System deviation
12	Test socket Position gain
13	Test socket Speed gain
14	Test socket Acceleration gain
15	Rotary potentiometer Position component
16	Rotary potentiometer Speed component
17	Rotary potentiometer Acceleration component
18	Rotary potentiometer Overall gain
19	Rotary switch Overall gain
20	Summation point
21	Rotary potentiometer for correcting variable offset
22	Range selector switch
23	Correcting variable output

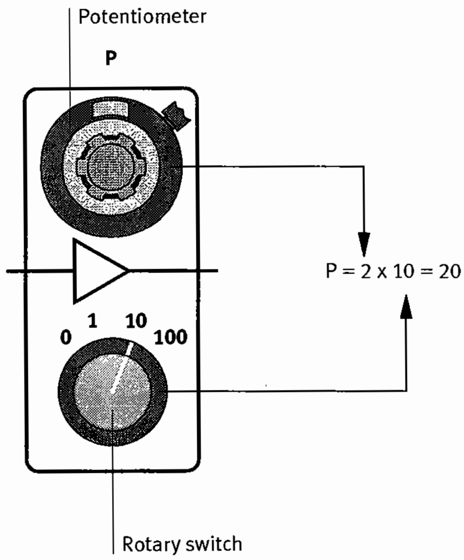
Power supply	The status controller requires a power supply of 24 V. This voltage is converted internally to +/- 15 V and fed to the controller electronics. The voltages are electrically isolated from each other, i.e. the controller card has two zero potentials (analogue ground and power-supply ground (0 V)).
Note	The analogue ground and power-supply ground should never be connected together, since this may cause interference to signals. The 15 V should be used in conjunction with the analogue ground as the power supply for sensors in order to ensure that noise signals are kept to a minimum.
Differential inputs	A differential input is provided in each case on the status controller for the setpoint and actual-value signals. The differential signal can be measured against analogue ground. The differential inputs are fitted with low-pass filters to suppress interference. Overmodulation of below -10 V or above +10 V is indicated by LEDs.
Comparator	The comparator is connected in series with the signal inputs and calculates the system deviation between the setpoint and actual value
Controller components	The three controller coefficients (Kx, $K\dot{x}$ und $K\ddot{x}$) can be infinitely adjusted by means of potentiometers within the range of [0..10].
Overall gain	The overall gain of the correcting variable, which consists of the sum of the controller component signals, can be adjusted by means of a rotary potentiometer and a step switch.
Correcting variable offset	The correcting variable offset can be used to impose constant voltages on the control signal in order, for example, to compensate for the zero-point shift of actuators.
Correcting variable limiter	The correcting-variable limiter converts the controller signals to the working range required by the actuators. Any overmodulation of the output signal is indicated by an LED.
Output	The correcting variable can be tapped against analogue ground at the output.
Test sockets	Various test sockets allow signal voltages to be measured against analogue ground.

162253

Status controller

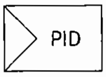
Setting the coefficients

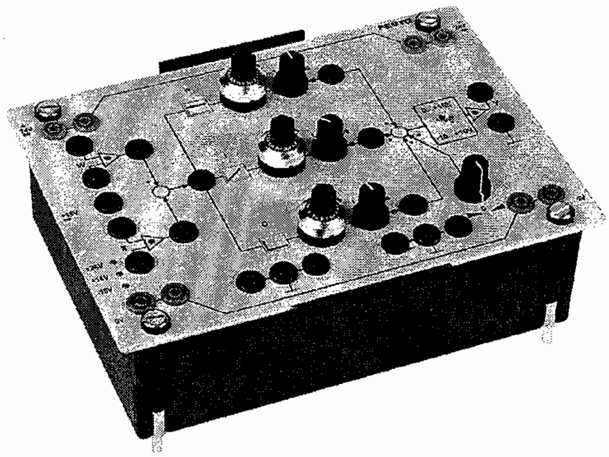
The overall gain is the product of the values set on the rotary potentiometer and rotary switch.



Technical data

Electrical	
Power supply	24 V DC +/-10 %
Overmodulation indicator	-10 > Ue > +10 V
Input voltage range	-13 V – +13 V
Position coefficient Kx	0 – 10
Speed coefficient K $\dot{x}$	0 – 100 ms
Acceleration coefficient K $\ddot{x}$	0 – 10 ms^2
Overall gain P	0 – 1000
Output voltage limitation	[0 V – +10 V] [-10 V – +10 V]
Correcting variable offset	5 V ±3,5 V bei [0 V – +10 V] 0 V ±7 V bei [-10 V – +10 V]
Connection	for 4 mm safety connector plug
Electromagnetic compatibility	CE
Emitted interference	tested to EN 500 81-1
Noise immunity	tested to EN 500 81-1





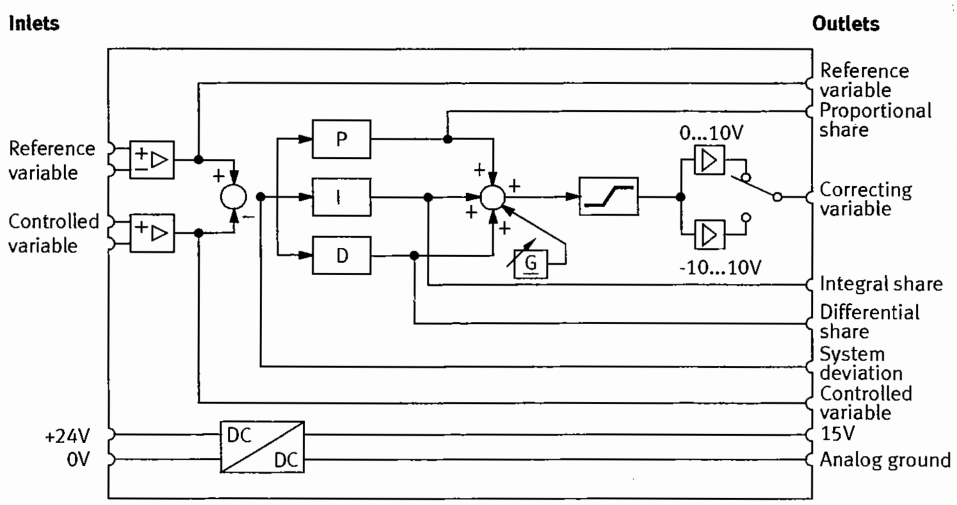
Design

The PID controller is made up of the following function areas:

