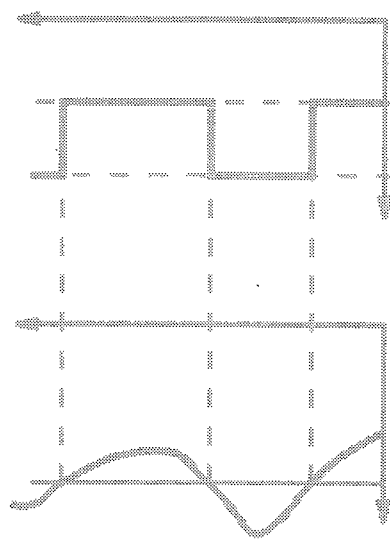


Closed-Loop Pneumatics

Workbook Basic Level



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Preface

The Learning System for Automation by Festo Didactic is formulated according to various training prerequisites and vocational requirements. It has been divided into the following training packages:

- Basic packages which convey basic knowledge spanning a wide range of technologies
- Technology packages which deal with important subjects of open and closed-loop control technology
- Function packages to explain the basic functions of automated systems
- Application packages to facilitate practice-orientated vocational and further training.

The technology packages deal with the technologies of pneumatics, electro-pneumatics, programmable logic controllers, hydraulics, electro-hydraulics, proportional hydraulics, closed-loop pneumatics and hydraulics.

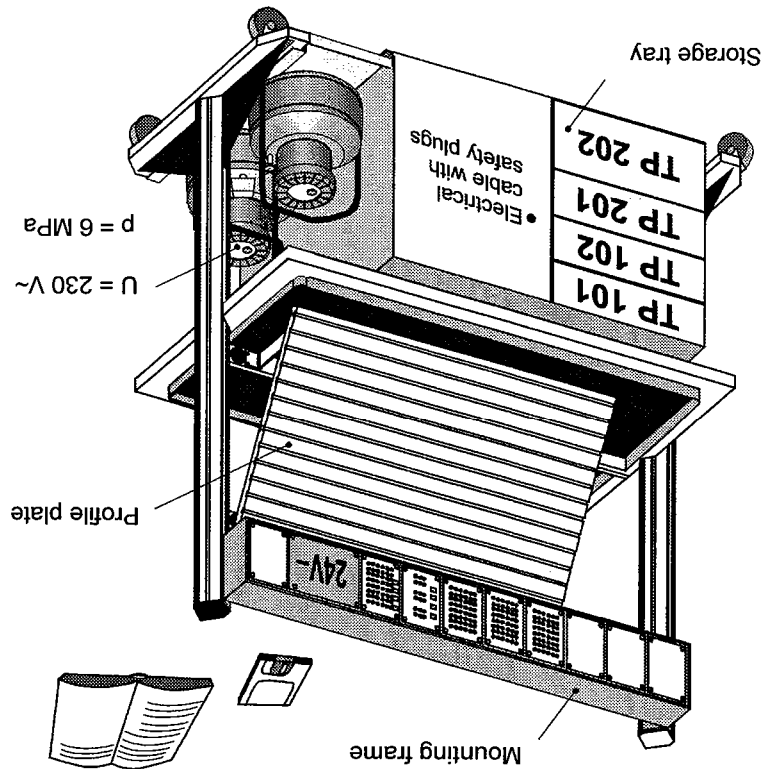


Fig. 1:
Pneumatics 2000 –
i.e. mobile workstation

The modular design of the Learning System permits applications beyond the scope of the individual packages. It is, for instance, possible to design PLC-controlled systems with pneumatic, hydraulic and electrical actuators.

All training packages are based on an identical structure:

- Hardware
- Teachware
- Software
- Seminars

The hardware consists of industrial components and systems which have been adapted for didactic purposes.

The courseware has been designed in line with didactic methods and coordinated for use with the training hardware. The courseware comprises:

- Textbooks (with exercises and examples)
- Workbooks (with practical exercises, explanatory notes, solutions and data sheets)
- Transparencies and videos (to create a lively training environment)

The training and learning media is available in several languages, which has been designed for use in the classroom as well as for self-tuition.

The software sector serves as a basis for providing computer training programs and programming software for programmable logic controllers.

A comprehensive range of seminars on the subject of the various technology packages completes our program of vocational and further training.

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Technology package TP 111 "Closed-Loop Pneumatics"

The technology package TP111 "Closed-Loop Pneumatics" forms part of Festo Didactic's Learning System for Automation and Communications.

The training aims of TP111 are concerned with analogue closed-loop control technology. Actuators are activated via electrical open and closed-loop components.

Students working through technology package TP110 should preferably have basic knowledge of electropneumatics and measuring systems.

The equipment set is designed in such a way that the number of components required becomes larger from one exercise to the next. This makes it possible to begin a study of closed-loop control technology with a small number of components, which can then be added to as necessary.

The exercises of TP111 are concerned with three main subjects:

- Non-dynamic pressure regulation (exercises 1 – 5)
- Dynamic pressure regulation (exercises 6 – 16)
- Position control (exercises 17 – 21)

The components required for particular exercises can be seen in the component/exercise table over leaf.

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
Service unit with on/off valve	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Manifold	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
PUN tubing 10 m	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Signal input plate	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Analogue pressure sensor	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Comparator		1		1	1	1															
Reservoir			2	1	1	1				1				2	2	2					
One-way flow control valve			1	2	2					1				1	2	2					
Pressure gauge			1	1	1	1				1				1	1	1					
3/2-way solenoid valve with push button			1	2																	
Push-in T connector				1	2									1	2	2					
3/2-way solenoid valve			1	1											1	1					
5/3-way solenoid valve					1																
Connector components				1	1					1				1	1	1	1	1	1	1	1
5/3-way proportional valve						1				1				1	1	1	1	1	1	1	1
PID controller							1	1	1	1	1	1	1	1	1	1					
Linear actuator 450 mm																	1		1	1	1
Mounting kit for potentiometer																		1	1	1	1
Loading weight 50 N																					1
Linear potentiometer																			1	1	1
Status controller																		1	1	1	1
Scale 450 mm																	1				
Cable set	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Digital multimeter	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
Setpoint card						(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)
Storage oscilloscope			1	1						1	1	1	1	1	1	1			1	1	1
Cable BNC-4 mm			2	2		1	1	1	1	3	3	3	3	3	3	3	1	3	3	3	3
Connection panel																					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-loop control circuits.

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

Section C, “Solutions”, gives the results of the exercises in Section A, with explanatory notes.

Section B, “Fundamentals”, contains general technical knowledge which complements the training aims of the exercises in Section A. Theoretical relationships are demonstrated and the necessary specialist terminology is explained in an easily understandable way with examples.

Section D, “Appendix”, is intended for use as a reference work. It contains data sheets, a list of literature and an index.

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

Equipment set TP111**Order No.: 184467***General***Equipment set TP111 – 100/200, Order No.: 184468**

Description	Order No.	Quantity
Signal input plate, electrical	162242	1
Push-in T connector	153128	3
Plastic tubing, 10 m, silver-metallic, 4 x 0.75	151496	1
Plastic tubing, 5 m, silver-metallic, 6 x 1.0	152963	1
3/2-way valve with pushbutton	152860	2
Pressure gauge	152865	1
One-way flow control valve	152881	2
Service unit with on/off valve	152894	1
Manifold	152896	1
Connector components	152898	1
3/2-way solenoid valve, normally closed	167073	1

*Pressure regulation***Equipment set TP111 – Pressure, Order No.: 184469**

Description	Order No.	Quantity
Komparatorkarte	162257	1
PID-Reglerkarte	162254	1
5/3-Wege-Magnetventil, in Ruhestellung gesperst	167077	1
Druckluftspeicher	152912	2
Analog-Drucksensor	167094	1
5/3-Wege-Proportionalventil	167078	1

Description	Order No.	Quantity
Cable set	167091	3
Digital multimeter	035681	1
Setpoint card	162256	1
Power supply unit	159396	1
Oscilloscope	152917	1
Function generator	152918	1
Cable BNC 4 mm	152919	3
Plug-in adapter	323571	16

Accessories

Description	Order No.	Quantity
Workbook german	94459	1
Workbook english	94465	1

Courseware

Description	Order No.	Quantity
Scale 450 mm	525927	1
Loading weight	034065	1
Connection panel (loading weight)	167032	1
Linear actuator 450 mm	192501	1
Status controller card	162253	1
Linear potentiometer	152628	1
Mounting kit for potentiometer	178441	1
Cable for linear potentiometer	376177	1
Shock absorber	34572	2

Equipment set TP111 – Position, Order No.: 184470

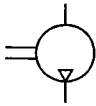
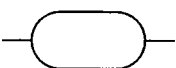
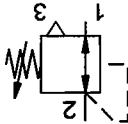
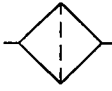
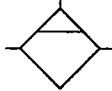
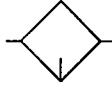
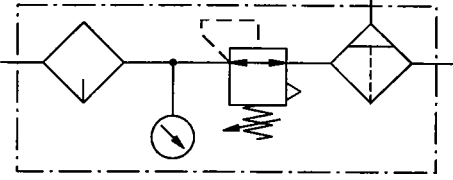
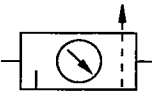
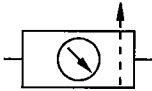
Positioning



Safety instructions

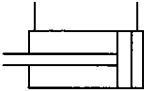
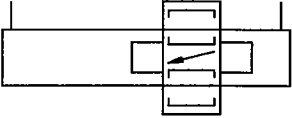
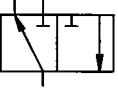
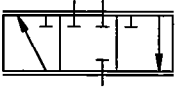
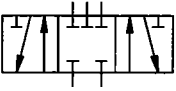
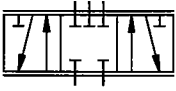
- In the interests of your own safety, please follow the instructions given below:
- Mount all components securely on the plate.
 - When commissioning control circuits, always switch on first the electrical power supply and then the compressed air. When switching off, work in reverse order.
 - Do not switch on the compressed air until you have connected up and secured all the tubing.
 - Exercise great care when switching on the compressed air. Cylinders may advance or retract unexpectedly.
 - Shut off the compressed air supply immediately if tubing becomes detached. This will help to prevent accidents.
 - Never disconnect tubing while this is under pressure.
 - Never exceed the maximum permissible operating pressure of 8 bar. You will need a maximum of 6 bar to carry out the exercises in the course.
 - Please also observe the general safety instructions of DIN58126 and VDE 100.
 - Use only extra-low voltage supplies, maximum 24 V DC.
 - Before commissioning closed-loop control circuits, check not only the pneumatic lines but also the electrical cables and connections.
 - Please note that the slide of the linear drive is fitted with powerful magnets. Do not bring any diskettes or other objects sensitive to magnetic fields into the vicinity of these magnets.
 - Observe the data sheets referring to individual components, particularly with regard to safety instructions.

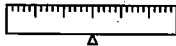
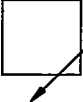
Symbols for equipment set

Compressor with constant displacement volume 	Pressure source 
Reservoir 	
Pressure regulating valve 	One-way flow control valve 
Filter: Separating and filtering of dirt particles 	Water separator, manual actuation 
Water separator, automatic 	Lubricator: Metered quantities dispersed into air flow 
Service unit consisting of compressed air filter, pressure regulator, pressure gauge and lubricator 	
Service unit, simplified representation with lubricator 	Service unit, simplified representation without lubricator 

Symbols for equipment set

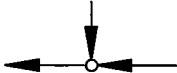
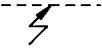
*Symbols for
equipment set*

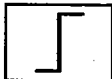
 Double-acting cylinder with single-ended piston rod	 Double-acting cylinder without piston rod	 Pressure gauge	 Manual operation	 Plugged port	 3/2-way valve normally closed	 3/3-way dynamic valve single working line	 5/2-way valve two working lines	 5/3-way valve mid position closed	 5/3-way dynamic valve two working lines
--	---	---	---	---	--	--	--	--	--

 Linear scale	 Converter general	 Pressure gauge general	 Pressure sensor electrical	 Amplifier general	 Electrical actuation solenoid with one winding	 Manual actuation by means of spring
 Regulator general	 Adjuster general	 Limiter electrical	 Pressure sensor pneumatic	 Operation amplifier general	 Electrical actuation solenoid with two opposed windings infinitely adjustable	 Pilot actuated indirect by application of pressure

Symbols of
equipment set

Symbole des Gerätesatzes

 Working line line for energy transmission	 Link collecting or summation point	 Line connection fixed connection	 Electrical line line for electrical power transmission	 Display indicator light	 Transmission element proportional time response	 Transmission element with integral time response	 Transmission element with differential time response

 Transmission element two step action without hysteresis	 Comparator	 Transmission element three step action	 Transmission element with PD time response	 Transmission element with PI time response	 Voltage generator D.C. voltage	 Voltage generator sine-wave voltage
 Transmission element hysteresis, differential	 Transmission element three step action	 Transmission element with PD time response	 Voltage generator square-wave voltage	 Voltage generator triangular-wave voltage	Symbols for equipment set	

Section A – Course

I. Non-dynamic closed-loop pressure control circuit

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II. Dynamic closed-loop pressure control circuit

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	without compensation	
	Mode of operation of a linear potentiometer	
Exercise 18:	Sorting device	A-187
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	Lag error and closed-loop gain	
Exercise 21:	Palletizing station	A-221
	Influence of mass load and tubing volume	

Subject

Title

Maintenance of a pressure gauge

Closed-loop pneumatics

- To be able to distinguish between sensors according to their signal types

- To be able to explain the design and mode of operation of an analogue pressure sensor
- To be able to produce and evaluate characteristics for sensors

Sensor

Technical knowledge

A sensor acquires a measured variable, such as temperature, filling level or torque, and converts this into an electrical or mechanical signal. Sensors are classified as binary, digital or analogue types, depending on the signal they produce.

- Binary sensor – A binary sensor produces an output signal which can have one of two switching statuses (e.g. on/off or 0 V / 10 V).

- Digital sensor – A digital sensor produces an output signal which corresponds to a number, created for example by the addition of several pulses.

- Analogue sensor – An analogue sensor produces an output signal which can be represented by a continuous curve (e.g. the deflection of the pointer of a pressure gauge)

Sensors are also occasionally referred to as signal pick-ups, signal converters or as measuring systems or measuring transducers.

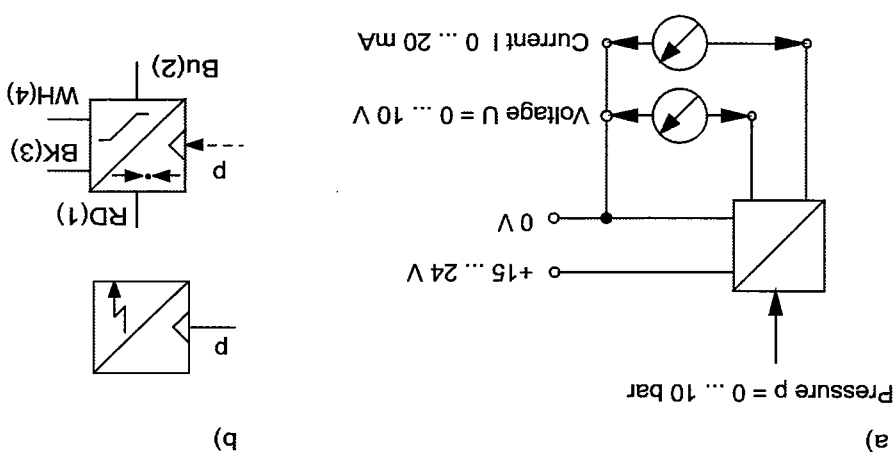
Analogue pressure sensors

The pressure sensor used in this case converts the measured variable "pressure" into an electrical signal. The permissible input pressure is between 0 and 10 bar positive pressure. The sensor supplies two output variables:

- A voltage of between 0 and 10 V,
- A current of between 0 and 20 mA.

The permissible supply voltage lies between 15 and 24 V.

Fig. A1.1:
Connection diagram,
pneumatic and electrical
symbols for analogue
pressure sensor



Characteristic

A characteristic is a graphic description of the relationship between an input variable and an output variable. Characteristics can be produced for components, devices or even complete installations. They are used for assessment and comparison purposes.

In the case of a pressure sensor, too, the relationship between the input variable and output variable can be represented by a characteristic, from which the following characteristic data can be read:

- **Input range** – The input range is the range between the smallest and largest input values which can be recorded (I_{min} , I_{max}). The pressure sensor used here has an input range of between 0 and 10 bar.
- **Output range** – The output range is the range between the smallest and largest output values (O_{min} , O_{max}). The pressure sensor used here has two output ranges: 0 to 10 V and 0 to 20 mA.

- **Linear range** – The linear range is the part of the characteristic line which has a constant gradient; in other words, the characteristic is a straight line in the linear range.

- **Hysteresis** – Measurements with an increasing input variable often produce a different characteristic than measurements with a decreasing input variable. Each input value is thus associated with two output values. The rising and falling characteristics form a hysteresis loop, whose maximum divergence, divided by the input range, gives the value for the hysteresis. The hysteresis H is specified as a percentage and is calculated as follows:

$$\text{Hysteresis} = \frac{\text{Maximum divergence}}{\text{Input range}} \cdot 100 \%$$

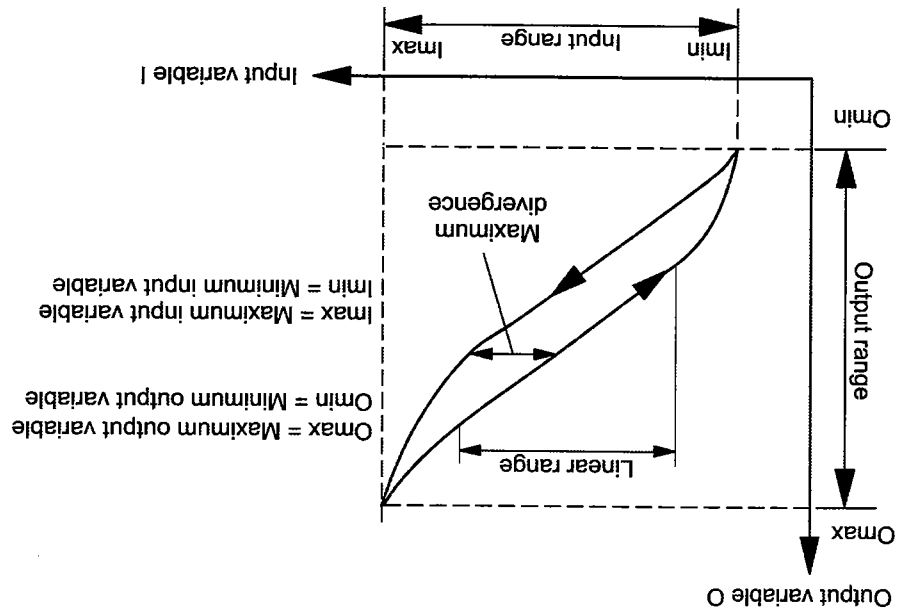
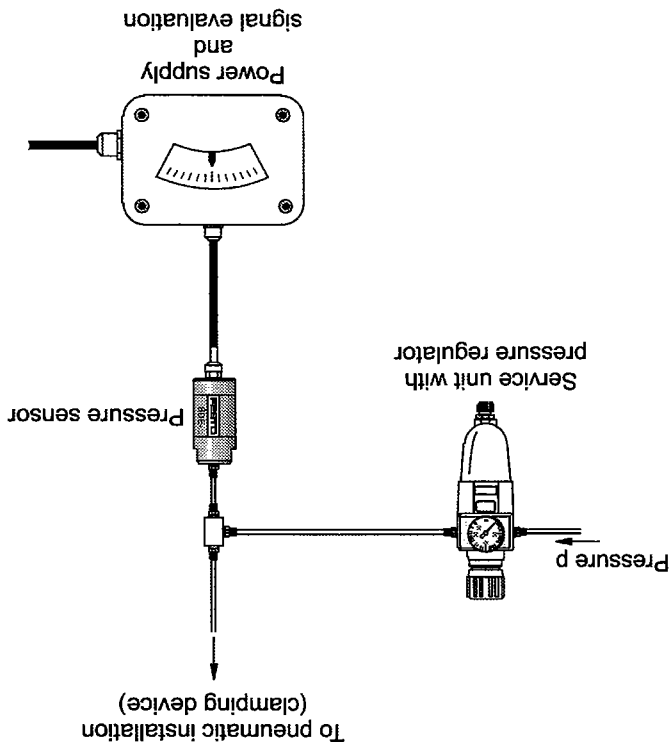


Fig. A1.2:
Characteristic for a
measuring system

Problem description

Routine maintenance work is to be carried out on a pneumatic clamping device. This work includes a check of the pressure gauge on the service unit.