- Power supply
- Differential inputs
- Comparator
- Controller components: Proportional component, Integral component, Differential component
- Correcting variable offset
- Summation point
- Limiter
- Output

Function

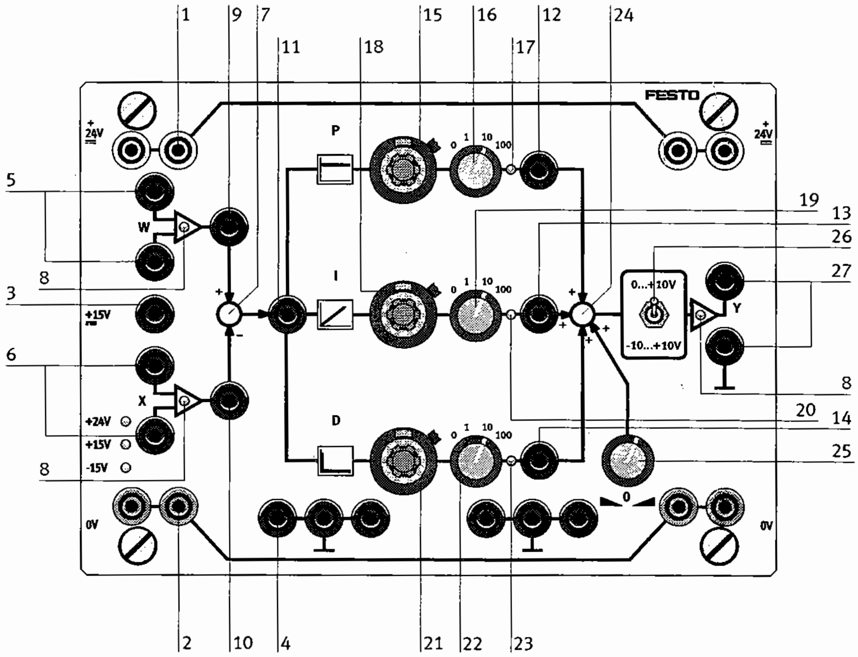
This PID controller can be used, among other things, as a controller for closed-loop pneumatic and hydraulic control circuits.



Representation in circuit diagram

162254

PID controller



Key to operator facilities

1 Power supply + 24 V
2 Power supply ground 0 V
3 Sensor power supply + 15 V
4 Sensor ground or analogue ground
5 Differential setpoint input
6 Differential actual-value input
7 Comparator
8 Overmodulation indicator
9 Test socket Setpoint
10 Test socket Actual value
11 Test socket System deviation
12 Test socket Proportional gain
13 Test socket Integral gain
14 Test socket Differential gain
15 Rotary potentiometer P component
16 Rotary switch P component
17 Power-on indicator P component
18 Rotary potentiometer I component
19 Rotary switch I component
20 Power-on indicator I component
21 Rotary potentiometer D component
22 Rotary switch D component
23 Power-on indicator D component
24 Summation point
25 Rotary potentiometer for correcting variable offset
26 Range selector switch
27 Correcting variable output

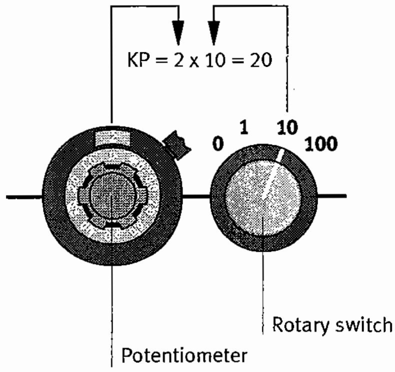
Power supply	The PID controller requires a power supply of 24 V. This voltage is converted internally to +/- 15 V and fed to the controller electronics. The voltages are electrically isolated from each other, i.e. the controller card has two zero potentials (analogue ground and power-supply ground (0 V)).
Note	The analogue ground and power-supply ground should never be connected together, since this may cause interference to signals. The 15 V should be used in conjunction with the analogue ground as the power supply for sensors in order to ensure that noise signals are kept to a minimum.
Differential inputs	A differential input is provided in each case on the PID controller for the setpoint and actual-value signals. The differential signal can be measured against analogue ground. The differential inputs are fitted with low-pass filters to suppress interference. Overmodulation of below -10 V or above +10 V is indicated by LEDs.
Comparator	The comparator is connected in series with the signal inputs and calculates the system deviation between the setpoint and actual value.
Controller components	The three controller components (P, I and D components) can be switched on and off separately, allowing different combinations to be used. The individual controller parameters are adjusted with the aid of potentiometers and rotary switches.
Correcting variable offset	The correcting variable offset can be used to impose constant voltages on the control signal in order, for example, to compensate for the zero-point shift of actuators.
Correcting-variable limiter	The correcting-variable limiter converts the controller signals to the working range required by the actuators. Any overmodulation of the output signal is indicated by an LED.
Output	The correcting variable can be tapped against analogue ground at the output.
Test sockets	Various test sockets allow signal voltages to be measured against analogue ground.

162254

PID controller

Setting the coefficients

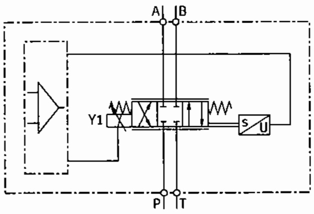
The coefficients KP, KI and KD of the controller components are the product of the values set on the rotary potentiometer and rotary switch.