Fig. A1.3:
Positional sketch



Exercise

In the course of the maintenance work, the accuracy of the reading of the pressure gauge must be checked. The following steps must be carried out:

1. Definition of measured variables and selection of measuring system
2. Assembly of measuring circuit
3. Production of characteristic for pressure gauge
4. Determination of hysteresis

1.1 Definition of measured variables and selection of measuring system

Execution

- Define the input and output variables of the measuring system. Assume that the output pressure of the service unit is to be measured and that you have a voltmeter available to measure the sensor output signal. Also specify the associated units for the measured variables.
- Select a measuring system which can handle the input and output variables which you have defined.

1.2 Assembly of measuring circuit

Note the following points with regard to the pneumatic circuit diagram:

- The pressure-gauge function for the pneumatic clamping device is provided by a service unit with an integral pressure regulator and pressure gauge.
- A pressure sensor is connected directly to the compressed-air output of the service unit by means of a piece of tubing.

Note the following with regard to the electrical measuring circuit:

- The power supply for the pressure sensor is 24 V.
 - A multimeter is used to display the sensor output voltage.
- The sockets of the signal input unit are used to connect up the sensor plugs.
- Assemble the measuring circuits in accordance with the circuit diagrams provided.

1.3 Plotting the pressure gauge characteristic

In order to produce the characteristic for the pressure gauge, the output voltage of the pressure sensor must be determined and recorded.

- Start the measurements at 0 bar. Then turn the adjusting knob of the service unit to increase the pressure slowly until the gauge pressure specified in the worksheet is reached.



Ensure that you go directly to the desired pressure value in order to ensure that you do not need to turn the adjusting knob back, which would reduce the hysteresis.

- Read the measured values carefully and record the values in the table on the worksheet.
- Take one measurement with rising pressure and one with falling pressure.
- Then enter the values on the graph provided.

1.4 Determining the hysteresis

- Determine the maximum divergence between the two measurement curves.
- Calculate the hysteresis with the aid of the hysteresis equation.

WORKSHEET

1.1 Definition of measured variables and selection of measuring system

Measured variables and units

Input variable: ()

Output variable: ()

Measuring system:

1.2 Assembly of measuring circuit

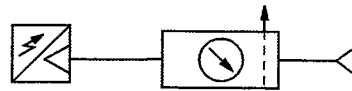


Fig. A1.4:

Pneumatic circuit diagram

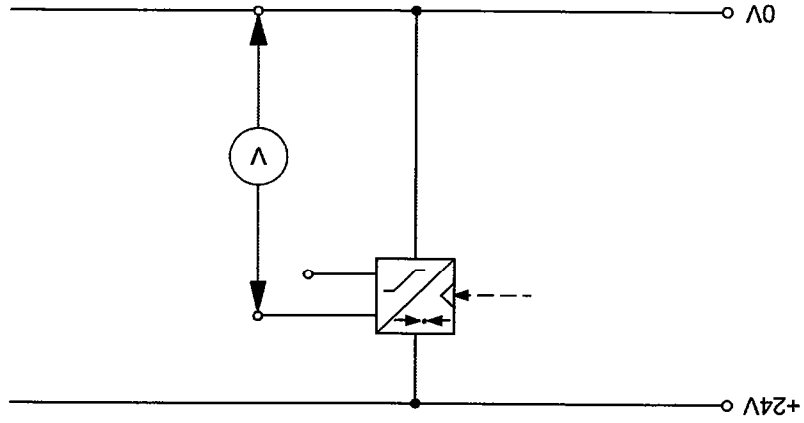


Fig. A1.5:

Electrical circuit diagram

1.3 Plotting the pressure gauge characteristic

Measure the output voltages of the pressure sensor for the various readings of the pressure gauge.

Measurement with increasing pressure

Table A1.1:

Pressure gauge reading [bar]	Pressure sensor voltage [V]
0	
1	
2	
3	
4	
5	
6	

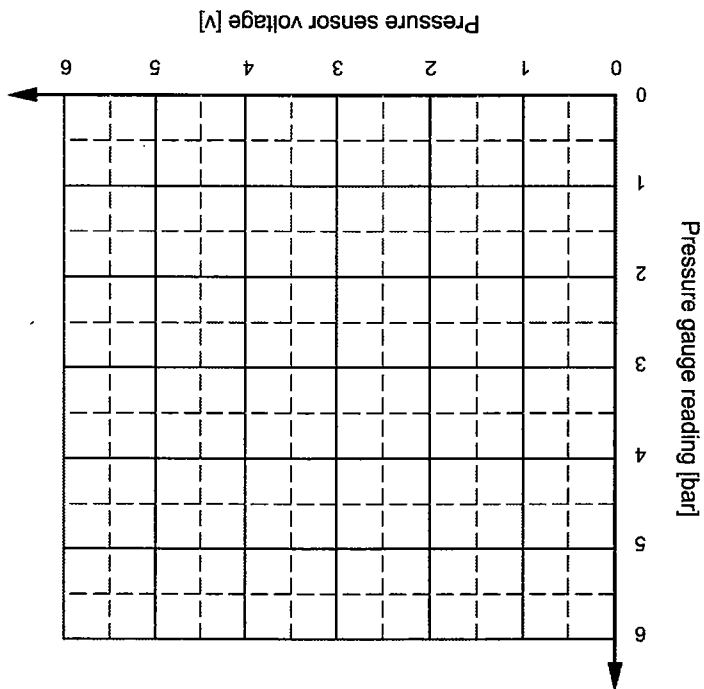
Measurement with decreasing pressure

Table A1.2:

Pressure gauge reading [bar]	Pressure sensor voltage [V]
6	
5	
4	
3	
2	
1	
0	

Enter the measured values into the prepared graph.

Fig. A1.6:
Diagram



WORKSHEET

1.4 Determining the hysteresis

How great is the hysteresis of the pressure gauge?

$$H = \frac{\text{Max. divergence}}{\text{Input range}} \cdot 100 \%$$

$$H = \text{-----} \cdot 100\% = \text{-----} \%$$

Subject

Title

Training aims

- To be able to describe the mode of operation of a comparator
- To be able to set setpoints and switching differences (hysteresis)

Spot-welding machine

Closed-loop pneumatics

Comparator

A comparator compares two analogue voltages with each other. One voltage forms the setpoint and is compared with the input voltage. The comparator output is energised in accordance with the result of this comparison. A positive-switching comparator exhibits the following behaviour:

- The output is set when the input signal exceeds the setpoint.
 - The output is reset when the input signal falls below the setpoint.
- A negative-switching comparator behaves in the opposite way.

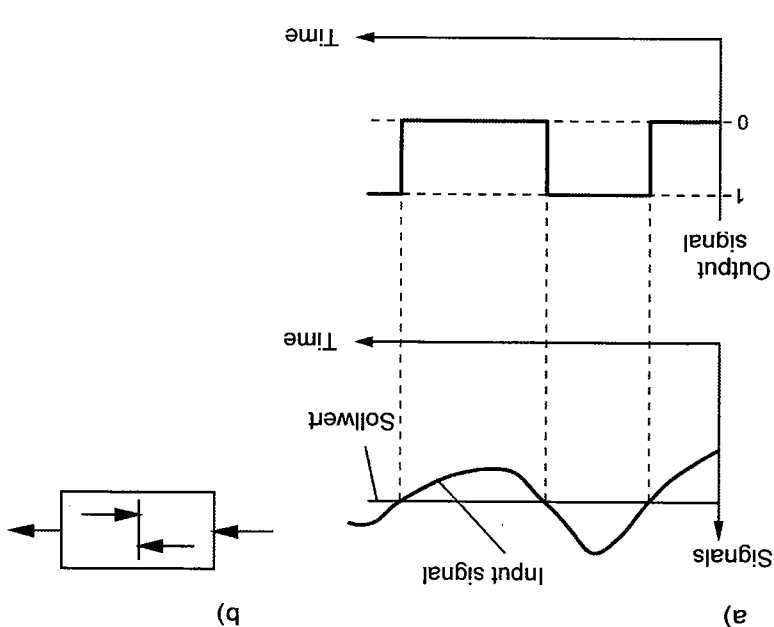


Fig. A2.1:
Mode of operation and
symbol for a
positive-switching
comparator

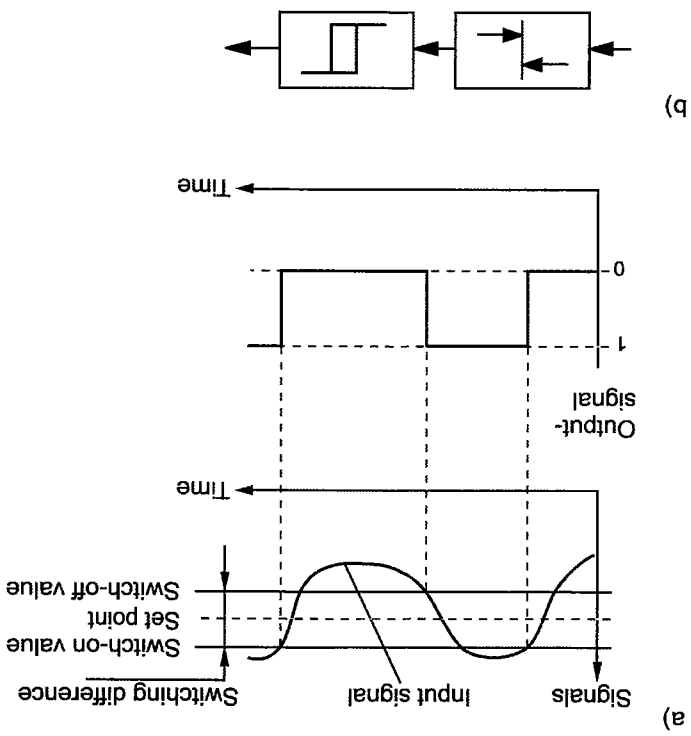
With some comparators, the switching behaviour depends on whether the input signal is rising or falling. In this case, the comparator output switches at two different input values (switch-on and switch-off value). The difference between these two input signal values is known as the switching difference or hysteresis.

A positive-switching comparator with switching difference exhibits the following behaviour:

- The output is set when the input signal exceeds the switch-on value.
- The output is reset when the input signal falls below the switch-off value.

The output of a negative-switching comparator with switching difference behaves in the opposite way.

Fig. A2.2:
Mode of operation and
symbolic representation
a positive-switching
comparator with
switching difference



A comparator with switching difference is also known as a Schmitt trigger.

Comparator card

The comparator card used here has two separate inputs (IN A, IN B), each of which acts on one of two independent comparators. The outputs of these are designated OUT A1, A2 and OUT B1, B2. The energisation of outputs is shown by LEDs.

The following voltage values can be set on each comparator:

- Setpoint voltage: - 10 V ... 10 V,
- Hysteresis: 0 V ... 5 V.

The switch-on and switch-off values are defined as follows:

- Switch-on value = Setpoint + 1/2 hysteresis,
- Switch-off value = Setpoint - 1/2 hysteresis.

The setpoints and hysteresis values are selected by means of a selector switch. The voltage settings are made with the aid of an adjusting knob. The values can be read on a display.

The power supply for the comparator card is 24 V.

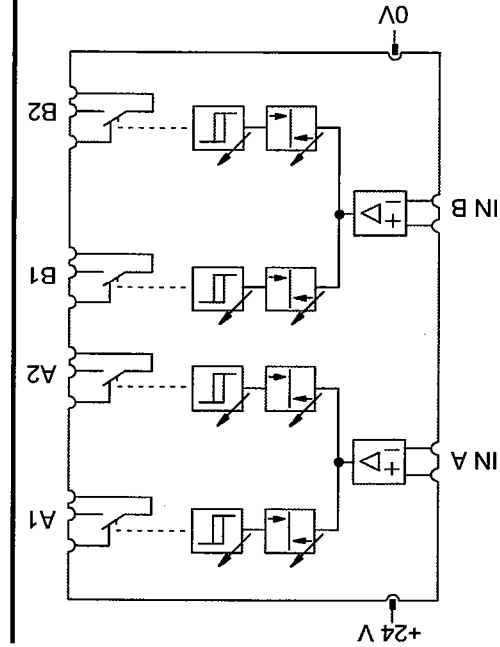
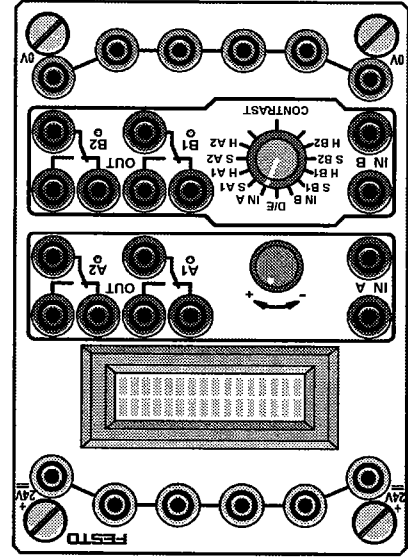


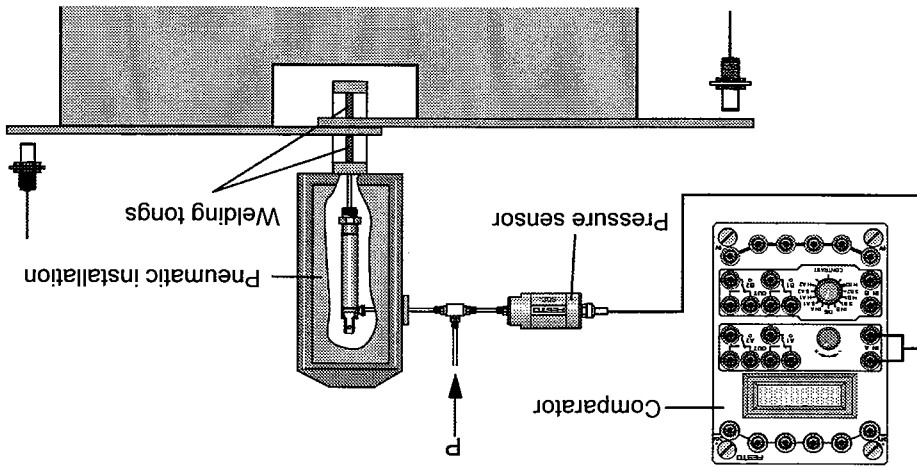
Fig. A2.3:
Front panel and
schematic representation
of comparator card

Problem description

Sheet-metal components of various thicknesses are fed to a spot-welding machine and pressed together by pneumatically-driven welding tongs. The various metal thicknesses are measured by sensors. In order to prevent holes from being burnt in the material during the welding operation, the force of the welding tongs must be varied according to the material thickness.

- The tongs pressure is proportional to the pressure in the cylinder chamber. The pressure in the cylinder is thus measured in order to check the tongs force. A pressure sensor measures the instantaneous pressure and outputs a corresponding voltage signal to a comparator. This evaluates whether the tongs force is within the permissible hysteresis range:
- As soon as the permissible upper limit for the tongs force is exceeded, an indicating light is to be illuminated.
 - The light must remain illuminated until the tongs force again falls below the permissible upper limit.

Fig. A2.4:
Positional sketch



Exercise

Various comparators must be set during the commissioning of the spot-welding machine. The following steps must be carried out for this purpose:

1. Calculation of the setpoints and switching differences
2. Setting of the setpoints and switching differences
3. Drawing of pneumatic and electrical test circuit
4. Assembly of test circuit and checking of switching values

2.1 Calculation of the setpoints and switching differences

Execution

The various tongs forces correspond in each case to a certain pressure in the cylinder. A pressure sensor measures this chamber pressure and generates a corresponding output voltage. The first step must be to determine the relationship between the permissible tongs forces and the sensor output voltages.

Let us assume for the sake of simplicity: Tongs force = Cylinder force.

The cylinder force can be calculated using the following formula:

$$\text{Cylinder force [N]} = \frac{\text{Chamber pressure [bar]} \cdot \text{Piston dia}^2 [\text{mm}^2] \cdot 3.14}{40}$$

This can be re-stated to obtain the formula for the chamber pressure:

$$\text{Chamber pressure [bar]} = \frac{40 \cdot \text{Cylinder force [N]}}{\text{Piston dia}^2 [\text{mm}^2] \cdot 3.14}$$

The characteristic for the pressure sensor is shown in the graph below.

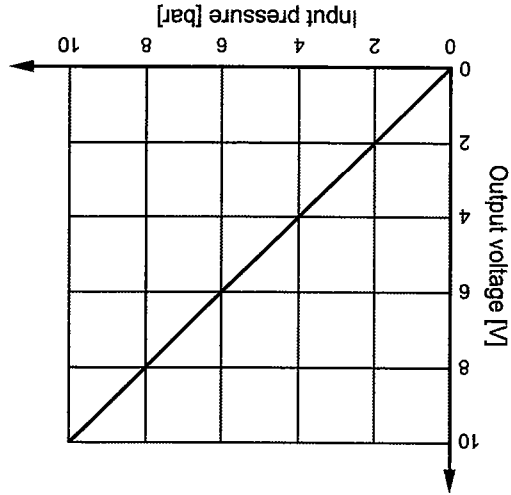


Fig. A2.5:
Characteristic for analogue
pressure sensor

2.2 Setting the setpoints and switching differences

The setpoints and switching differences which have been determined are set on the comparator card as follows:

- Assemble the specified electrical circuit.
- Switch on the electrical power supply.

- Set the selector switch to "S A1".
 - Turn the rotary knob until the calculated setpoint voltage is shown on the display.
 - Set the rotary switch to "H A1".
 - Turn the potentiometer until the calculated switching difference is shown on the display.
- The comparators A2 and B1 are set in the same way.

2.3 Drawing the pneumatic and electrical test circuit

- After the setpoints have been determined and set, the values must be checked using a test circuit. This test circuit should be as follows:
- A pressure sensor should be connected to the air output of a service unit by means of a piece of tubing.
 - The voltage output of the pressure sensor should be connected to the inputs of the comparator card.
 - Each comparator output should be connected to an indicating light on the signal input plate, which will then light to show that the output in question is energised.