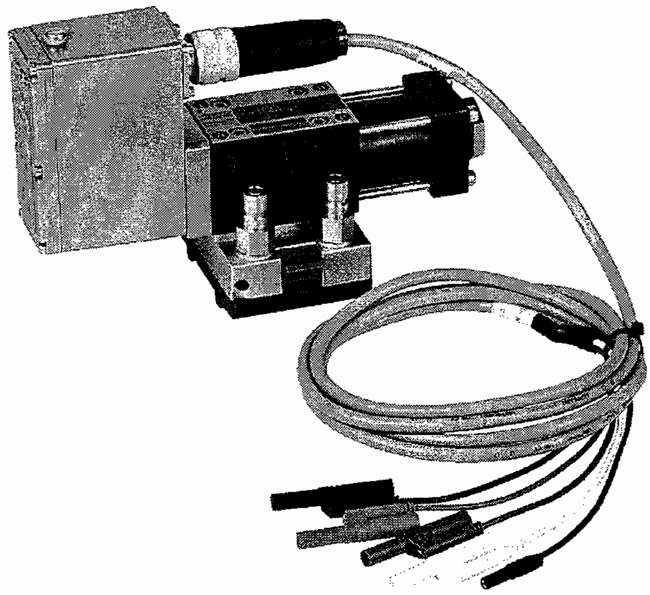


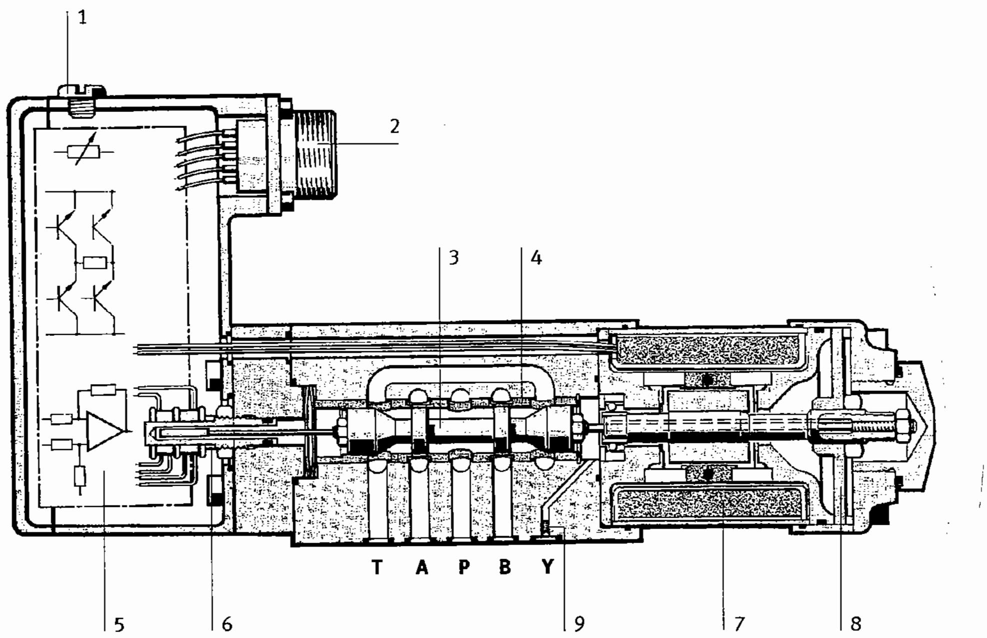
Technical data

Electrical	
Power supply	24 V DC +/-10 %
Overmodulation indicator	-10 > Ue > +10 V
Input voltage range	-13 V – +13 V
Position coefficient Kx	0 – 10
Speed coefficient K $\dot{x}$	0 – 100 ms
Acceleration coefficient K $\ddot{x}$	0 – 10 ms^2
Overall gain P	0 – 1000
Output voltage limitation	[0 V – +10 V] [-10 V – +10 V]
Correcting variable offset	5 V ±3,5 V bei [0 V – +10 V] 0 V ±7 V bei [-10 V – +10 V]
Connection	for 4 mm safety connector plug
Electromagnetic compatibility	CE
Emitted interference	tested to EN 500 81-1
Noise immunity	tested to EN 500 81-1

4/3-way regulating valve

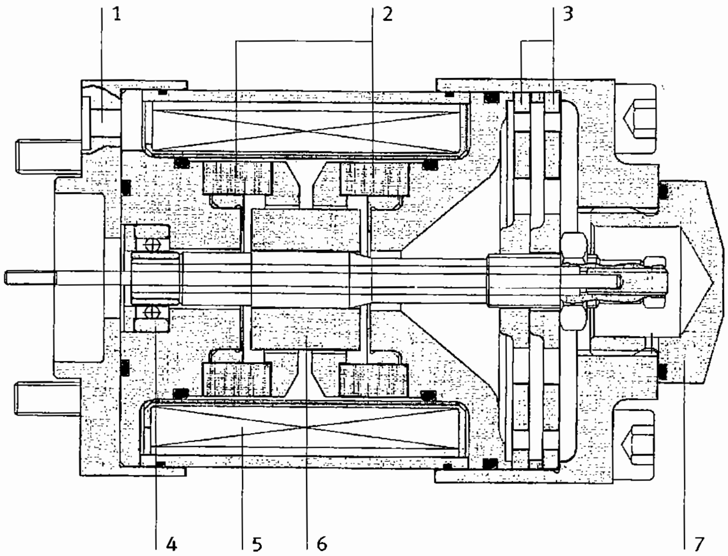






Construction of directional control valve	Plug screw for zero setting (1), Extension plug (2), Control sleeve (3), Control socket (4), Integrated electronics (5), Position encoder (6), Linear motor (7), Reset spring (8), Plug (9).
Function of directional control valve	An electrical control signal (in effect a control piston setpoint position value, but subsequently referred to as a setpoint volumetric flow rate value) is output to the integrated position controller, which drives the linear motor via the pulse-width modulated (PWM) driver electronics. The position encoder supplied via an oscillator measures the position of the control piston. This actual value signal is rectified via a

demodulator, returned to the position controller and compared with the setpoint value. The position controller now activates the linear motor until the setpoint and actual value are the same, whereby the position of the control piston is proportional to the electrical input signal. The actual flow rate q is, however, not only dependent on this electrical input signal, but also critically depends on the pressure drop Δp at individual control edges.



Construction of linear motor

Cable through hole (1), Permanent magnets (2), Reset springs (3), Bearing (4), Coil (5), Armature (6), Plug screw (7).

Function of linear motor

The linear motor is a differential motor energised via a permanent magnet. This means that part of the required magnetic force is already built-in. As a result of this, the current requirement of the linear motor is significantly less than that of comparable proportional magnets. The linear motor has a neutral mid-position and from this position is able to generate strokes and forces in both directions. These are proportional to the flow. Proportional solenoid systems, however require either two proportional solenoids with correspondingly complex wiring or operate unilaterally against a spring, whereby a reliable spring setting can only be achieved by means of overtravelling a power port (A or B). This can lead to uncontrollable movements on the drive unit. The linear motor does not draw any current in the spring centered position (mid or out of trim position). The high spring rigidity and the resulting reset force is overcome when advancing from the mid-position as are external forces, in-creased frictional forces due to contamination of the piston spool). When returning in the direction of zero position, the spring force is combined with the motor force, i.e. maximum force is always available when the piston spool closes.

Volumenstrom und Druckabfall

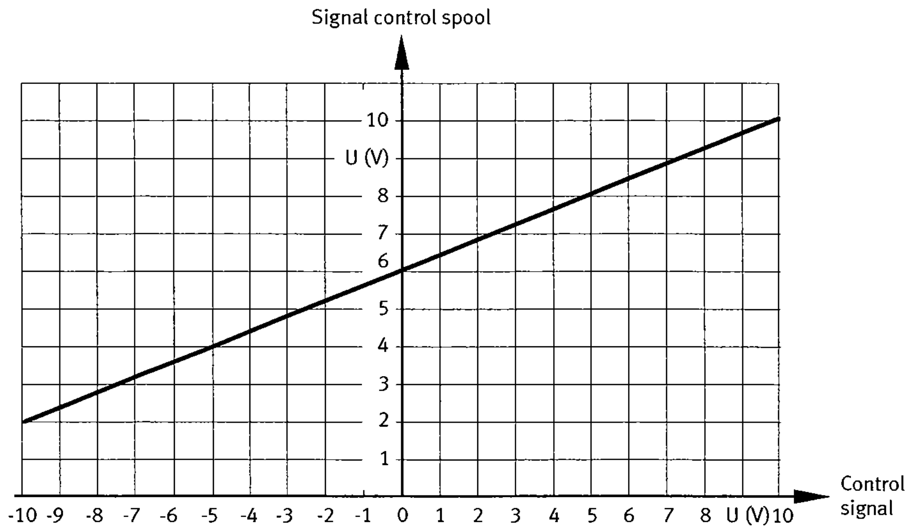
Volumetric flow rate and pressure drop A 100% setpoint input (e.g. +10 V DC = valve fully opened) and a nominal pressure drop Δp_N = 35 bar per control edge results in a nominal volumetric flow rate q_N per control edge. If the pressure drop is varied, the volumetric flow rate q also changes with the setpoint signal in accordance with the function below. The volumetric flow rate q thus calculated should not exceed an average flow velocity of 30 m/s at ports P, A, B and T.

Function for sharp-edged orifices (corresponds to control edges):

$$q = q_N \sqrt{\frac{\Delta p}{\Delta p_N}}$$

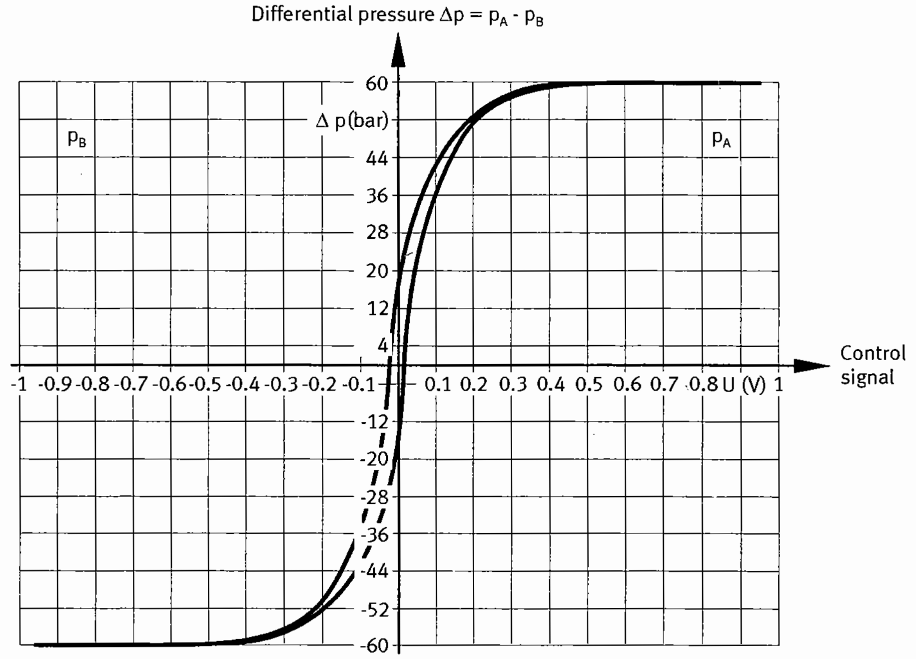
q (l/min)	= Actual volumetric flow rate per control edge at Δp
q_N (l/min)	= Nominal volumetric flow rate per control edge at p_N
Δp (bar)	= Actual pressure drop per control edge
Δp_N (bar)	= Nominal pressure drop per control edge