2.4 Assembly of test circuit and checking of switching values

- Assemble the circuit which you have previously drawn.
- Switch on the electrical power supply.
- Set the selector switch of the comparator card to "IN A"; the input voltage will now be displayed.
- Increase the pressure slowly from 0 bar to 6 bar. Note the switch-on voltages of the comparators (shown by the fact that the indicating lights are illuminated).
- Reduce the pressure slowly from 6 bar to 0 bar. Note the switch-off voltages of the comparators (shown by the fact that the indicator lamps go out).
- Determine the corresponding chamber pressures (sensor characteristic) for the measured switching voltages.
- Calculate the cylinder forces for these pressures (using the formula).
- Evaluate the test results by comparing the cylinder force settings with the required forces.

WORKSHEET

2.1 Calculation of setpoints and switching differences

Calculate the upper and lower chamber pressures for the permissible cylinder forces. Then calculate the difference between the chamber pressures.

The cylinder diameter is 50 mm.

Calculate the corresponding setpoint voltages and switching differences. Use the characteristic for the pressure sensor to determine the voltages.

Chamber pressure = Sensor input pressure

Switching difference = Difference between chamber pressures

Setpoint = Upper chamber pressure – 1/2 switching difference

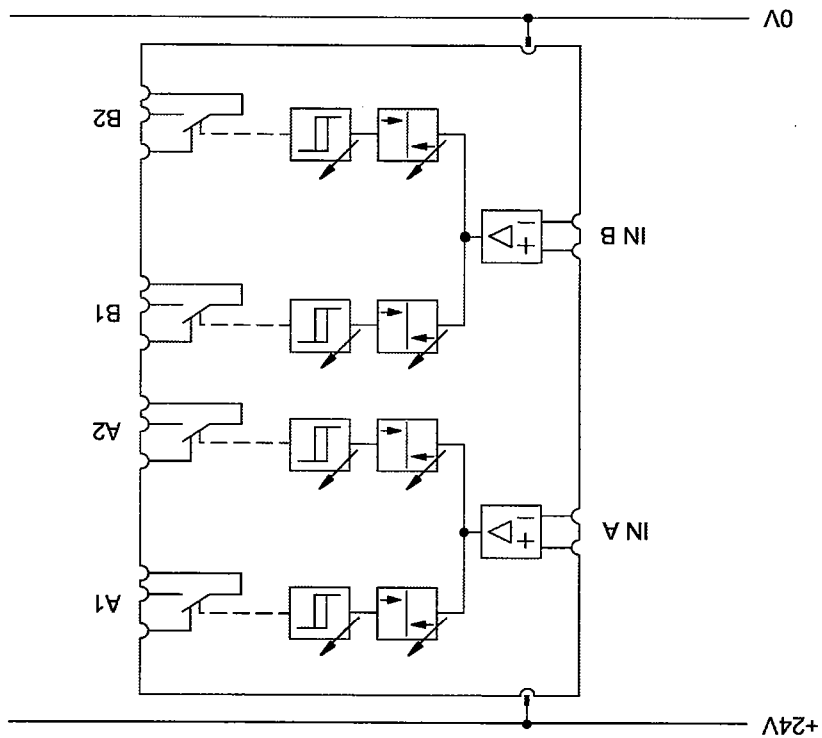
Enter all the values into the prepared table.

Table A2.1:

Permissible lower cylinder force [N]	Permissible upper cylinder force [N]	lower chamber pressure [bar]	upper chamber pressure [bar]	Difference between chamber pressures [bar]	Setpoint [V]	Switching difference [V]
392.50	471.00					
588.75	745.75					
785.00	981.25					

2.2 Setting the setpoints and switching differences

Fig. A2.6:
Electrical circuit diagram



2.3 Drawing the pneumatic and electrical test circuit

Complete the pneumatic and electrical test circuits.

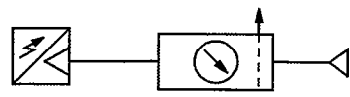


Fig. A2.7:

Pneumatic circuit diagram

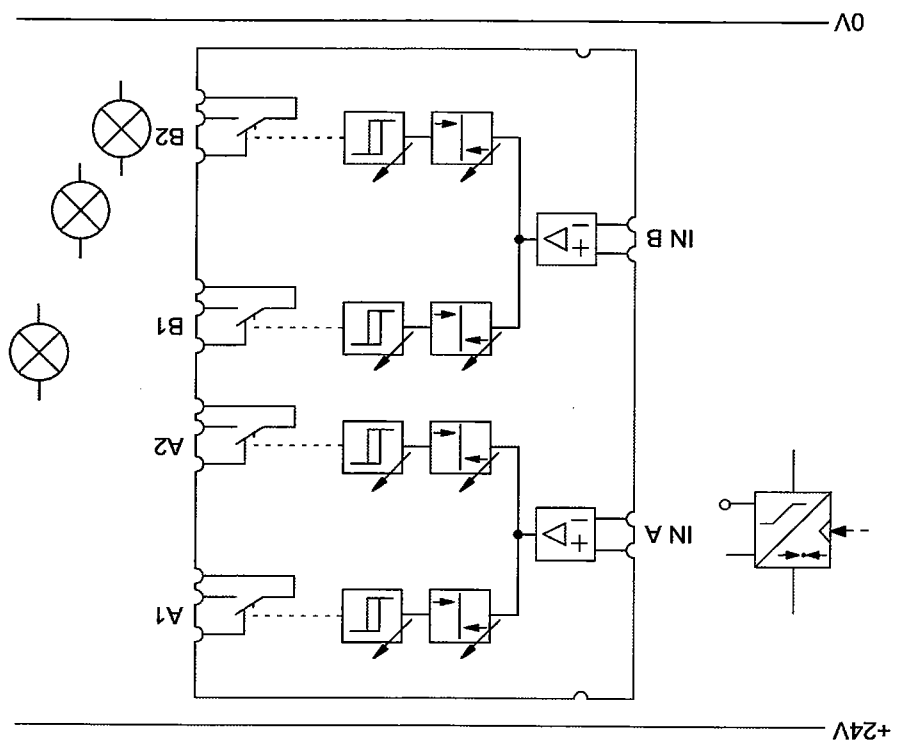


Fig. A2.8:

Electrical circuit diagram

2.4 Assembly of test circuit and checking of switching values

Table A2.2:

Switch-on voltage [V]	Switch-off voltage [V]	Lower chamber pressure [bar]	Upper chamber- pressure [bar]	Lower cylinder force [N]	Upper cylinder force [N]

What is the maximum deviation between the required and set cylinder forces?

Subject

Title

Training aims

- To be able to explain the term "runtime performance"
- To be able to classify controlled systems according to their runtime performance
- To be able to produce and assess transition functions

Pneumatic controlled system

Technical knowledge

The term "pneumatic controlled system" is used to describe parts of a pneumatic circuit, which generally consists of a combination of valves, cylinders, reservoirs and tubing.

In closed-loop control technology, the relationship between the input and output variables of a controlled system is of great importance. An input variable may be, for example, a suddenly-changing pressure which acts on a reservoir. The output variable obtained in this case is a change in the internal reservoir pressure.

This change in internal pressure does not, however, take place suddenly but is subject to a time delay, which may be of a greater or lesser duration. We speak in this case of the runtime performance of a controlled system.

The time-related relationship between an output signal and the step-change of an input signal is known as a transition function or a step response. Fig. A3.1 shows a transition function and the corresponding block diagram.

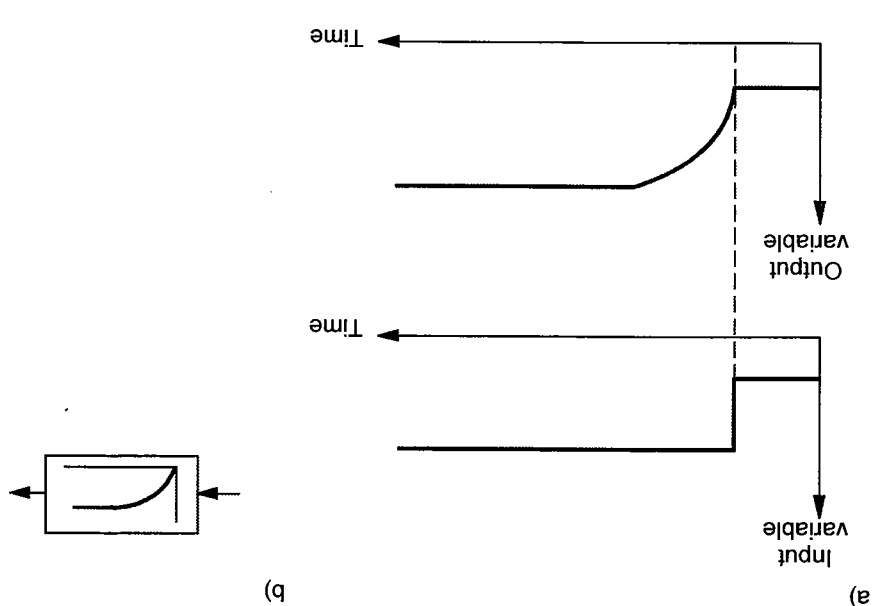


Fig. A3.1:
Transition function and
symbol for a
controlled system

Closed-loop pneumatics

Packaging machine

Controlled systems are classified into different types, according to their runtime performance.

Table A3.1:
Types of controlled systems

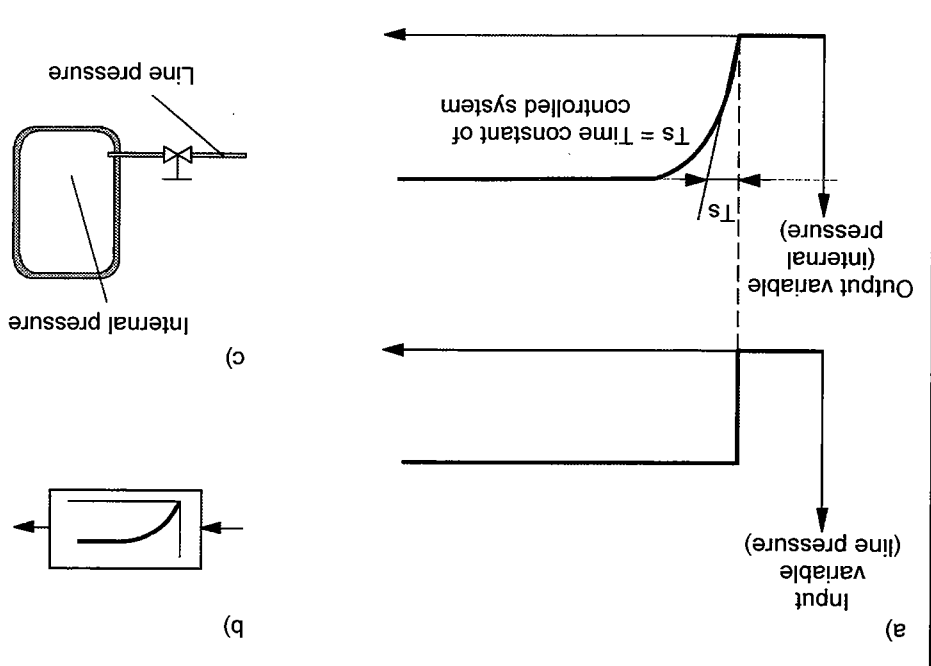
Controlled system	with compensation	
	without compensation	with/without delay
	without compensation	with/without delay

A controlled system with compensation is characterised by the fact that its output variable tends towards a new constant value after a step-change in the input variable.

One example of a controlled system with compensation is a reservoir with an upstream flow control valve. The line pressure upstream of the flow control valve forms the input variable of the controlled system. The internal pressure of the reservoir forms the output variable. In a steady state, the line pressure equals the internal pressure. If the line pressure is now abruptly increased, the internal pressure will again equal the line pressure after a certain time.

Controlled systems with a delay are not able to provide immediate compensation for disturbances. They react with a delay, which means that the output variable becomes equal to the new value only gradually. The magnitude of the delay is expressed by the time constant T_s . This is determined by a tangent construction and expressed in the unit of seconds.

Fig. A3.2:
Controlled system with compensation and delay



A connection in series of several reservoirs separated by flow control valves produces controlled systems with several time constants. We speak in this case of *controlled systems with a higher-order delay*. A *controlled system with compensation and without a delay* is characterised by the fact that the output variable immediately follows the input variable. An example of a controlled system of this kind is a mechanical lever.

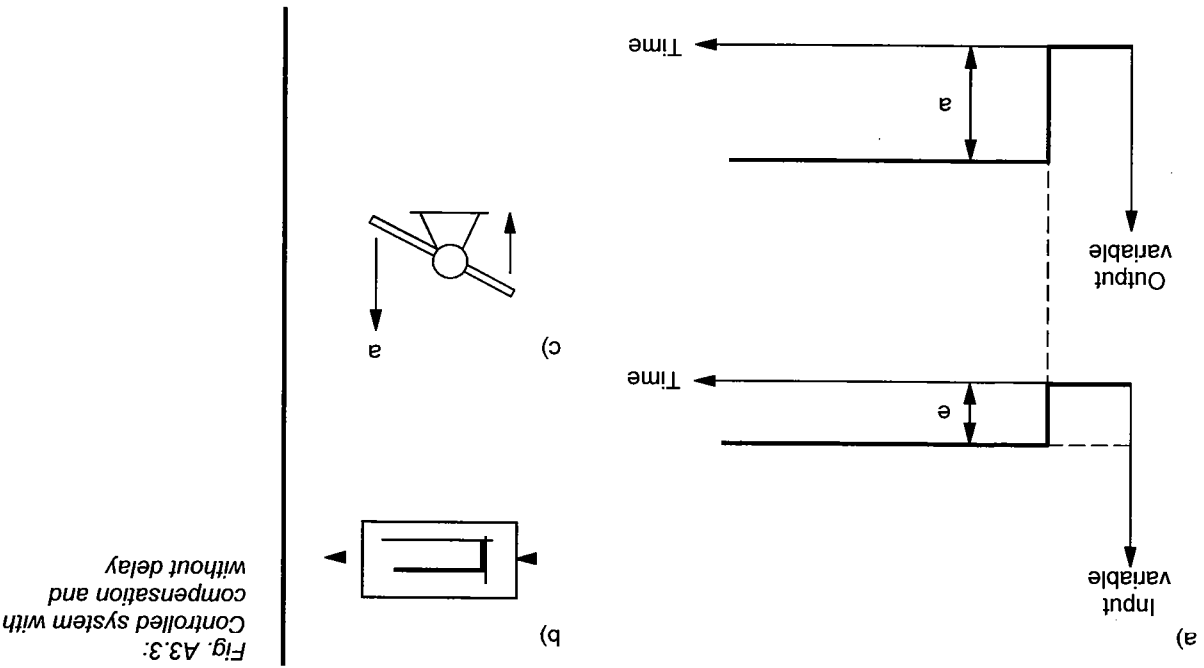
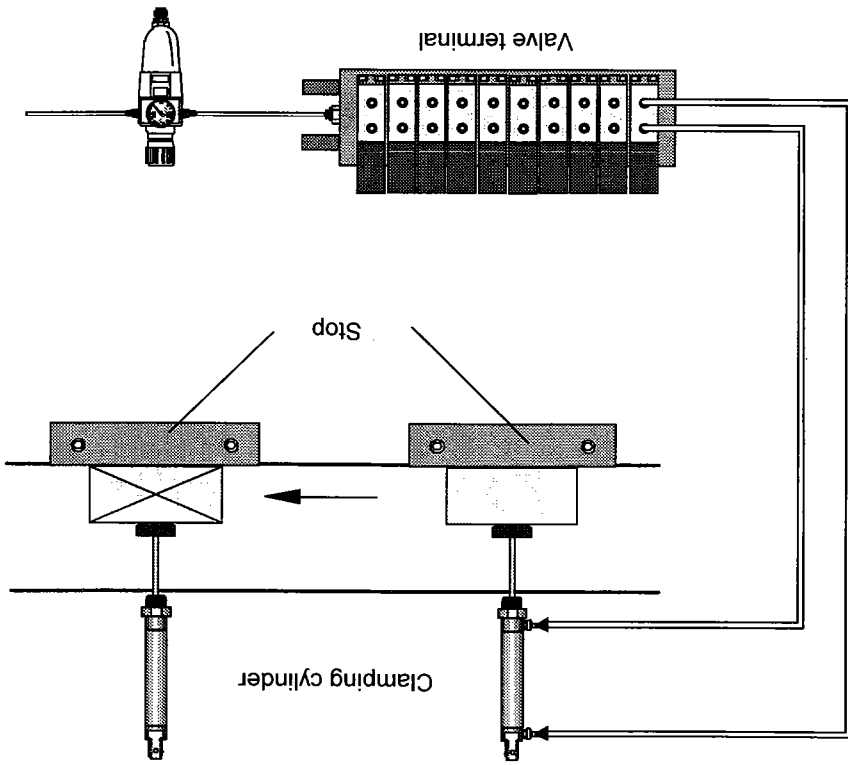


Fig. A3.3:
Controlled system with
compensation and
without delay

Problem description

A packaging machine is equipped with a pneumatic clamping device. This device incorporates pneumatic cylinders, the pressure of which is controlled. The necessary valves are mounted on a valve terminal. Very long supply lines are required in order to bridge the distances between the valve terminal and the cylinders. These supply lines retard the pressure build-up and influence the runtime performance of the installation. This delay depends on the volume of the tubing. A knowledge of the relationship between the air volume and the resulting delay is necessary in order to optimise the motion sequence of the machine.

*Fig. A3.4:
Positional sketch*



Exercise

- A test assembly must be produced and commissioned in order to determine the time constants. The following steps must be carried out:
1. Assembly in accordance with the pneumatic and electrical diagrams
 2. Production of transition functions and measurement of the time constants

3.1 Assembly in accordance with the pneumatic and electrical circuit diagrams

Execution

Various lengths of tubing and reservoirs are to be pressurised in a step-change to a pressure of 6 bar. The tubing and reservoirs are installed between a 3/2-way solenoid valve and a pressure sensor. The following controlled systems must be investigated:

- Tubing with lengths of approx. 250 mm, 750 mm and 2000 mm
- A reservoir with a volume of 0.4 l
- Two reservoirs in series, each with a volume of 0.4 l, linked by a flow control valve. The flow control valve should be opened fully.

The electrical circuit diagram is as follows:

- The power supply for the pressure sensor is 24 V.
- The solenoid of the switching valve is connected to the 24 V supply via a pushbutton on the signal input plate. This pushbutton is used to actuate the valve.

- The relevant transition functions are recorded on a two-channel storage oscilloscope. One channel is used to display the sensor output signal and the other for the electrical actuating signal for the switching valve.

3.2 Determining transition functions and measurement of the time constants

The transition functions and time constant are determined as follows:

- Install the longest piece of tubing between the valve and sensor.
- Switch on the electrical power supply and compressed air supply.
- Press the pushbutton on the signal input plate.
- Display the step-change energisation of the switching valve and the voltage rise at the pressure sensor on the oscilloscope. The curve for the sensor voltage represents the transition function.
- Use a tangent construction to determine the time constants for the various controlled systems.
- Follow the same procedure for the other lengths of tubing and reservoirs.



There is a time delay, due to the switching time of the valve, between the energisation of the solenoid valve and the start of the pressure rise. This delay has no influence on the time constant.

WORKSHEET

3.1 Assembly in accordance with the pneumatic and electrical circuit diagrams

Assemble the pneumatic and electrical circuits.