Static characteristics

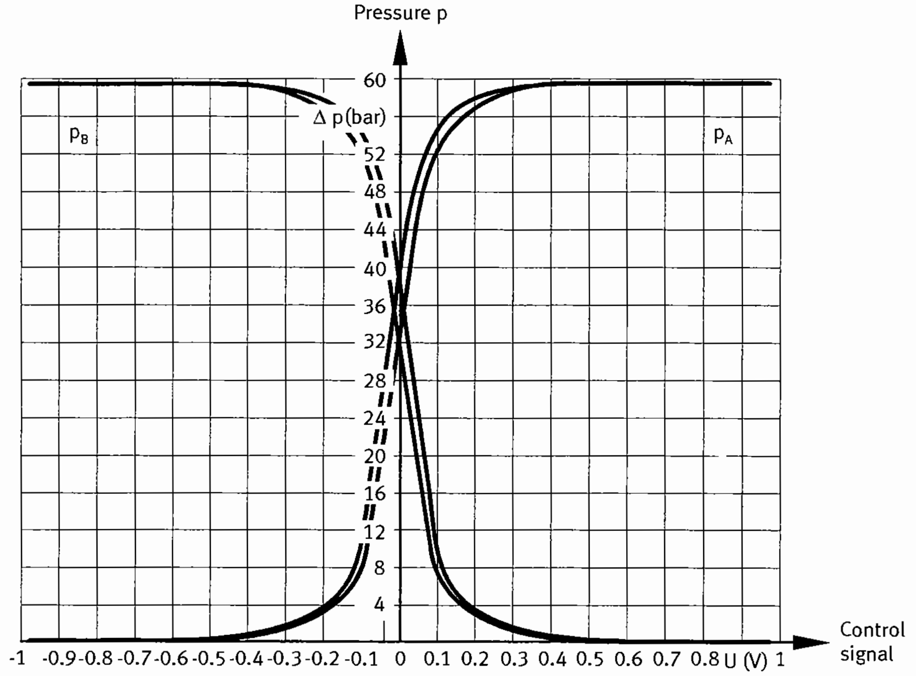


Control piston/signal characteristic curve

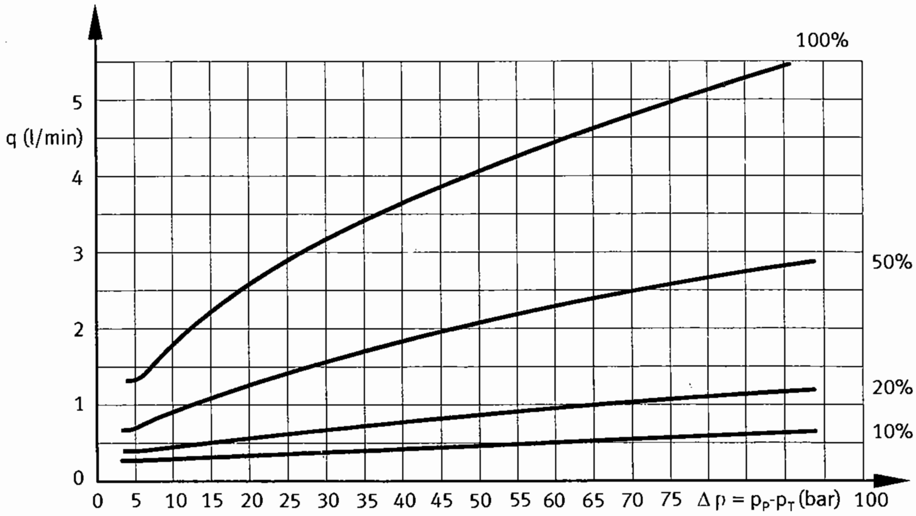
4/3-way regulating valve



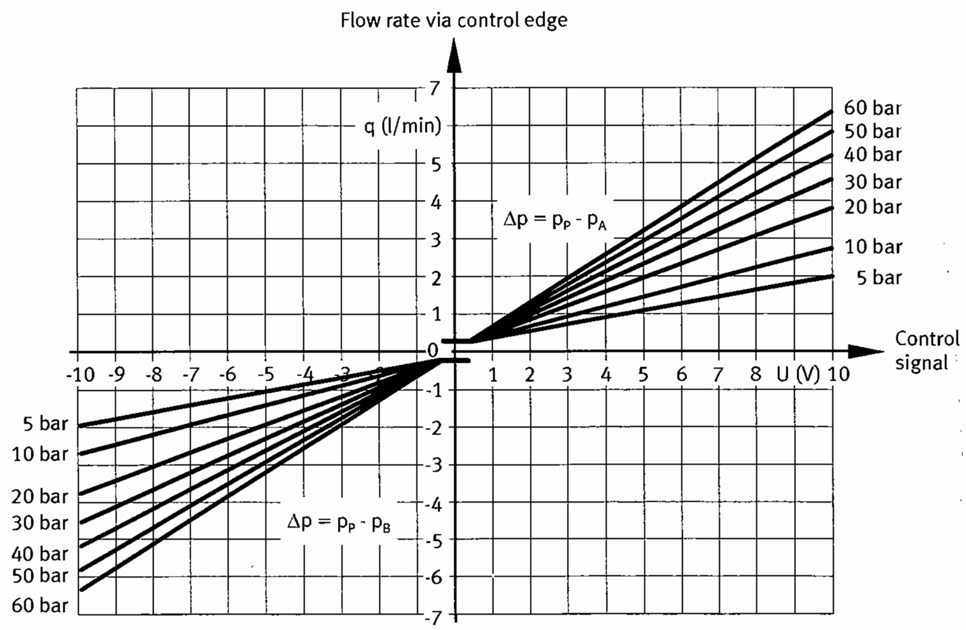
Pressure/signal characteristic curve



Pressure/signal characteristic curve

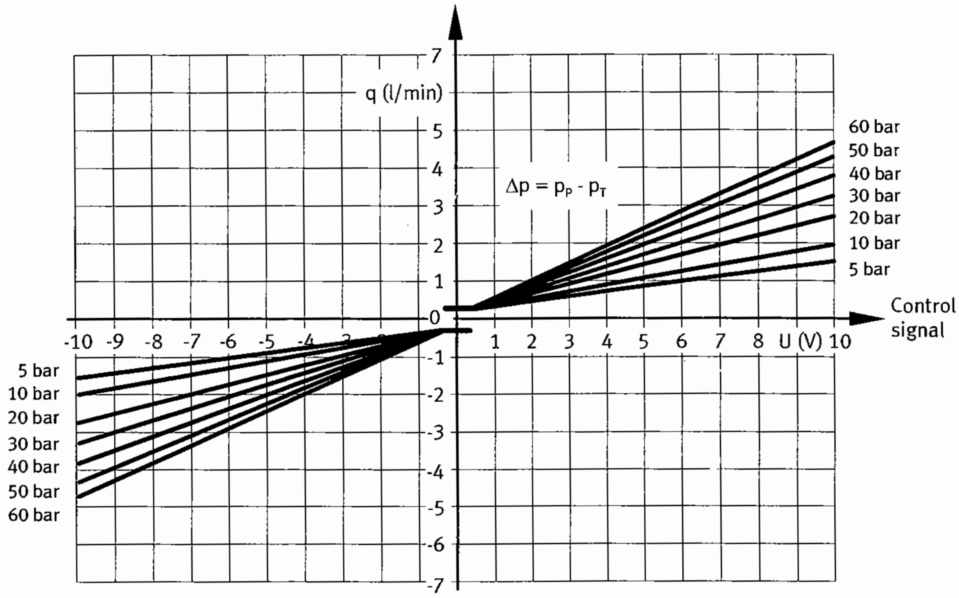


Flow rate/differentialpressure characteristic curve



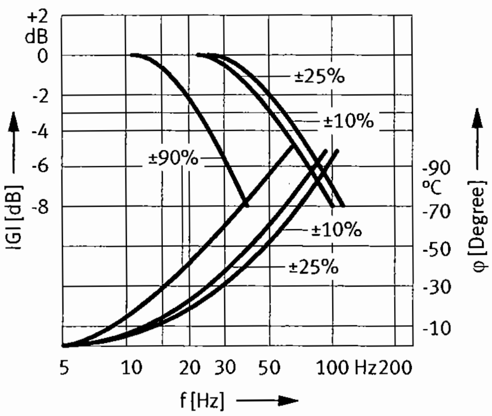
Flow rate/signal characteristic curve

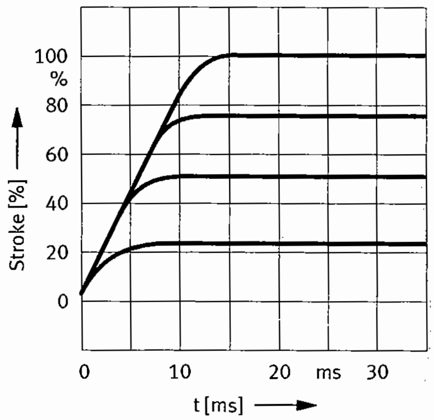
4/3-way regulating valve



Flow rate/signal characteristic curve

Dynamic characteristics

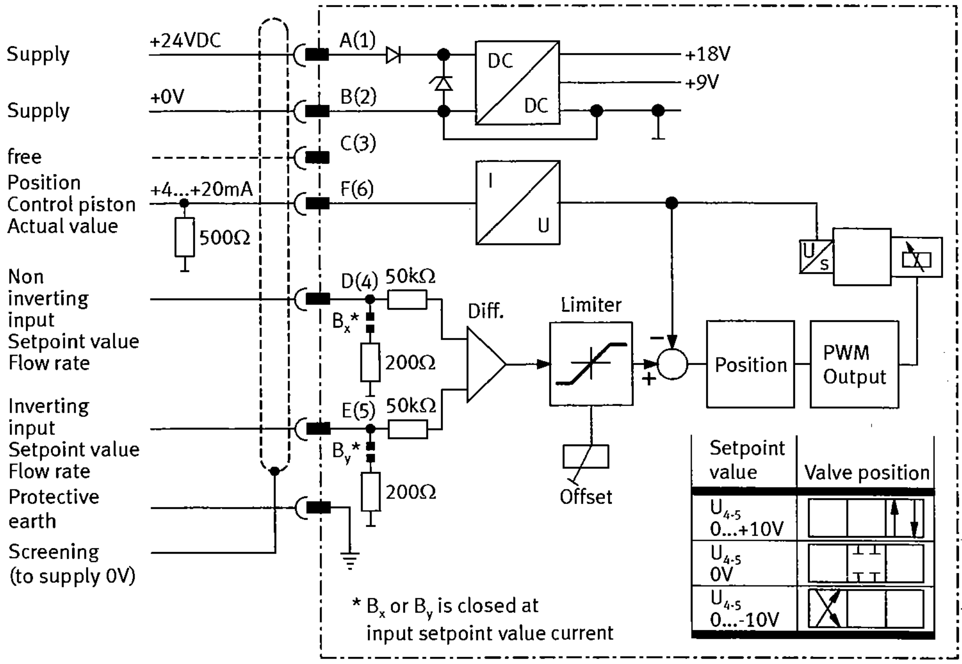




Pin assignment

Valve plug	**Designation**		**Plug colour**
A	Supply +	24 V	red
B	Supply –	0 V	blue
C			
D	Setpoint value +	0 – ±10 V	yellow
E	Setpoint value –	0 – ±10 V	green
F	Signal of control piston	4 – 20 mA	(coupling)

A resistor of 500 Ω has been soldered in between B and F resulting in a 2 to 10 V control piston signal.



Technical data

Hydraulic, Electrical	
Valve design	spool valve, single-stage with control sleeve
Actuation	direct via permanent magnet linear motor
Port pattern DIN 24340/ISO 4401/Cetop	Form A6/Cetop 3
Port diameter P, A, B, T	7.9 mm
Control oil supply	none
Leakage oil connection	blocked

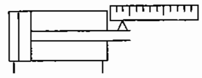
Technical data (continuation)

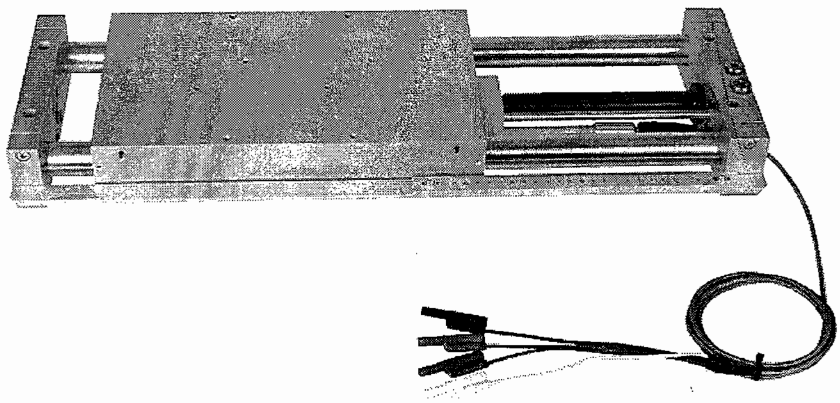
Hydraulic, Electrical	
Mounting position	any
Sealing material	NBR
Protection class DIN 40050, with assembled mating plug	IP 65
Nominal flow rate q_N	5 l/min at Δp_N = 35 bar (Tolerance ±10 %) 2 l/min at Δp_N = 5 bar (Tolerance ±10 %)
Leakage oil flow q_L	0.15 l/min at 140 bar
Max. operating pressure p_{max}, static	connections P, A, B: 350 bar connection T: 50 bar
Extension plug DIN 43563	6 + PE
Op. voltage supply of integrated electronics UB	+24 V DC
Op. voltage tolerance range min UB_{min}	+22 V DC
Op. voltage max UB_{max}	+28 V DC
Nominal current at UB = +24 V DC, Min. current IB_{min} at setpoint value zero	0.15 A
Max. current IB_{max} at setpoint value and 140 bar	1.2 A
Setpoint value signal	±10 V DC
Actual value signal	+4 – +20 mA
Relative duty cycle	100 % ED
Manipulating time signal step 0 – 100 %	< 12 ms
Inversion range	< 0,1 %
Hysteresis at 140 bar	< 0,2 %
Zero shift at ΔT = 55 K	< 1.5 %
Operating fluid DIN 51524	Mineral-based hydraulic oil
Oil temperature range	-20 – +80 °C
viscosity	recommended: 15 – 45 mm^2/s permissible: 5 – 400 mm^2/s
grade of filtration	recommended: x < 6 (6 µm absolut) permissible: x < 10 (10 µm absolut)
Contamination category	to NAS 1638 minimum: 6 to ISO 4406 minimum: 15/11
System filter	High pressure main flow filter, without bypass, but with contamination indicator