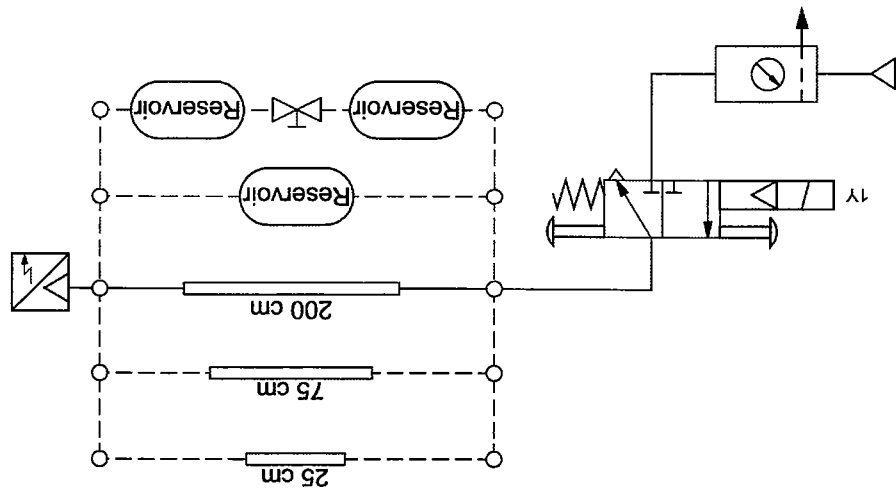


Fig. A3.5:

Pneumatic circuit diagram

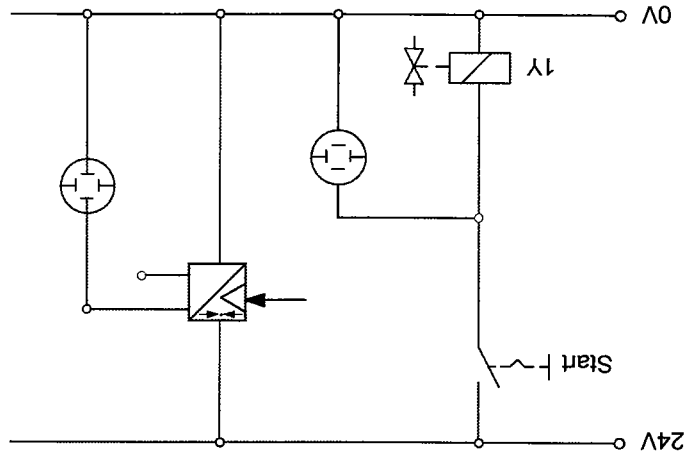


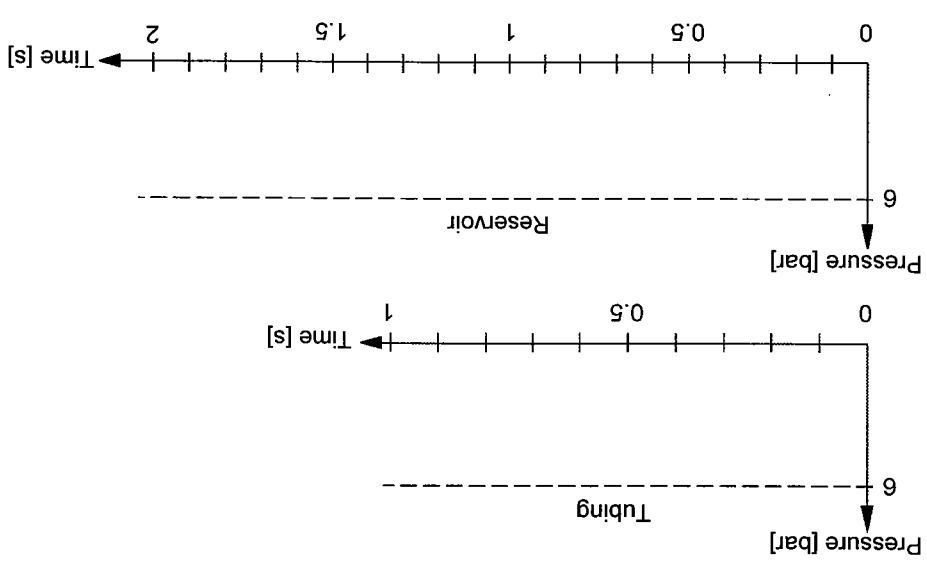
Fig. A3.6:

Electrical circuit diagram

3.2 Determining transition functions and measurement of the time constants

Draw the transition functions for tubing of various lengths (approx. 250 mm, 750 mm and 2000 mm) and one or two reservoirs (each of 0.4 l):

Fig. A3.7:



What property of air is the reason for the difference in the time constants?

- ☐ Becomes larger
- ☐ Becomes smaller
- ☐ Stays the same

How does the time constant change as the volume of the controlled system increases?

Controlled system	Length Volume	Time constant T_s [s]	Recommended oscilloscope setting (time/division)
Tubing	250 mm		10 ms
Tubing	750 mm		10 ms
Tubing	2000 mm		20 ms
One reservoir	0.4 l		200 ms
Two reservoirs	Each 0.4 l		500 ms

Table A3.2:

Determine the time constants and enter these into the table below.

WORKSHEET

Subject Title

Reservoir-charging circuit

- To be able to explain the difference between open-loop control and closed-loop control
- Familiarisation with the configuration of a closed-loop control circuit
- To be able to explain the mode of operation of a two-step-action controller with a switching difference
- To be able to commission a two-step-action controller

Open-loop and closed-loop control

Technical knowledge

The term "closed-loop control" is used to describe a process in which a measured variable (controlled variable) is continuously measured and compared with another variable (reference variable). Depending on the result of this comparison, the controlled variable is influenced in order to make it equal to the reference variable. This is achieved by arranging for the controlled variable to act on itself. This feedback effect creates a closed process of action (closed control loop). Fig. A4.1 compares the process of action of an open and closed control loop.

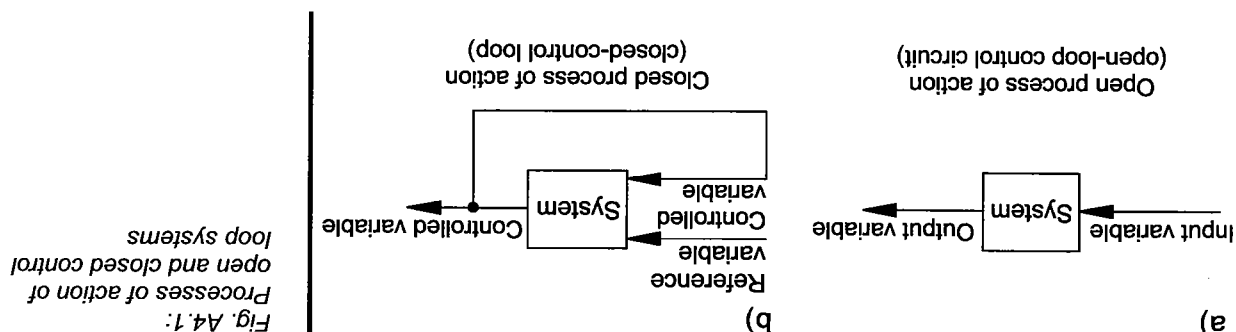


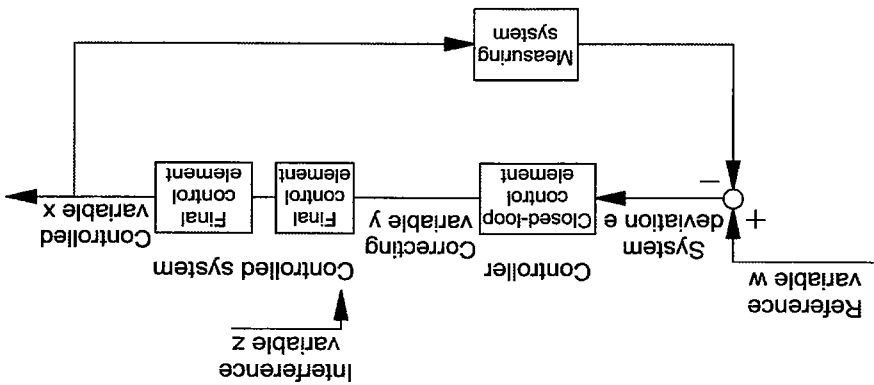
Fig. A4.1:

Processes of action of open and closed control loop systems

The *closed control loop* is made up of the whole of the parts (components) which participate in and influence the closed sequence of actions of the closed loop control. The main components of a closed control loop are the controller, the controlled system and the measuring system. These closed control loop components are connected to each other by signal lines.

Fig. A4.2 provides an overview of a complete closed control loop and the designations used for this.

Fig. A4.2:
Block diagram of a
closed-loop control circuit



Controller

The controller compares two input variables, the controlled variable and reference variable (correcting variable) is generated. Controllers are divided into two groups, dynamic-action and non-dynamic-action controllers.

- With dynamic controllers, the correcting variable can assume any value within a certain range (control range).
- In the case of non-dynamic controllers, the correcting variable can assume only two, three or several defined values.

Controllers whose correcting variable can assume two, three or several defined values are known as two-step-action, three-step-action or multi-step-action controllers. An example of a non-dynamic controller is a comparator.

Two-step-action controller with switching difference

A two-step-action controller with switching difference is designed to keep the controlled variable within the specified switching difference. For this purpose, it generates a correcting variable which can assume two different statuses. This variable activates a downstream final control element, which in turn acts on the controlled variable.

The mode of operation of a two-step-action controller with switching difference is similar to that of a comparator. The time curve for the controlled variable and correcting variable can be illustrated by the example of an reservoir-discharging circuit for the air reservoir of a truck braking system.

Mode of operation of a reservoir-discharging circuit

Phase 1: The truck engine is started at the end of phase 1.
The truck compressor begins to charge the air reservoir.

Phase 2: The reservoir pressure rises and reaches the maximum charging pressure.

Phase 3: The pressure exceeds the maximum charging pressure. The exhaust valve is actuated until the reservoir pressure has fallen to the minimum charging pressure.

Phase 4: The exhaust valve is closed. The pressure rises again.

Phase 5: Same as phase 3.

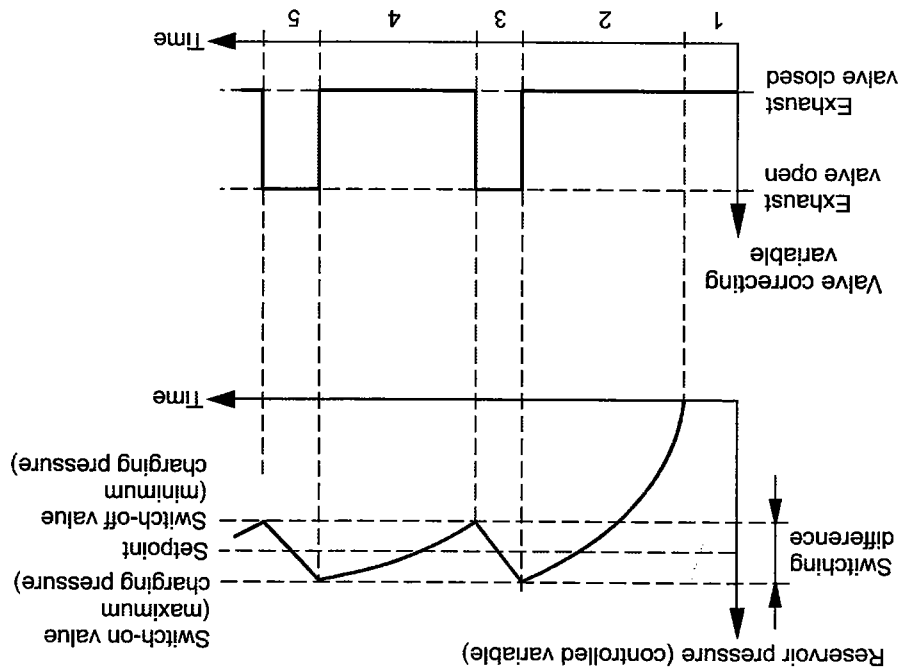


Fig. A4.3:
Examples of curves for a
correcting variable and
controlled variable for a
two-step-action controller
with switching difference

Influence of switching differences

The pressure signal curve is influenced by, among other things, the switching difference (hysteresis) which has been set. Small switching differences produce an accurate closed-loop control action but mean that the valves must switch more frequently. This higher switching frequency in turn means more wear of the final control elements.

Block diagrams for two-step-action controllers with and without a switching difference are shown in Figs. A4.4 and A4.5.

Fig. A4.4:
Symbol for a
two-step-action controller
without switching difference

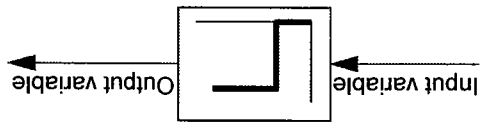
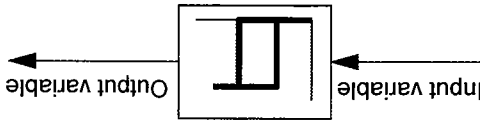
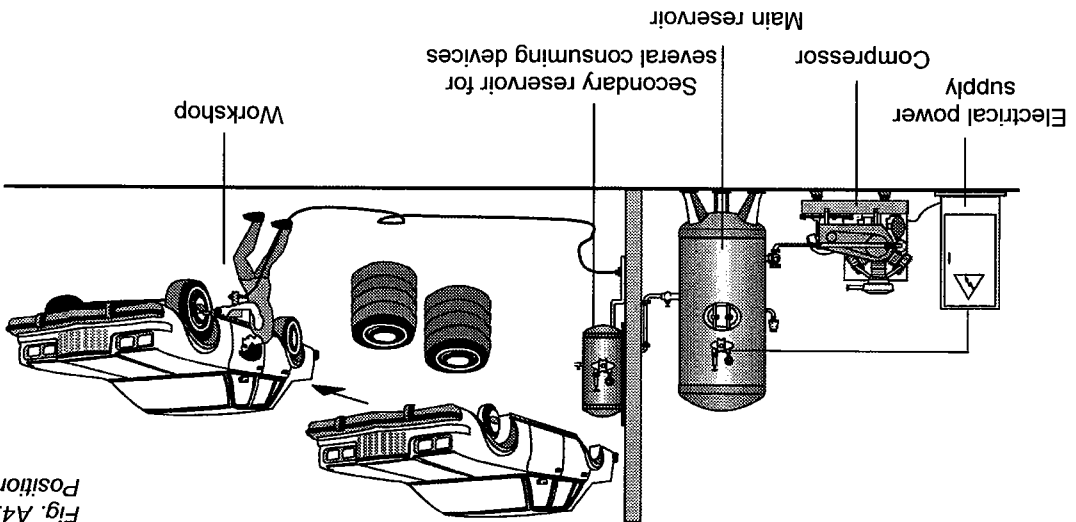


Fig. A4.5:
Symbol for a
two-step-action controller
with switching difference



A closed-loop pressure control system (reservoir-charging circuit) is to be used to ensure that the supply pressure for hand-held pneumatic tools is kept within certain limits. The compressed air supply for the installation is obtained from a reservoir, which is in turn fed by a compressor. As soon as the charging pressure falls below a minimum value, the reservoir must be topped up by the compressor. The compressor must be switched off again when the maximum reservoir pressure is once again reached.

Fig. A4.6:
Positional sketch



This reservoir-charging circuit will be produced using a two-step-action controller with switching difference. The procedure for this is as follows:

1. Drafting of closed-loop control circuit
2. Assembly in accordance with the pneumatic and electrical circuit diagram
3. Commissioning of closed-loop control circuit

4.1 Drafting of closed-loop control circuit

Execution

The closed-loop control circuit for the reservoir-charging circuit is as follows:

- The pressure in the reservoir represents the controlled variable.
- A pressure sensor assumes the function of a measuring system. It measures the reservoir pressure.
- A comparator acts as a two-step-action controller. It is used to set the minimum and maximum charging pressure for the reservoir.

- The compressor is simulated by a 3/2-way valve. The switching position "compressor off" corresponds to the closed valve position (the reservoir is not fed with pressure). The switching position "compressor on" corresponds to the open valve position (the reservoir is fed with pressure).
- The consumption of compressed air is controlled by a 3/2-way panel-mounted valve. This simulates an interference variable.

4.2 Assembly in accordance with the pneumatic and electrical circuit diagram

- In order to ensure correct operation of the closed-loop control circuit, note the following points regarding the pneumatic circuit diagram:
- The closed-loop control circuit components must be matched one to another. In the case of the reservoir-charging circuit, this means that the air output to the tool must always be less than the delivery of the compressor. Only then can it be ensured that reservoir pressure can always be maintained reliably. The outlet flow rate can be limited with a one-way flow control valve (1V3 open only slightly).
 - A further one-way flow control valve (1V2) prevents compressed air from escaping via the solenoid valve when not actuated. The flow control valve should accordingly be fully closed (ensure the valve is installed in the correct direction!).
 - The measuring system must be correctly installed. In the case of the reservoir-charging circuit, this means that the pressure sensor must be installed at a point at which no or only very slight pressure fluctuations occur. Pressure fluctuations are caused by variations in flow conditions. A suitable point is on the supply side of the reservoir.
 - A pressure gauge should be fitted to the reservoir to provide a pressure reading.
 - Connect an oscilloscope into the circuit at a suitable point to measure the reservoir pressure and the correcting variable for the valve.

4.3 Commissioning of closed-loop control circuit

Check the circuit which you have assembled and switch on the electrical power supply and compressed air.

Set the following values on the comparator:

Setpoint = 3.5 V

Switching difference = 1.0 V

Actuate the panel-mounted valve and observe the curves for the controlled variable and correcting variable on the oscilloscope.

Recommended oscilloscope setting Time: 1 s/division

Amplitude: 2 V/division

Compare the correcting variables for

– the reservoir-charging circuit and

– the reservoir-discharging circuit (Fig. A4.3)

WORKSHEET

4.1 Drafting of closed-loop control circuit

Produce a block diagram for the closed-loop control circuit by labelling the components in the prepared diagram below.

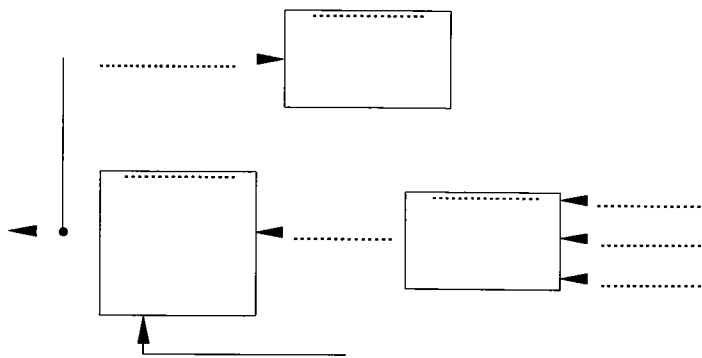


Fig. A4.7:

Block diagram for closed-loop control circuit

4.2 Assembly in accordance with the pneumatic and electrical circuit diagram

Assemble the circuit in accordance with the pneumatic and electrical circuit diagrams provided.