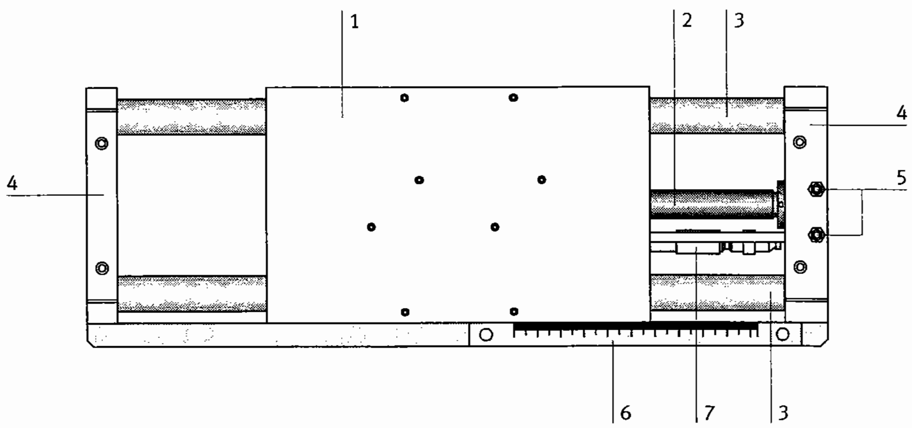
⚠ The maximum operating pressure of the valve sub-base and quick connection coupling is 120 bar.

167089

Linear drive, 200 mm stroke







Construction

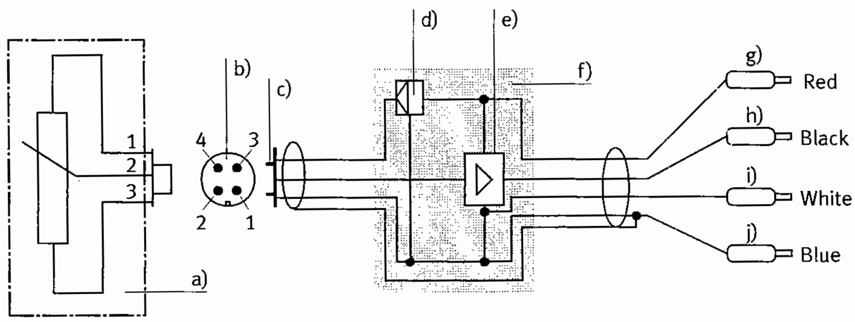
The linear drive consists of the following components:
a slide (1), a double-acting cylinder (2), two guide rods (3), two yokes (4), two hydraulic quick connection couplings (5), a scale (6), a displacement encoder (7).

Function

The cylinder chambers are pressurised via the two hydraulic quick connection couplings. The chamber pressures and the effective piston surfaces produce a resulting force, which acts upon the slide. The traversing speed is determined by the prevailing oil flow rate, whereby the flow rates vary from the plain piston surface to the piston rod side.
The slide is of low friction running on ball bearing guides.
The displacement encoder has been fitted underneath the slide next to the hydraulic cylinder and is thus largely protected from damage.
A scale has been attached to the mounting brackets for visual measurement of position. This can be adjusted slightly towards the mounting bracket.

Linear drive, 200 mm stroke

Construction and connection of the displacement encoder



a)	Potentiometer	f)	Housing
b)	Pin assignment	g)	Supply voltage
c)	Plug	h)	+ Signal
d)	Reference voltage source	i)	– Signal
e)	Impedance converter	j)	Supply earth

Function of displacement encoder

The potentiometer is supplied with 10 V from a reference voltage source located in the supply line. The voltage tapped via the follower is proportional to the distance travelled by the connecting rod. For safety reasons, the tapped voltage is protected against short-circuit and unacceptably high wiper current by means of an impedance converter. This has no effect on the level of the tapped voltage.

Commissioning

- Screw the couplings provided into the yoke.
- Connect the slide unit hydraulically. Limit the inlet of oil flow to a low value so that the slide only moves slowly. Traverse from end position to end position several times until the movement can be performed jolt-free. Venting is facilitated by means of short hose sections between the valve and the slide unit.
- The built-in potentiometer is connected via the enclosed plug, where the plug is first entered through the yoke and then screwed onto the potentiometer. If the potentiometer is to be replaced, the working cylinder is to be retracted completely. The potentiometer is then inserted into the mounting bracket at the head of the cylinder and its connecting rod screwed into the slide. Make sure that the connecting rod is screwed in straight. Establish the electrical connection of the potentiometer and move it until you can still just obtain an output voltage of 0 V. Fix the potentiometer in this position. Move the slide to the opposite end position and check whether you can still just reach the output voltage of 10 V. At no time must the potentiometer reach its mechanical end stop.

Notes on safety

- Hydraulic components, such as cylinders and couplings, are designed for a maximum pressure of 120 bar. Due to the differing cylinder piston surfaces, a pressure transference factor of around 1.6 is obtained. We therefore recommend a maximum supply pressure of 75 bar. The slide unit is to be attached to a stable base capable of absorbing acceleration forces occurring during operation. (When securing the unit with T-head nuts, make sure that the nuts turn by 90° when the screws are tightened.) Forces may occur as a result of deceleration and acceleration, which can cause the laboratory trolley to move.
- Loads attached to the slide are to be secured against any possible acceleration forces. Structures overhanging the slide are to be attached in such a way as not to interfere with either hydraulic couplings and hoses or with the adjoining devices and structures. With structures of this type, note that there are no safety clearances relative to the slide and there is therefore the risk of objects becoming trapped. Different safety measures will need to be implemented if this is the case (e. g. covers). Make sure that the slide does not rub against any electrical lines or hoses, or sever these. If the cylinder is not vented, this leads to uncontrolled movements of the slide.
- Repeated high speed impact on the end positions at full speed is not permitted, since the cylinder does not have end position cushioning and may therefore lead to permanent damage. If you intend to mount the unit vertically, it will have to be connected hydraulically in the horizontal position first, or supported while it is being coupled. The lower cylinder chamber is pressurised in the vertical position and coupling is therefore no longer possible.