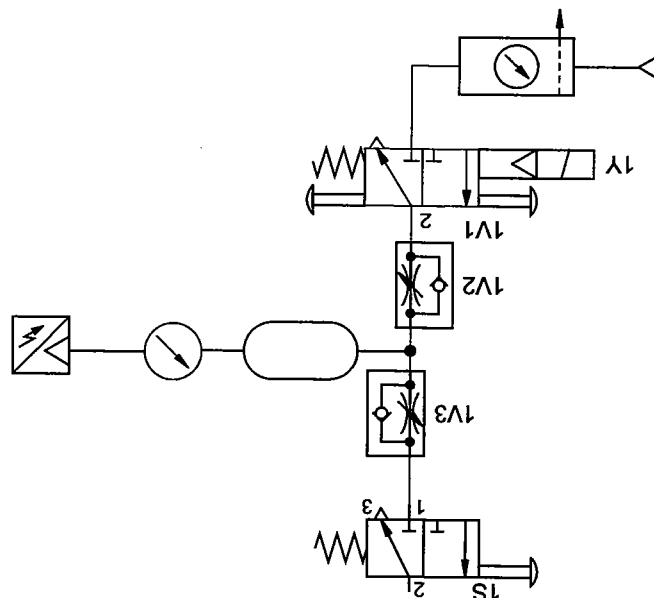
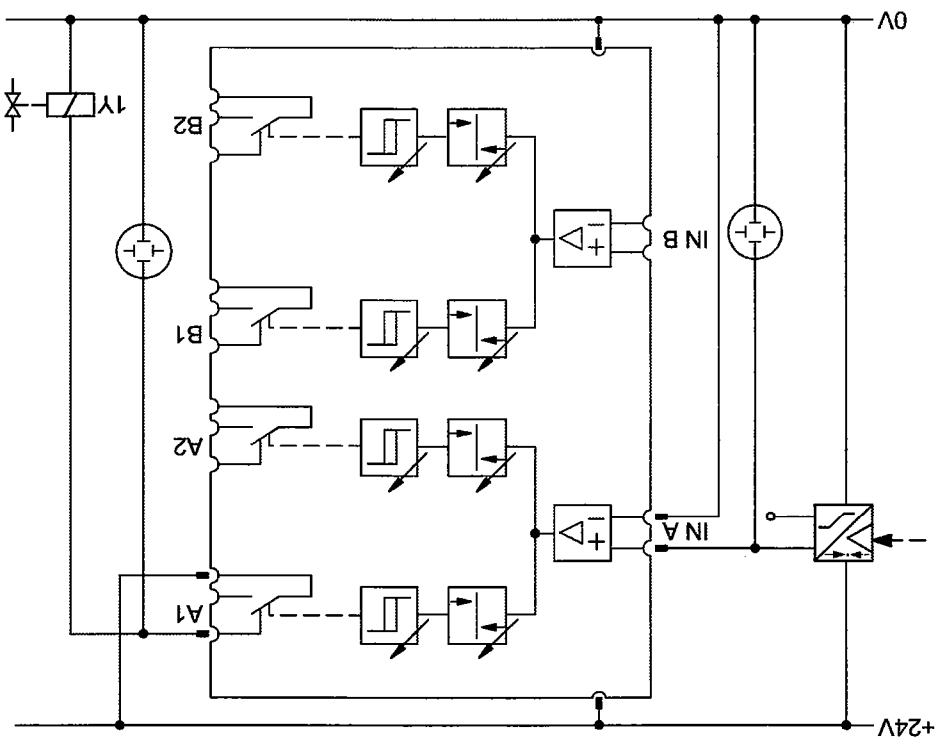


Fig. A4.8:

Pneumatic circuit diagram

Fig. A4.9:
Electrical circuit diagram



WORKSHEET

4.3 Commissioning of closed-loop control circuit

The diagram below shows a possible curve for the controlled variable of the reservoir-charging circuit. Add the curve for the correcting variable and the missing labelling.

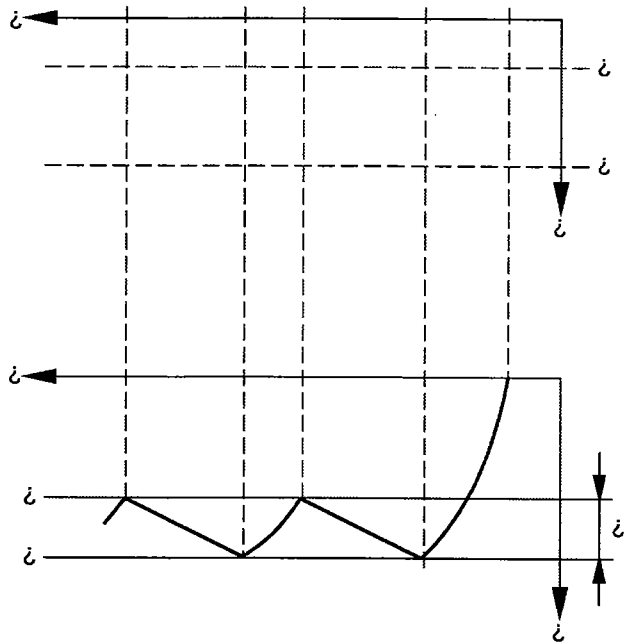


Fig. A4.10:
Curves for controlled
and correcting variables

What do you notice when you compare this correcting variable curve with Fig. A4.3?

Explain your observations:

Subject

Title

Training aims

- To be able to explain the mode of operation of a three-step-action controller
- To be able to commission a three-step-action controller

Technical knowledge

Like a two-step-action controller, a three-step-action controller is classified as a non-dynamic controller.

A three-step-action controller uses an input variable to produce up to three different correcting variables. These may be used, for example, to energise a 5/3-way solenoid valve. The range between the upper and lower switching values is known as the dead zone U_t .

Three-step-action controllers may exhibit one or two switching differences. Figs. A5.2 and A5.3 show the symbols for these.

Closed-loop pneumatics

Tyre test-rig

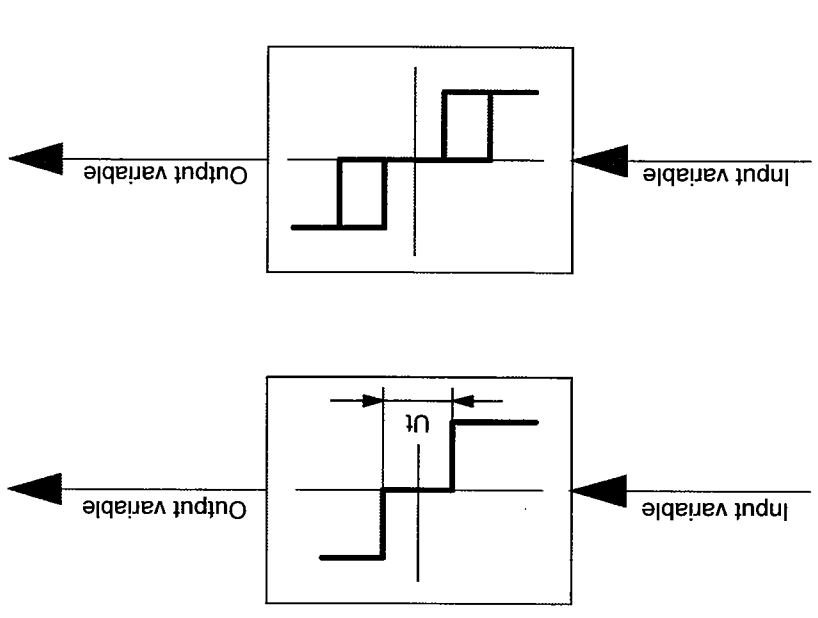


Fig. A5.1:

Symbol for

three-step-action controller

Fig. A5.2:

Symbol for

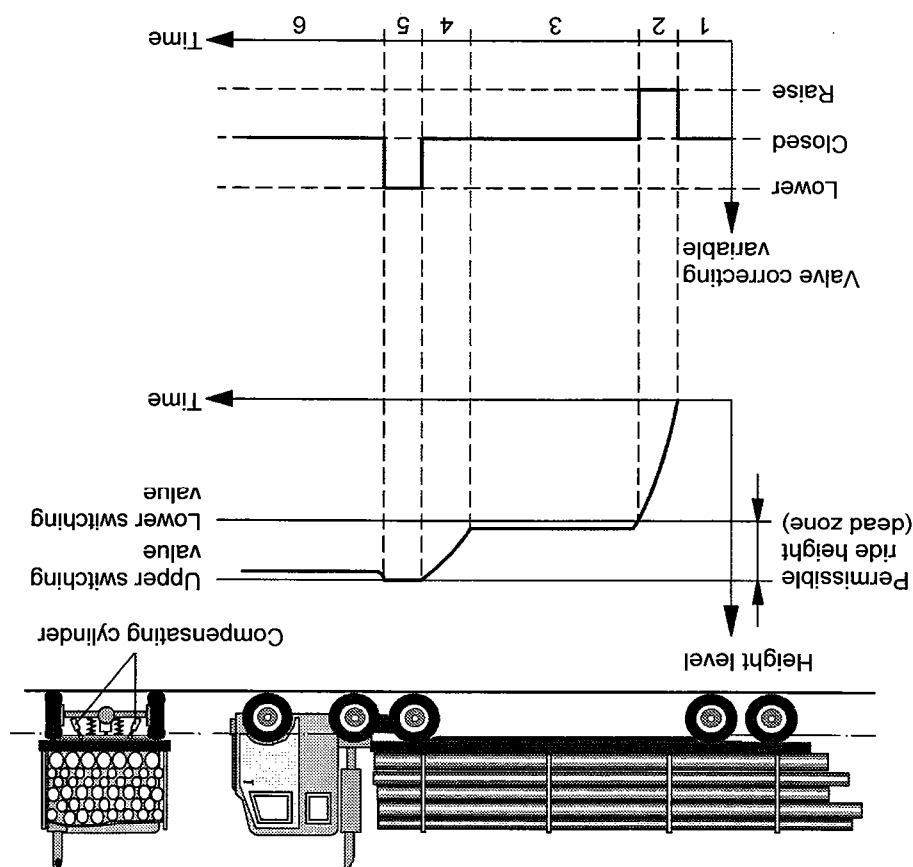
three-step-action controller

with two switching

differences

The time curve for the correcting and controlled variables of a three-step-action controller can be explained by taking the example of a truck ride-height control system. This system compensates for the changes in ride height which result from the loading and unloading of the truck. The truck chassis can be raised or lowered with the aid of a 5/3-way solenoid valve and two compensating cylinders.

Fig. A5.3:
Examples of curves for a
controlled variable and
correcting variable for a
three-step-action controller



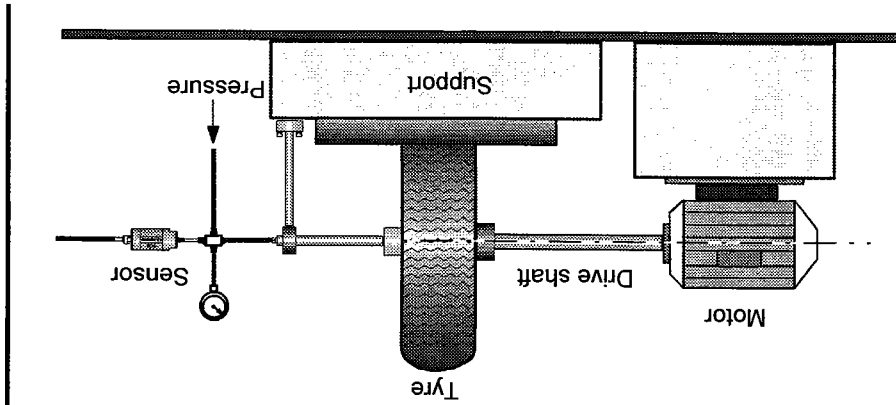
Mode of operation of a three-step-action controller

- Phase 1: The closed-loop control process is started at the end of phase 1.
- Phase 2: The chassis height lies outside the permissible level. The switching valve is switched to "raise" and the compensating cylinders advance.
- Phase 3: The permissible level is reached. The valve is closed.
- Phase 4: The truck is unloaded, as the result of which the chassis rises.
- Phase 5: Due to the unloading of cargo, the permissible level is exceeded. To prevent the truck chassis from rising further, the valve is switched to "lower" and compressed air is blown off.
- Phase 6: The permissible level is reached again, allowing the valve to be closed.

Automobile tyres are endurance-tested on a test-rig. Variations in load and temperature produce pressure fluctuations in the tyres. A pressure control system is to compensate for these fluctuations and maintain the tyre pressure within a specified range.

If the maximum value for a given period is exceeded, compressed air must be blown off. If the tyre pressure falls below the minimum value, compressed air must be pumped in.

Fig. A5.4:
Positional sketch



- A three-step-action controller is to be used to monitor the pressure. The procedure is as follows:
1. Drafting of closed-loop control circuit
 2. Assembly of three-step-action controller
 3. Commissioning of three-step-action controller

Execution

5.1 Drafting of closed-loop control circuit

The closed-loop control circuit for the tyre test-rig is as follows:

- The tyre pressure represents the controlled variable.
- A pressure sensor acts as a measuring system. It measures the tyre pressure.
- The three-step-action controller takes the form of two comparators. These are used to set the two switching values (comparator set-points). The associated switching differences are zero.
- The tyre is represented by a pneumatic reservoir.
- A 5/3-way solenoid valve is used as a final control element. This valve and the reservoir form the controlled system.
- Pressure fluctuations are produced using two 3/2-way panel-mounted valves.

5.2 Assembly of three-step-action controller

Follow the instructions below when assembling the three-step-action controller:

- The 5/3-way solenoid valve is installed between the service unit and the reservoir. Outlet port 2 should be blanked off.
- The function of the two panel-mounted valves (1S1 and 1S2) is defined as follows:
 - Actuation of SV1 causes the tyre pressure to be increased.
 - Actuation of SV2 causes the tyre pressure to be reduced.
- A pressure gauge is fitted to the reservoir to show the tyre pressure.
- Two one-way flow control valves (1V1 and 1V3) regulate the flow of compressed air. 1V1 is fitted to the working port of 1S1 in order to prevent a discharge of compressed air via 1S1. 1V3 is fitted to port 1 of 1S2 to limit the volumetric flow via 1S2 (check that the valve is installed in the correct direction!).

The 5/3-way solenoid valve and the comparators should be connected up as follows:

- The solenoid (1Y1 supply air) should be energised when the tyre pressure is below the lower switching value
- The solenoid (1Y2 exhaust air) should be energised when the tyre pressure is above the upper switching value
- Neither solenoid should be energised when the tyre pressure lies between the two switching values.

5.3 Commissioning of three-step-action controller

The one-way flow control valves should be set as follows:

- 1V1 should be fully closed.
- 1V3 should be half-closed.

Switch on the electrical power supply and the compressed air.

Set the following values on the comparators:

- Comparator A1
 - Lower switching value SA1 = 3 V
 - Switching difference HA1 = 0 V
- Comparator A2
 - Upper switching value SA2 = 4 V
 - Switching difference HA2 = 0 V

Now actuate the two switching valves alternately and observe the resulting switching behaviour.

Name the characteristics of various two-step-action and three-step-action controllers by completing the prepared table.

WORKSHEET

5.1 Drafting of closed-loop control circuit

Complete the block diagram for the closed-loop control circuit by labeling the control components in the prepared diagram.

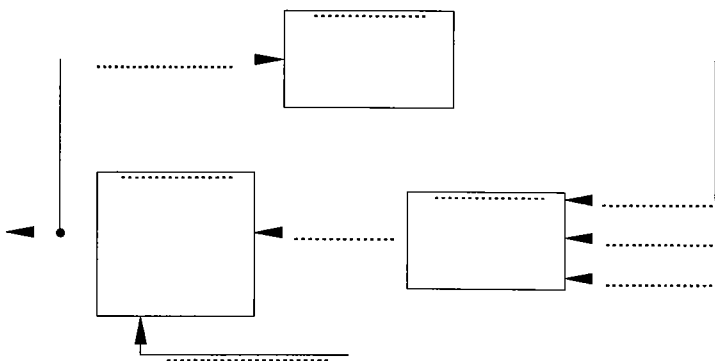


Fig. A5.5:

Block diagram of closed-loop control circuit

5.2 Assembly of three-step-action controller

Assemble the pneumatic and electrical circuits.

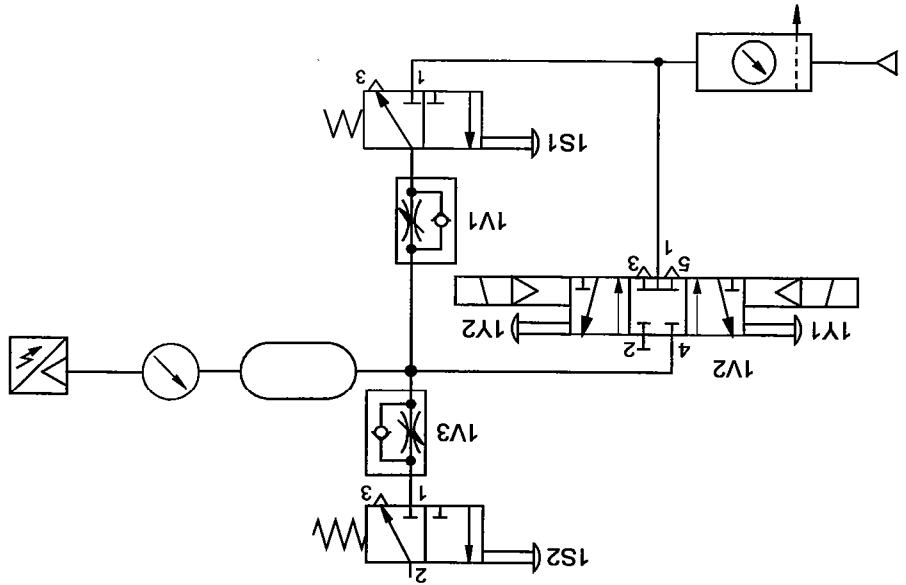
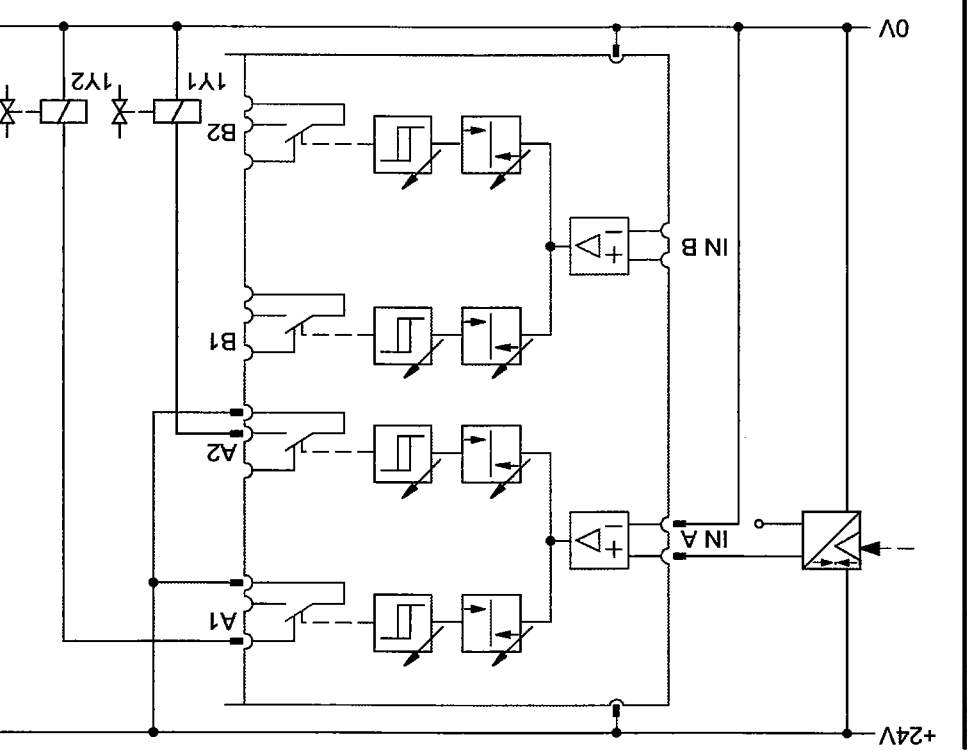


Fig. A5.6:

Pneumatic circuit diagram

Fig. A5.7:
Electrical circuit diagram



5.3 Commissioning the three-step-action controller

Compare the various types of controllers on the basis of the listed criteria.

Table A5.1:

Criteria	Number of setpoints	Number of switching differences	Maximum number of correcting variable values	Number of dead zones
Two-step-action controller without difference				
Two-step-action controller with difference				
Three-step-action controller without difference				
Three-step-action controller with difference				
Two-step-action controller with 2 switching differences				

Subject

Title

Training aims

- To be able to explain the function of a proportional directional control valve
- To be able to produce and evaluate a pressure/signal characteristic

Dynamic valve

Technical knowledge

Dynamic valves are used in fluidics for infinite control. In contrast to switching valves, dynamic valves can assume any number of intermediate positions between their two main switching positions. Dynamic valves are classified into the following groups:

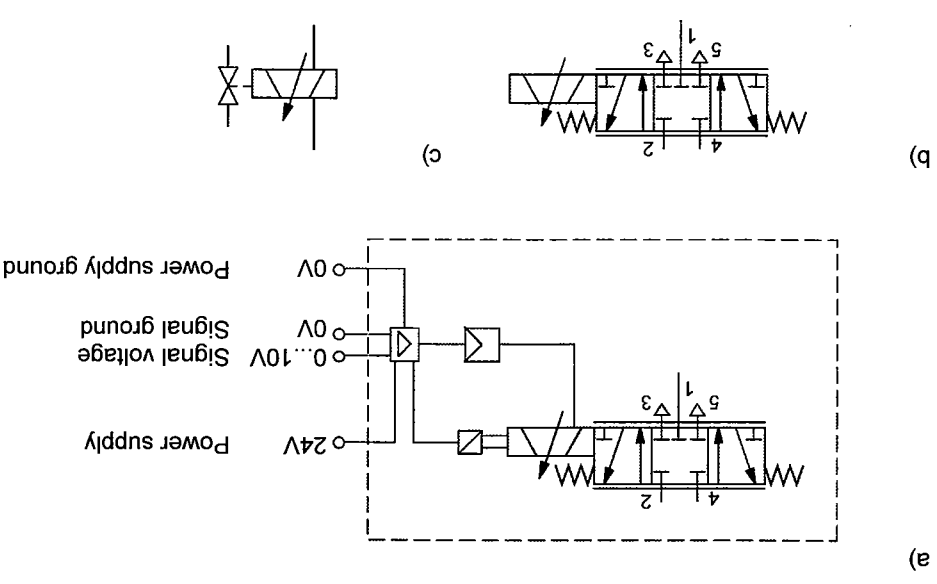
Classification according to function	Classfication according to dynamic behaviour
Pressure control valve	Regulating valve
Directional control valve	Proportional valve
Flow control valve	Servo valve

Table A6.1:

5/3-way proportional valve

The 5/3-way proportional valve used here has five pneumatic ports and three main spool positions. A plunger-armature acts directly on a control spool. This controls the flow rate through the valve when energised appropriately. The valve incorporates a closed-loop control system which gives improved accuracy.

Fig. A6.1:
Connection diagram and
symbols for
5/3-way proportional
directional control valve



A signal voltage of between 0 and 10 V is used to *energise* the valve. The relationship between the energisation voltage and the valve flow rate is as follows:

Table A6.2:

Energisation voltage	Flow rate
0 V	Full flow rate between 1 and 2 or 4 and 5
0 ... 5 V	Reduced flow rate between 1 and 2 or 4 and 5
5 V	Closed mid-position
5 ... 10 V	Reduced flow rate between 1 and 4 or 2 and 3
10 V	Full flow rate between 1 and 4 or 2 and 3

The valve requires a power supply of 24 V.

Pressure/signal characteristic

Characteristics are used to assess dynamic valves. An important assessment criterion is the pressure/signal characteristic. This shows how the operating pressure varies as a function of the input signal.

The pressure/signal characteristic is measured with the working lines closed.

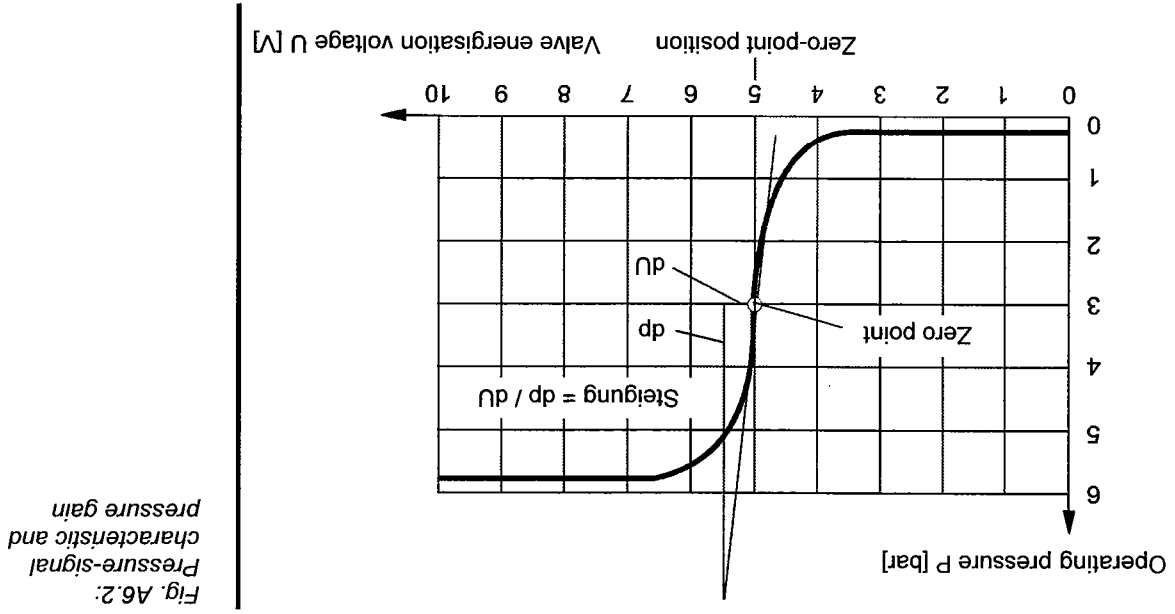
■ Pressure gain

■ Asymmetry and

■ Overlap

of the valve.

The gradient of the characteristic at the zero point indicates the *pressure gain*. The gradient is specified in bar/V. The gradient can be determined with the aid of a tangent construction.



The *asymmetry* indicates the zero-point position of the valve. Asymmetry results in a horizontal shift of the characteristic to the right or left. Asymmetry can be compensated by means of offset voltages.

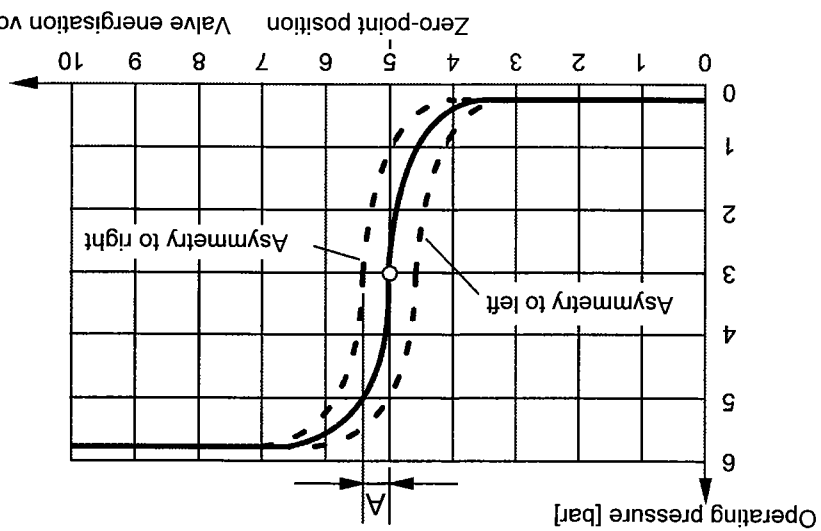


Fig. A6.3:
Influence of asymmetry on
pressure/signal
characteristic

The type of *overlap* between the control spool and the valve body can be determined from the shape of the pressure/signal characteristic:

- Negative overlap results in a steep curve gradient at the zero point.
- Zero overlap produces an almost vertical curve gradient at the zero point.
- Positive overlap is characterised by a shallow curve gradient at the zero point.

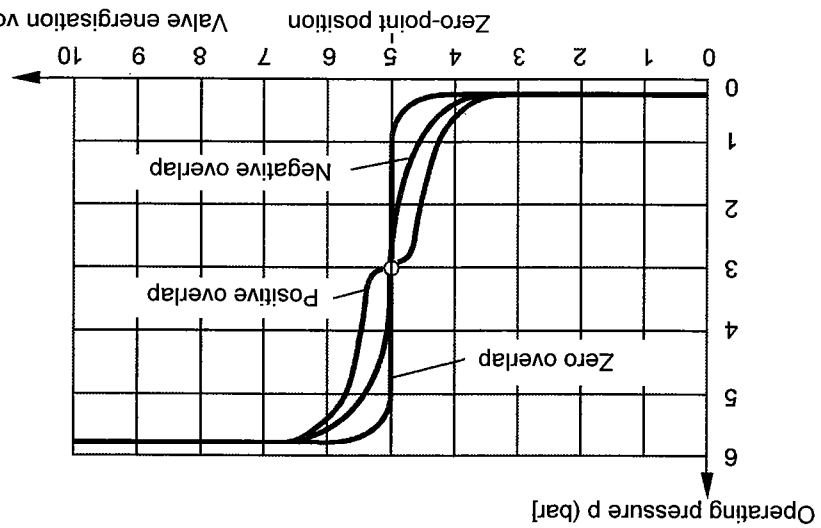
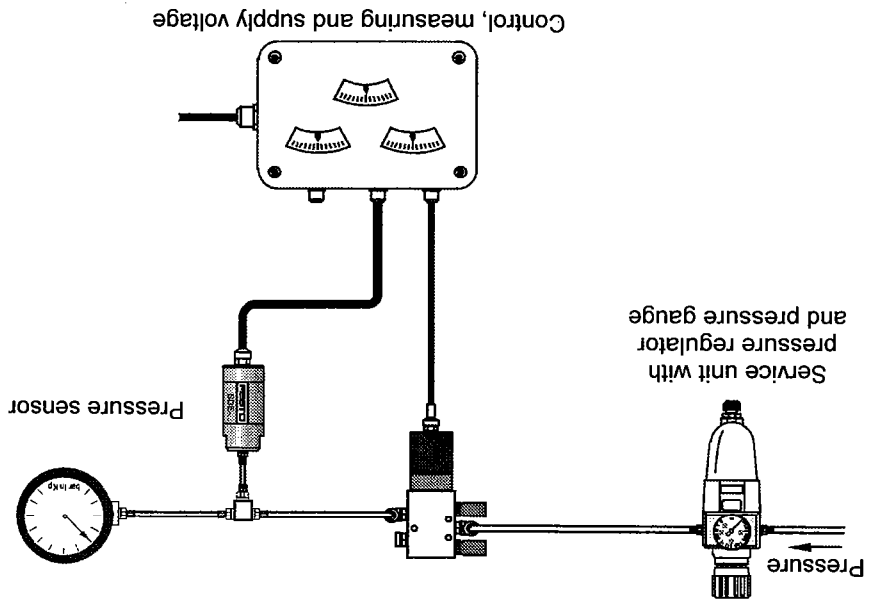


Fig. A6.4:
Influence of valve overlap
on pressure/signal
characteristic

A pneumatic press is to be fitted with a dynamic valve. This will be a 5/3-way proportional valve, Type MPYE 5-1/8. The valve must first be tested.

The pressure/signal characteristic is used to assess quality. It must be determined whether the characteristic data lie within specified tolerances.

Fig. A6.5:
Positional sketch



The procedure for the production of a pressure/signal characteristic is as follows:

1. Assembly of measuring circuit
2. Recording of pressure/signal characteristics
3. Determination of characteristic data and assessment of valve

6.1 Assembly of measuring circuit

Execution

- The valve power supply is 24 V.
- A voltage generator (function generator or setpoint card) provides an energisation voltage within the range of 0 to 10 V.
- The power supply for the pressure sensor is 24 V.
- A multimeter should be connected into the circuit at a suitable point to provide a reading of the sensor output voltage.
- A signal input plate is used to connect up the plugs of the signal lines.

A pressure/signal characteristic should be produced for each working port of the valve. Since the dynamic valve used in this case has two working ports (2 and 4), two characteristics should be produced. If only one pressure sensor is available, the characteristics should be recorded consecutively.

First, port 2 should be blanked off with a plug. Port 4 should be connected to the pressure sensor by means of a short piece of tubing. After the first characteristic has been produced, the connections to working ports 4 and 2 should be changed over. The characteristics should be recorded with a supply pressure of 6 bar.

6.2 Recording of pressure/signal characteristics

- Energise the valve with the specified voltage values.
- Measure the operating pressure and note the values (in bar).
- Enter the values into the prepared graph and join up the measuring points.

6.3 Determination of characteristic data and assessment of valve

For use in the pneumatic press, the proportional directional control valve should have the following characteristic data at both working ports:

Table A6.3:

Characteristic data	Data/tolerances
Asymmetry	Less than 0.5 V
Gradient at zero point	Greater than 5 bar/V
Overlap	Not specified

WORKSHEET

6.1 Assembly of measuring circuit

Assemble the test-rig in accordance with the circuit diagrams provided.

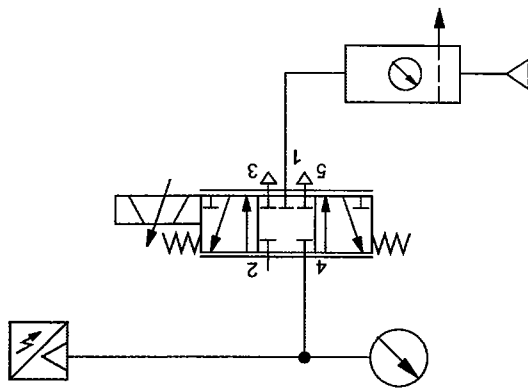


Fig. A6.6:
Pneumatic circuit diagram

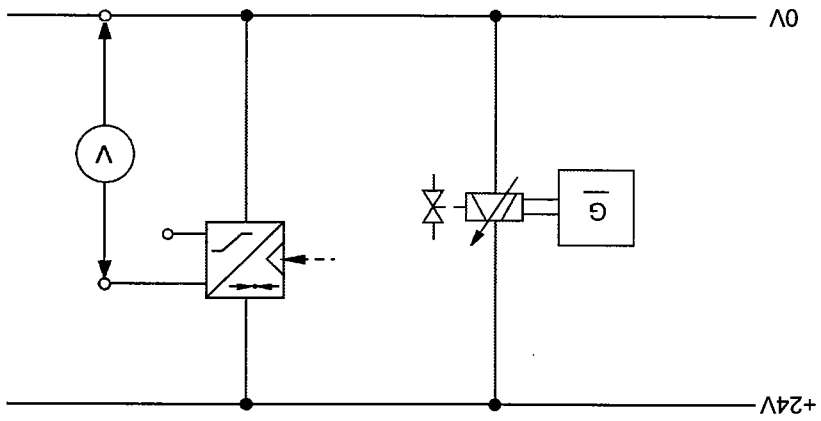


Fig. A6.6:
Electrical circuit diagram

6.2 Recording of pressure/signal characteristics

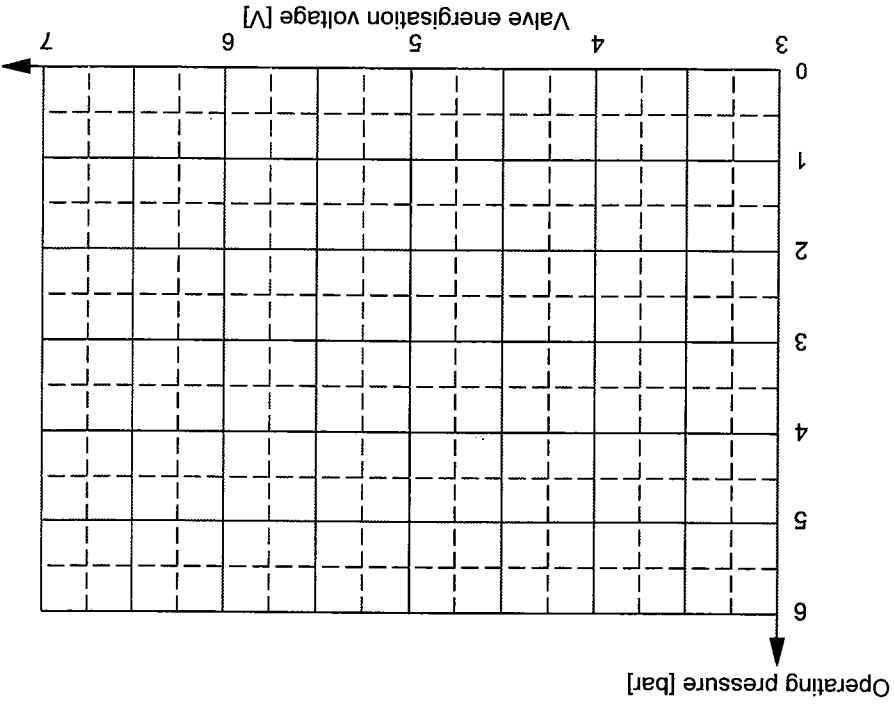
Table A6.4:
Value table for port 4

Correcting variable (V)	Operating pressure [bar]	U (V)	p [bar]
3		5	
3.5		5.05	
4		5.1	
4.5		5.15	
4.6		5.2	
4.7		5.3	
4.8		5.4	
4.85		5.5	
4.9		6	
4.95		6.5	
		7	

Table A6.5:
Value table for port 2

Correcting variable [V]	Operating pressure [bar]	U [V]	p [bar]
3		5	
3.5		5.05	
4		5.1	
4.5		5.15	
4.6		5.2	
4.7		5.3	
4.8		5.4	
4.85		5.5	
4.9		6	
4.95		6.5	
		7	

Fig. A6.7:
Pressure/signal
characteristic



WORKSHEET

6.3 Determination of characteristic data and assessment of valve

Determine the data for the pressure/signal characteristic from the graph above and enter the values into the table.

Table A6.6:

Characteristic data	Data/tolerances	Measured values at port	2
Asymmetry	Less than 0.5 V		
Gradient at zero point	Greater than 5 bar/V		
Overlap	Not specified		

Is the valve suitable for use with the pneumatic press?

☐

Only to a limited extent, because the tolerances

☐

are not maintained for the characteristic value

Subject

Quality assurance in the production of PID controller cards

Title

- To familiarise the student with the design of an electrical PID controller
- Training aims

Dynamic controller

Technical knowledge

Two-step-action, three-step-action or multi-step action controllers are often not sufficient to provide effective and accurate closed-loop control. In cases of this kind, dynamic controllers are used which allow stepless adjustment of the correcting variable.