Options

Cross slides
A second slide unit may be assembled on the slide in conjunction with a base plate.

Digital displacement measurement
A glass scale is provided in case the slide unit is to be operated with a digital displacement system. The scale is attached to the side of the slide unit by means of a bracket.

Loads
The slide unit can be loaded by securing individual 5 kg loads on the slide by means of M5 screws. A load of 10 kg is sufficient to enable you to detect the effect of loads on the control behaviour.

Load cylinders
The unit may be loaded by means of a weight mass or, for instance, a second cylinder (Pt. No. 152295). The dimensions of load and operating cylinders are identical. The forces between the load and operating cylinder are absorbed primarily by the guide rods, thus preventing additional stress on the base.

 Subject to change

167089

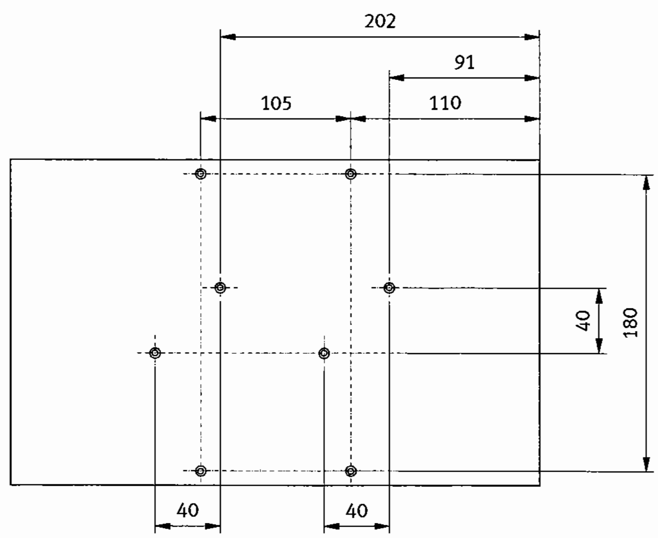
Linear drive, 200 mm stroke

Technical data

Dimensions	
Length	625 mm
Width	200 mm
Stroke	200 mm
Slide size (Length x Width)	320 x 198 mm
Mounting holes in the yokes	M6

Weight	
Slide unit	15.7 kg
Befestigungsbohrungen für Gewichte	M5
Mounting holes for weights and for second linear drive	M6

Position of the bores:



Drive unit	
Cylinder	16 x 10 x 200 mm
Area ratio	1 : 1.64
Medium	Mineral oil
Maximum operating pressure	12 MPa (120 bar)
Hydraulic connection	quick connection coupling
Drive force extending	2400 N
Drive force retracting	1450 N

167089

Linear drive, 200 mm stroke

Technical data
(continuation)

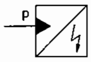
Useful load	
loads	maximum 50 kg

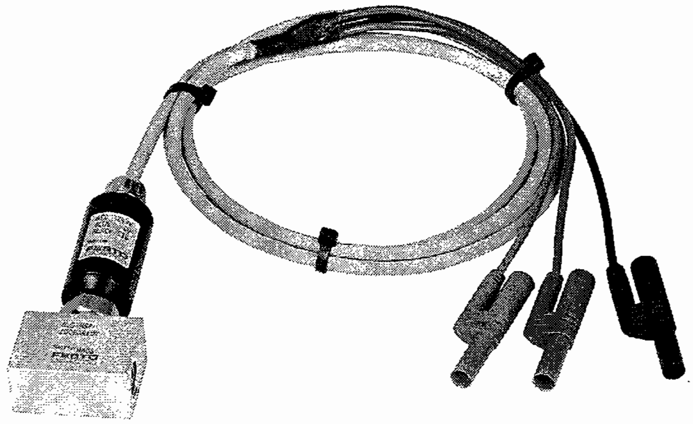
Displacement encoder, electrical	
Design	Potentiometer of 200 mm measured length, impedance converter and connecting cable
Supply voltage	+13 – +30 V
Output voltage	0 – 10 V
Linearity	±0,5 %
Mechanical stroke	204 mm
Maximum traversing speed	1.5 m/s
Operating temperature range	-40 – +150 °C
Protection class	IP 64

Displacement encoder, visual	
Design	Scale
Scale	Millimetre
Measuring length	210 mm

184133

Pressure sensor





Construction

The analogue pressure sensor is screwed into a T connector. It can be equipped with differing pairs of hydraulic couplings, e. g.:

- leak-proof coupling
  Quick coupling socket (Order No. 342046)
  Double nipple (Order No. 385936)
  Coupling nipple (Order No. 342047)
- NG6 Coupling
  Sealing coupling (Order No. 227901)
  Sealing nipple (Order No. 224513)

The couplings must be securely screwed into the connector. The electrical connection is established via the 4 mm safety connector plugs fitted to the connecting lead.

Function

A diaphragm inside the pressure sensor is distorted as a result of the measuring pressure applied. This distortion leads to a change in electrical resistance of the elements on the membrane (piezoresistive effect). This resistance change is electronically converted, temperature compensated and amplified.

Note

Please observe the polarity of the connected voltage during operation. The terminal plugs have been colour coded.

Terminal plugs		
Operating pressure	Positive terminal: Negative terminal:	red blue
Analogue output signals	Voltage:	black

184133

Pressure sensor

Technical data

Electrical	
Permissible operating voltage	15 – 30 V DC
Voltage output	0 – 10 V
Load resistance	≥4.7 kΩ
Measuring range	0 – 100 bar
Critical frequency	1 kHz
Ambient operating temperature	-10 – +70 °C
Temperature effect comp. range (-10 – +80 °C)	±0.2 % FSD*/10 K
Linearity	±0.5 % FSD*
Reproducibility	±0.1 % FSD*
Protection class (DIN 40 050)	IP 67
Weight	260 g
Connection	cable with 4 mm safety connector plugs

* FSD = full-scale deflection

 Subject to change