The types of controllers most commonly used are:

- Proportional controller (P controller)
- Integral controller (I controller)
- Derivative controller (D controller)

The individual types of controllers can be combined, e.g. to form PI, PD or PID controllers.

PID controller card

A dynamic-action PID controller is provided on the PID controller card. The electronic circuitry consists of the following function areas:

- Power supply
- Signal inputs
- PID controller
- Signal output

Fig. A7.1a:
Front panel of
controller card

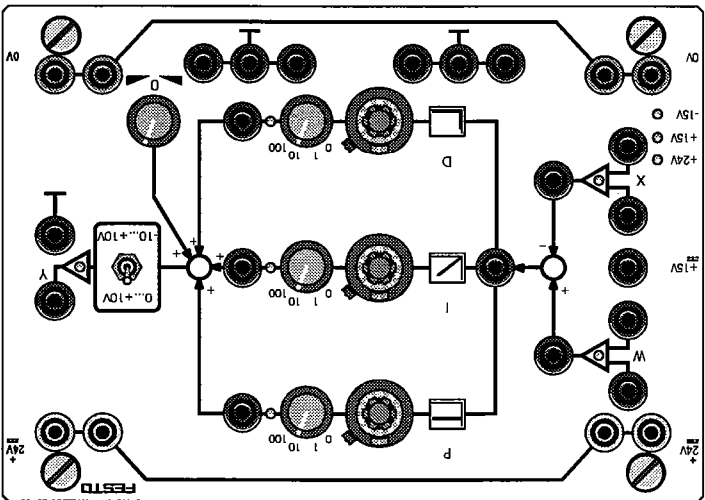
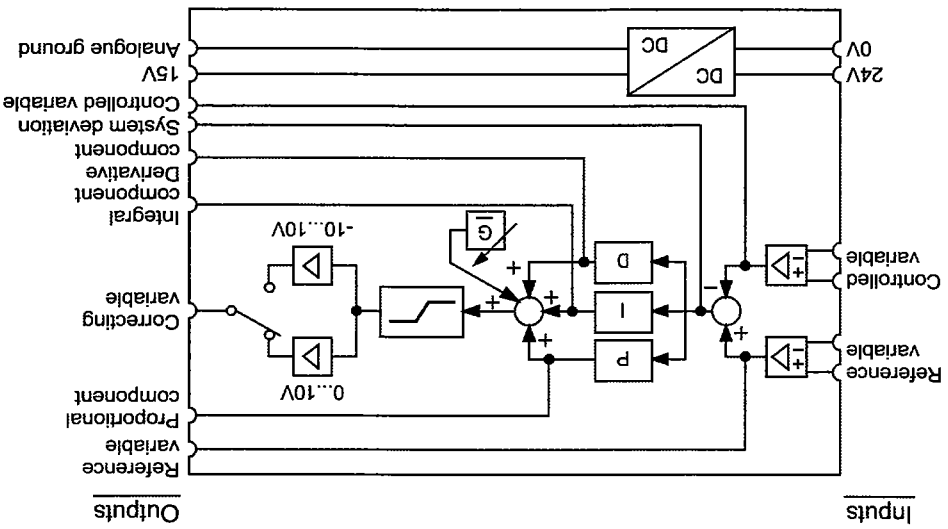


Fig. A7.1b:
Schematic representation
of controller card



The controller card requires a power supply of 24 V. This voltage is converted internally to ± 15 V and fed to the card electronics. The two voltages are electrically isolated from each other, i.e. the controller card has two zero potentials, (analogue ground and power-supply ground (0 V)).



Analogue and power-supply ground must never be connected together, since this may cause interference to signals. The 15 V voltage can be tapped by means of a special socket. This should be used together with analogue ground as the sensor power supply. This ensures that noise signals are reduced to a minimum.

One *signal input* each is provided on the controller card for the reference variable and controlled variable. Both these inputs are differential inputs, i.e. only the difference between the input signals is processed further. This differential signal can be measured against analogue ground.

Both inputs are fitted with *filters* to suppress interference. *Overloads* are indicated by light-emitting diodes (LEDs). An overload occurs when a permissible voltage limit is exceeded (in this case approx. ± 10 V). At a *summation point* following the signal inputs, the controlled variable is deducted from the reference variable and fed to the controller as a deviation.

The *PID controller* which follows this is made up of three parallel branches:

- A proportional component
- An integral component
- A derivative component

All three controller branches can be switched off and on independently, allowing different combinations to be produced. The individual controller branches can be adjusted by means of potentiometers and rotary switches.

The controlled signals can be measured against analogue ground at individual measuring sockets. All three signals are added together at a summation point.

The signals generated by the controller components are processed on the output side to match them to the final control element which follows. This is carried out using a correcting variable offset, a voltage limiter and a range selector switch.

The *correcting variable offset* allows constant voltages to be applied to the control signal, in order for example to compensate for the zero-point shifts of final control elements. The summation point adds the signals from the controller branches and the correcting variable offset.

Depending on their design, final control elements will require different ranges of *energisation voltage*. Dynamic valves generally operate in the range of 0...10 V or $-10 \dots 10$ V. The *range selector switch* converts the controller signals into the desired energisation voltage range. Any output voltage overload which may occur is indicated by an LED.

Problem description

Random-sample electronics testing is to be carried out to ensure consistent quality in the production of controller cards. This must indicate whether the required functions are available and whether the specified tolerances have been maintained.

Measuring and test station

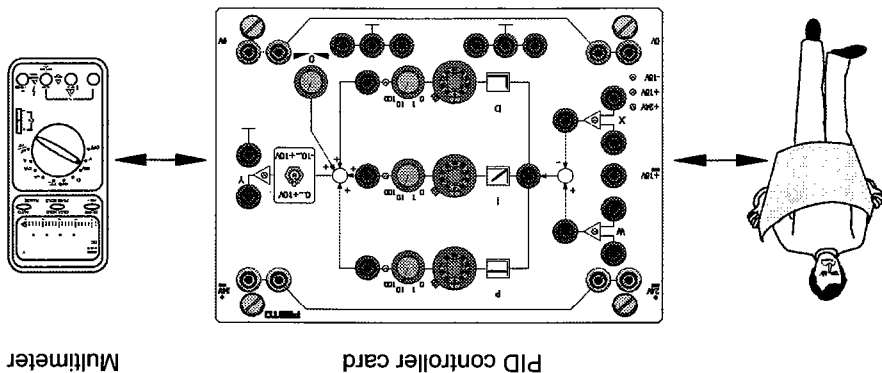


Fig. A7.2:
Positional sketch

Exercise

- For the functional test of the controller card, the following measurement and tests must be carried out at the inputs and outputs:
1. Determination of the overload voltage of the differential inputs
 2. Check of the function of the input summation point
 3. Determination of the correcting variable offset range
 4. Check of the 15 V power supply

Execution

7.1 Determining the overload voltage of the differential inputs

Assemble the measuring circuit in accordance with the circuit diagram below.

- Connect a power supply to the reference variable input.
- Increase the voltage slowly from 0 V until the LED for the differential input is just illuminated.
- Measure and record this voltage.
- Now adjust the voltage into the negative range and record the negative overload voltage.

The overload voltage for the controlled variable input should be determined in the same way.

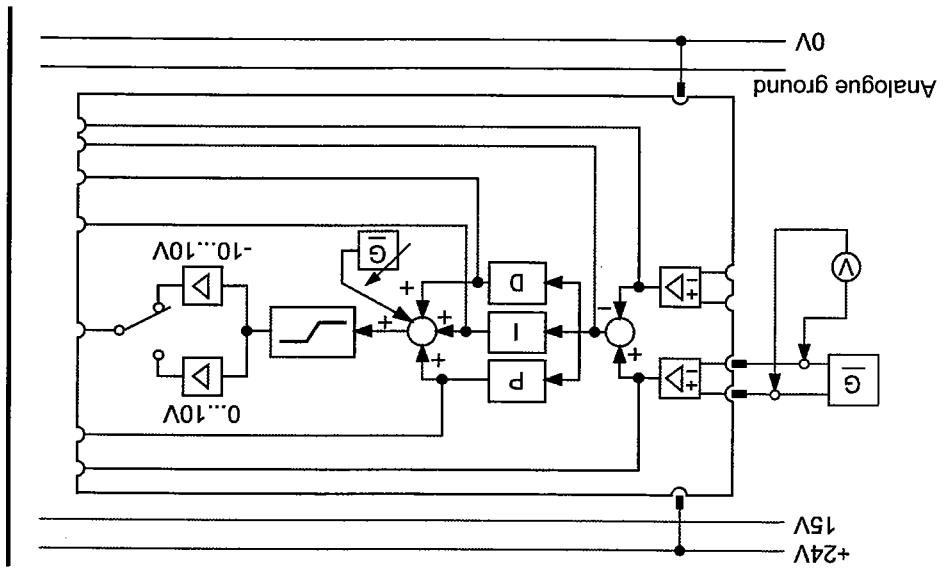


Fig. A7.3:
Electrical circuit diagram

7.2 Check of the function of the input summation point

In order to check the function of the internal summation point, various constant voltages are applied to the inputs for the reference variable and controlled variable.

While this is being done, the voltage downstream of the input summation point is measured at the appropriate measuring socket. The voltage corresponds to the deviation.

Only one power supply of 1 V is required. Negative voltages can be produced by reversing the polarity of the input.

The measurements should be taken as shown in the circuit diagram below.

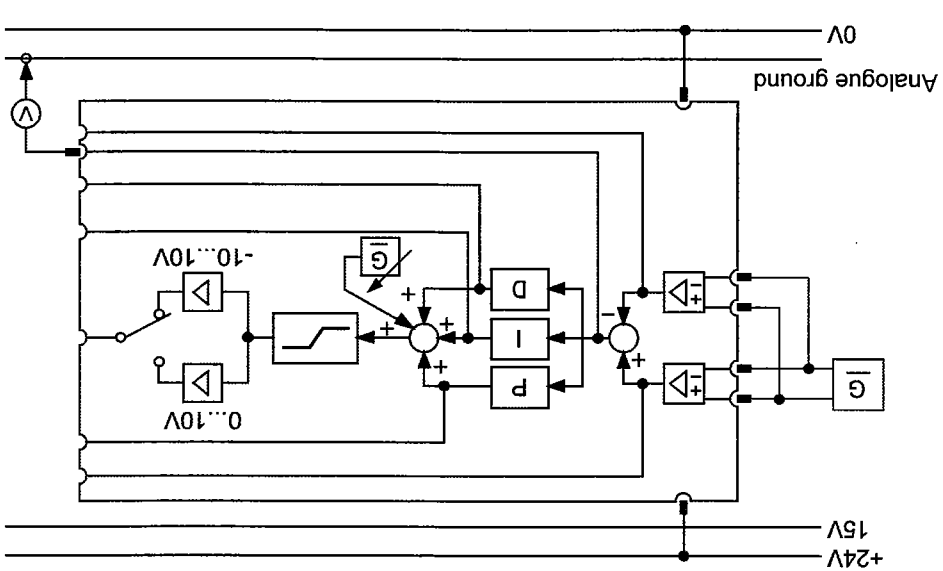


Fig. A7.4:
Electrical circuit diagram

7.3 Determining the correcting variable offset range

- Set all rotary switches and potentiometers to zero.
 - Set the range selector switch to [-10 ... 10 V].
 - Turn the correcting variable offset fully to the left and measure the output voltage (correcting variable) of the controller card.
 - Turn the correcting variable offset fully to the right and once again measure the output voltage.
 - Calculate the difference between these two settings.
 - Now set the range selector switch to [0 ... 10 V] and repeat the measurements.
- The measurements should be taken as shown in the circuit diagram below.

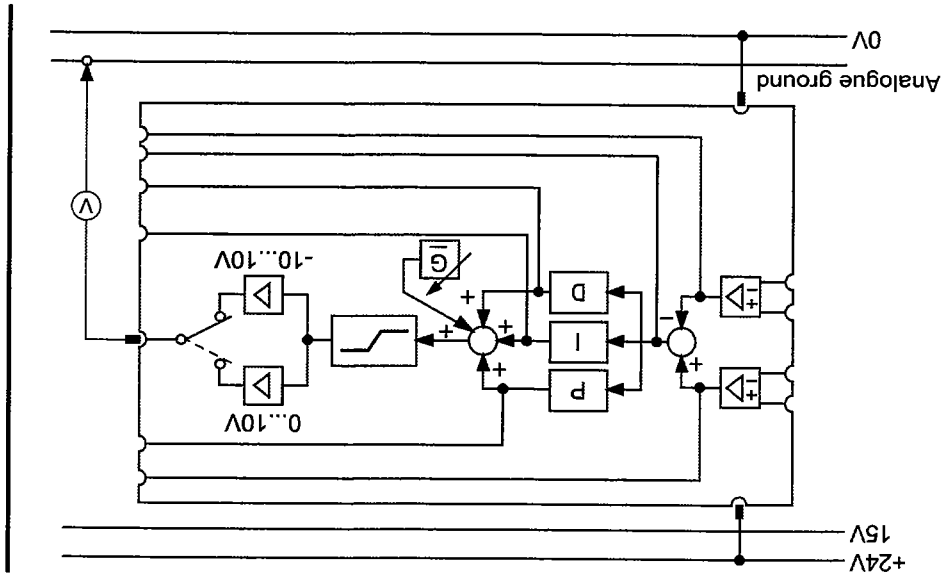


Fig. A7.5:
Electrical circuit diagram

7.4 Check of 15 V power supply

- Connect the pressure sensor to the 15 V power supply of the controller card.
 - Connect the voltage output of the sensor to the controlled variable input.
 - Connect the pneumatic connection of the sensor to a compressed air supply via a service unit.
 - Use the voltage generator to apply a 5 V signal to the reference variable input and measure the deviations at the summation point.
 - Adjust the pressure until the deviation becomes zero.
- The measurements should be taken as shown in the circuit diagram below.

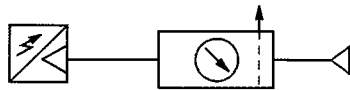


Fig. A7.6:
Pneumatic circuit diagram

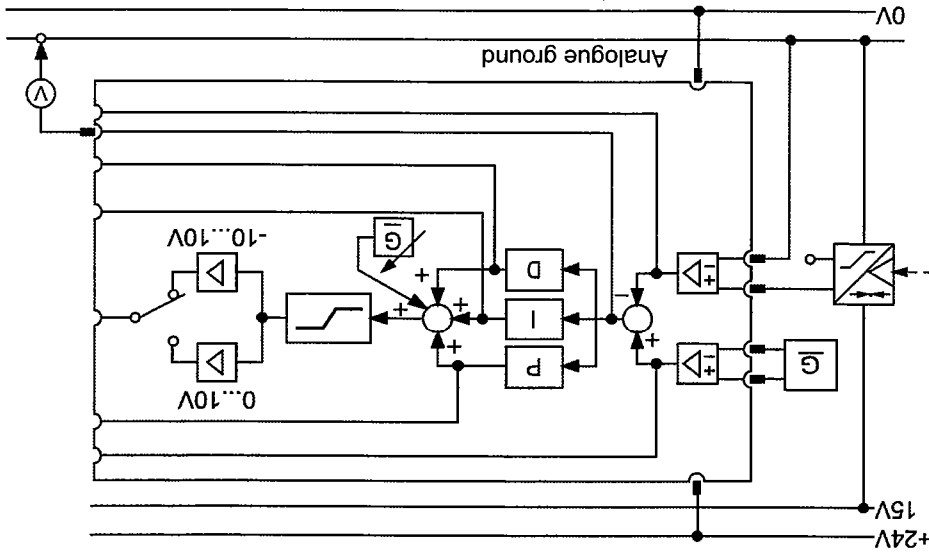


Fig. A7.7:
Electrical circuit diagram

WORKSHEET

7.1 Determining the overload voltage of the differential inputs

Overload voltage	Positive range	Negative range
– of reference variable		
– of controlled variable		

7.2 Check of the function of the input summation point

Apply the listed voltages to the differential inputs and measure the deviation which occurs downstream of the input summation point.

Table A7.1:

Reference variable voltage w [V]	Controlled variable voltage x [V]	System deviation e [V]
1	0	
1	1	
1	-1	
0	1	
0	-1	
-1	0	

Table A7.2:

7.3 Determining the correcting variable offset range

What are the minimum and maximum correcting variable offsets which can be measured on the output side?

Table A7.3:

Range selector switch	on - 10 V ... 10 V		
	Minimum value	Maximum value	Difference
on 0 V ... 10 V			

7.4 Check of 15 V power supply

What is the pressure when the deviation is equal to zero?

bar

Subject

Title

Training aims

- To be able to explain the design of a proportional controller
- To be able to produce and assess a transition function with a P controller
- To familiarise the student with various signal forms

Baffle-plate flow sensor

Closed-loop pneumatics

Proportional controller (P controller)

Technical knowledge

A proportional controller is made up of the following areas:

- The reference variable and the controlled variable are fed to the two *inputs*. The controlled variable can assume various values within a given range. This is known as the control range x_h .
- The *comparator* uses the reference variable and controlled variable to produce a system deviation e .
- The *proportional controller* amplifies the system deviation and generates the correcting variable y_P . The magnitude of the gain depends on the proportional coefficient K_P . The relationship between the system deviation and the correcting variable is described by the equation $y_P = K_P \cdot e$
- The purpose of the *limiter* is to limit the correcting variable of the P controller to within the energisation range of the final control element which follows. This range is known as the correcting range y_h .
- The correcting variable y can be tapped at the *output*.

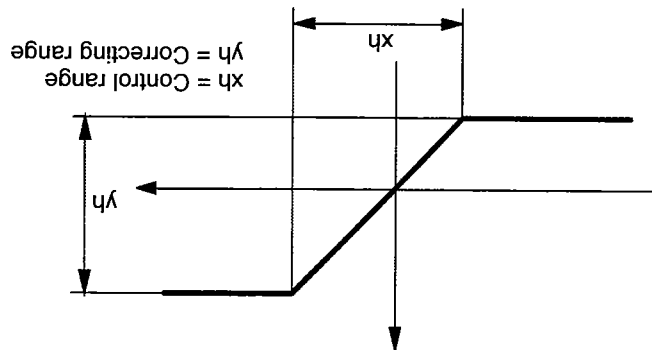


Fig. A8.2:
Schematic representation
and symbol for
proportional-action
controller

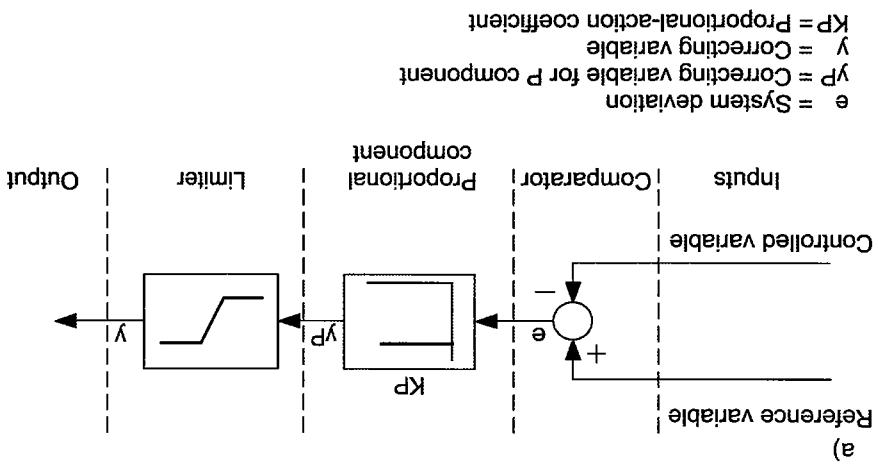
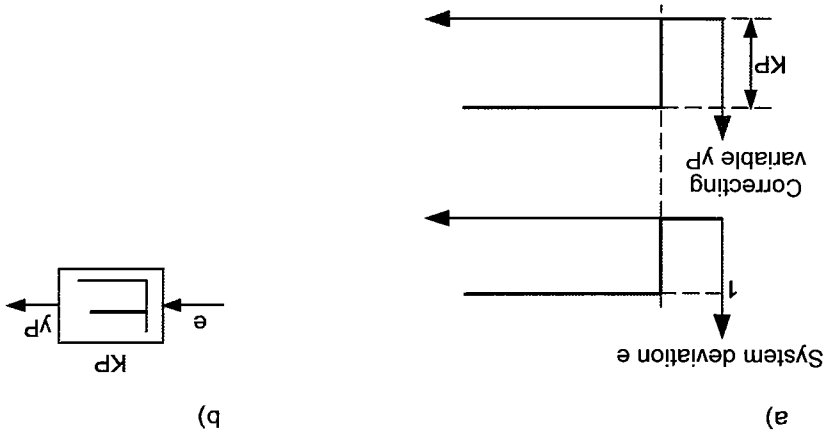


Fig. A8.3:
Transition function
and symbol for
P component



The P controller converts a step-change input signal directly into a step-change output signal. P controllers have fast response characteristics.

P controller on controller card

The proportional coefficient is set on the controller card as follows:

- A multi-position rotary switch is used for the coarse setting. The switch has scale divisions of 0, 1, 10 and 100.
 - The fine setting of the coefficient is carried out with a 10-turn potentiometer. The potentiometer is scaled infinitely from 0 to 10.
- The product of the two settings is the proportional coefficient K_P of the P controller.

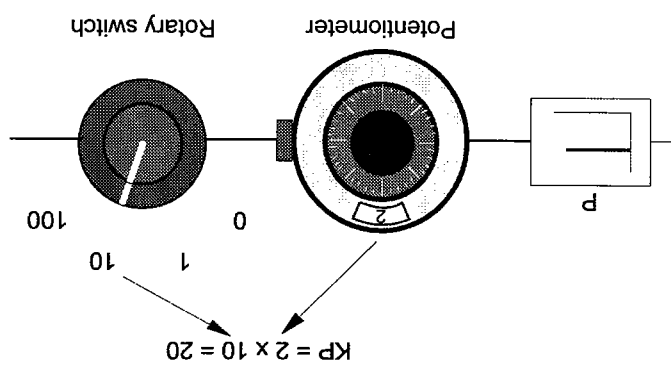


Fig. A8.4:
Setting the proportional-
action coefficient on the
controller card

Signal forms

Signals are required for measurements and experiments. The three most commonly-used signal forms are:

- Square-wave signals (jump)
- Triangular-wave signals (ramp) and
- Sine-wave signals

The required signal is generated as an electrical voltage by a function generator. The illustration below summarises the signals and their generator symbols:

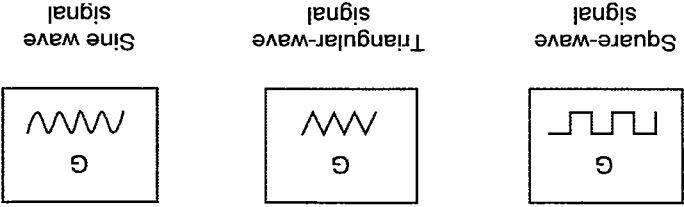


Fig. A8.5:
Signal forms and their
generator symbols

The periodic duration and amplitude of the signals are variable. The amplitude A is a measure of the maximum signal value. The periodic duration T specifies the time required for one oscillation. The frequency f is also generally used. This specifies the number of oscillations per second. The offset specifies the displacement from a reference point (the time axis in this case).

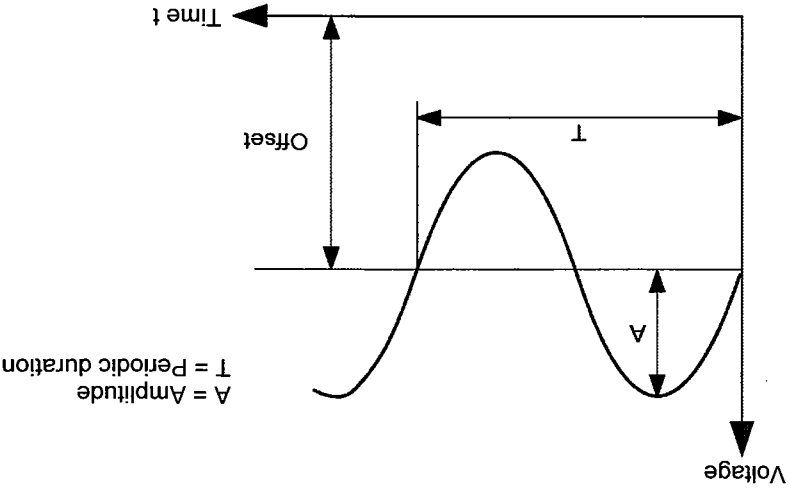


Fig. A8.6:
Terms used to describe a
sine-wave signal oscillation

Problem description

In process installations, defined quantities of gases are fed to a certain point and mixed together. A baffle-plate flow sensor is frequently used to monitor this process. This closed-loop control circuit consists essentially of a P controller, an adjustable throttle valve and a flow rate measuring system.

The flow rate measuring system consists of a flexible baffle plate, to which a strain gauge is fixed with adhesive. The strain gauge generates an output signal which is proportional to the degree to which the plate is bent. The higher the flow rate of the gas, the more the baffle plate is bent and the higher the sensor signal.

The volumetric flow rate is generally varied by means of a throttle valve which is driven by a positioning cylinder and thus opened to the desired cross-section.

The P controller on the controller card is to be used to provide a flow control function. Before this is put into service, it is necessary to determine a number of characteristic data for the P controller.

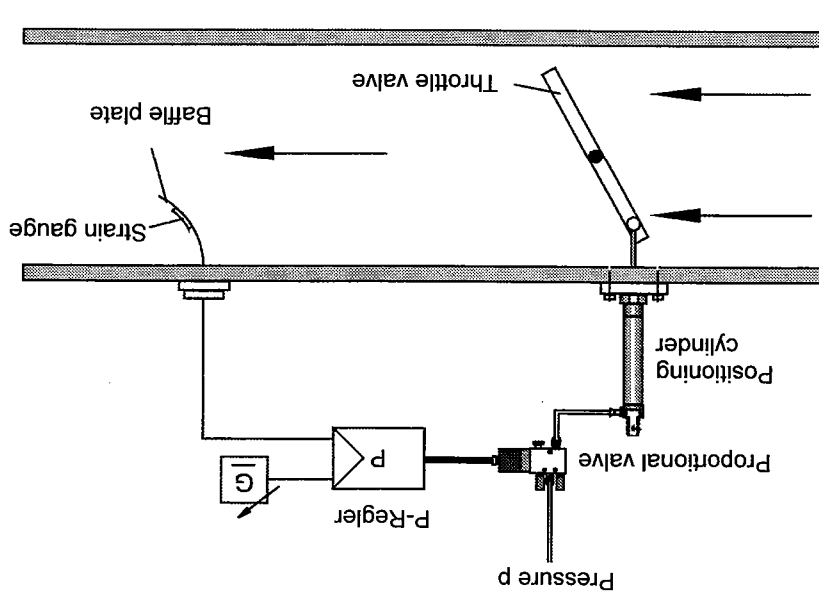


Fig. A8.7:
Positional sketch

Exercise

The execution of the experiment consists of the following steps:

1. Determination of the control range x_h of the P controller
2. Determination of the correcting range y_h of the P controller
3. Production of the P controller characteristics
4. Production of the limiter characteristic

Execution

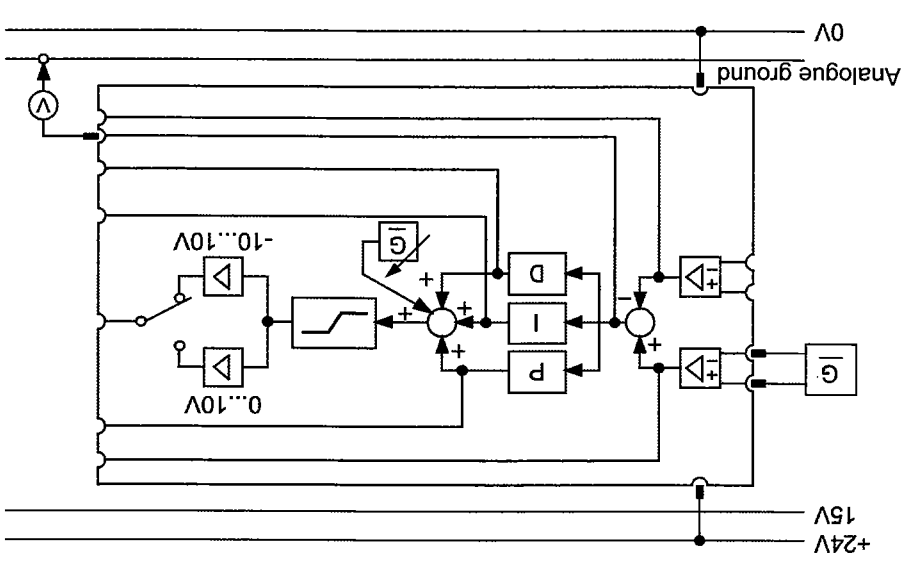
8.1 Determining the control range x_h of the P controller

The control range x_h is the range of voltages which the controlled variable can assume. In this case, it corresponds to the range defined by the positive and negative conducting-state voltages of the differential input, since only these voltages are fed to the P controller for further processing.

The procedure for the measurement of the maximum conducting-state voltage is as follows:

- Use the circuit diagram shown below. Measure the differential signal against analogue ground.
- Apply a voltage to the differential input and increase this. The maximum control range value is obtained when the measured voltage does not increase further when the input voltage is increased.
- Lower the voltage and use the same method to measure the minimum value of the control range.

Fig. A8.8:
Electrical circuit diagram



- 8.2 Determining the correcting range y_h of the P controller**
- The correcting range y_h is the range of voltages which the output signal of the controller (correcting variable) can assume.
- The following circuit should be used to measure the correcting range.
 - Set $K_P = 1$.
 - Set the correcting variable offset to zero. The coefficients of the other controllers should also be set to zero.
 - The range selector switch should be set to $[-10..10 \text{ V}]$.
 - Apply various negative and positive voltages to the reference variable and controlled variable inputs and increase these.
 - Measure the maximum and minimum voltages of the correcting range at the controller output.

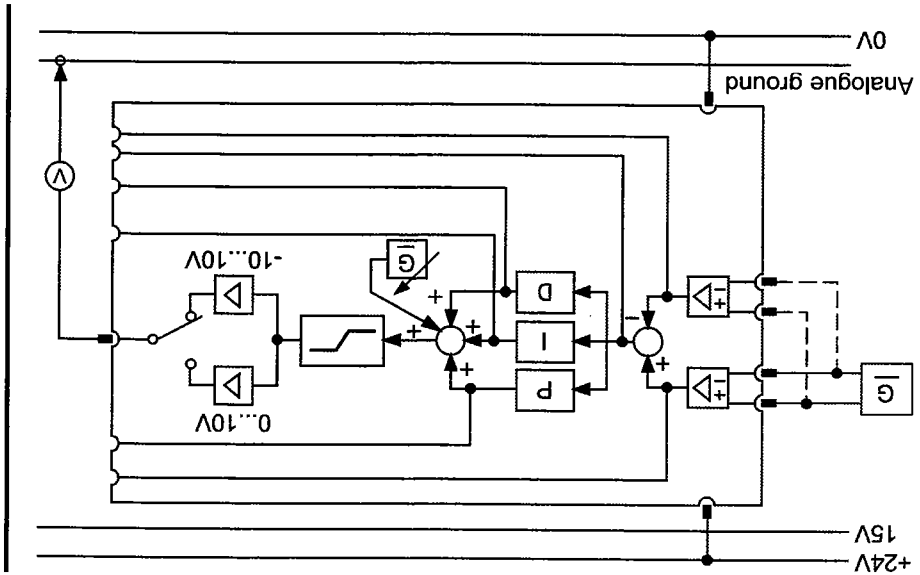
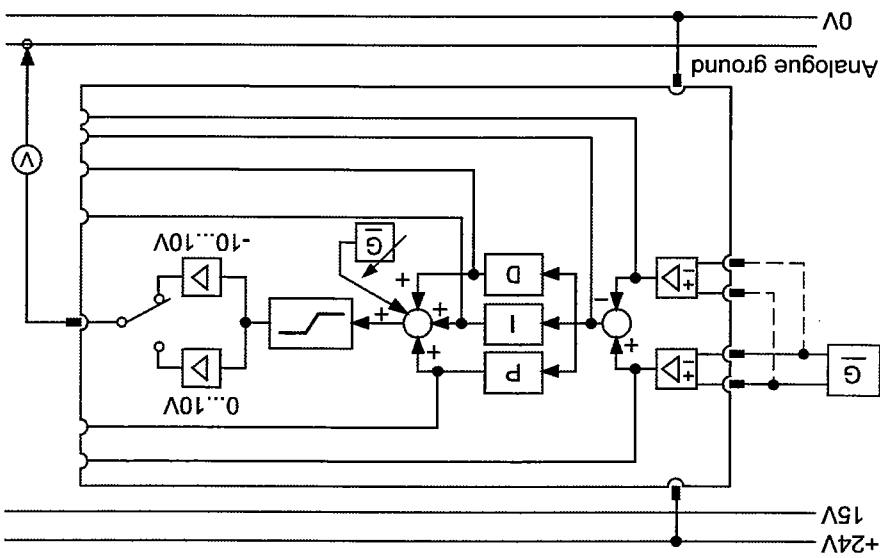


Fig. A8.9:
Electrical circuit diagram

8.3 Plotting the P controller characteristics

- Enter the ranges x_h and y_h previously determined into the prepared coordinate system.
- Then set a gain coefficient $K_P = 1$.
- Apply a positive voltage to the reference variable input. This value of this voltage should be selected so that the resulting correcting variable lies within the correcting range.
- Measure the correcting variable and enter this into the coordinate system.
- Proceed in the same way using a negative voltage. These two measuring points are now joined to form a characteristic.
- Characteristics should be produced in the same way for $K_P = 0.1$ and $K_P = 100$.

Fig. A8.10:
Electrical circuit diagram



8.4 Plotting the limiter characteristic

The procedure for the determination of the two possible limiter characteristics is as follows:

- Assemble the specified measuring circuit.
- Set the correcting variable offset to zero.
- Set a proportional coefficient of $K_P = 1$ on the P controller. The coefficients of the other two controllers should be set to zero.
- Apply the voltages specified on the worksheet to the reference variable input and record the correcting variables for the two ranges of the limiter ($[0..10\text{ V}]$ and $[-10..10\text{ V}]$).
- Then enter the measurements into the prepared graph.

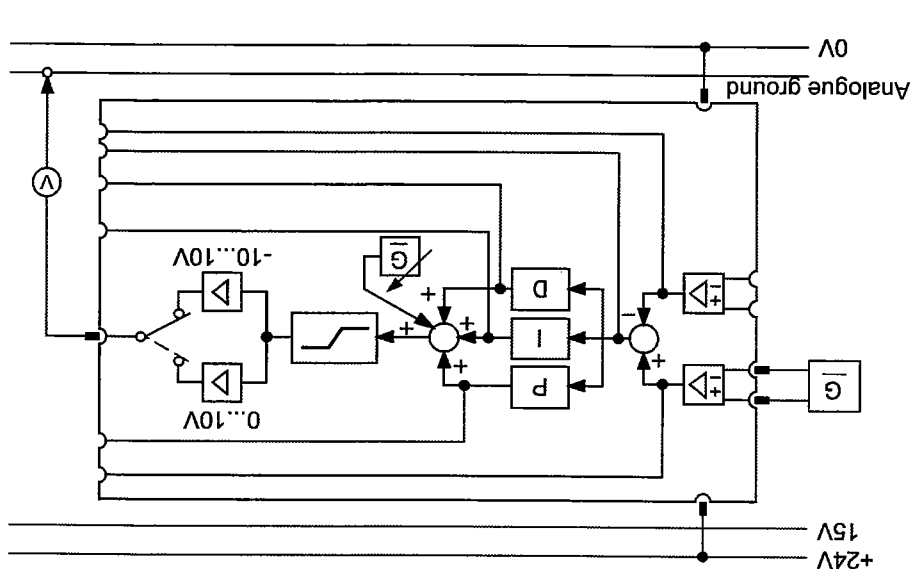


Fig. A8.11:
Electrical circuit diagram

WORKSHEET

8.1 Determining the control range x_h of the P controller

Determine the minimum and maximum values of the control range and enter these into the table.

Range	Minimum value	Maximalwert
Control range x_h		

Table A8.1:

8.2 Determining the correcting range y_h of the P controller

Measure the minimum and maximum values of the correcting range and enter these into the table.

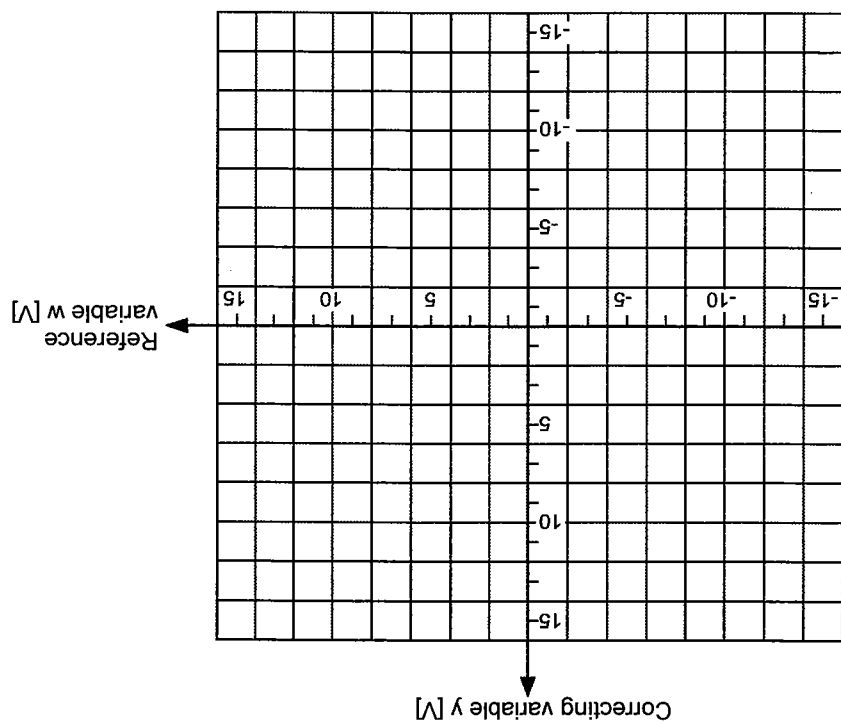
Range	Minimum value	Maximum value
Control range y_h		

Table A8.2:

8.3 Plotting the P controller characteristics

Enter the controller characteristics for the various gain values of the P controller into the prepared graph.

Fig. A8.12:
Diagram



WORKSHEET

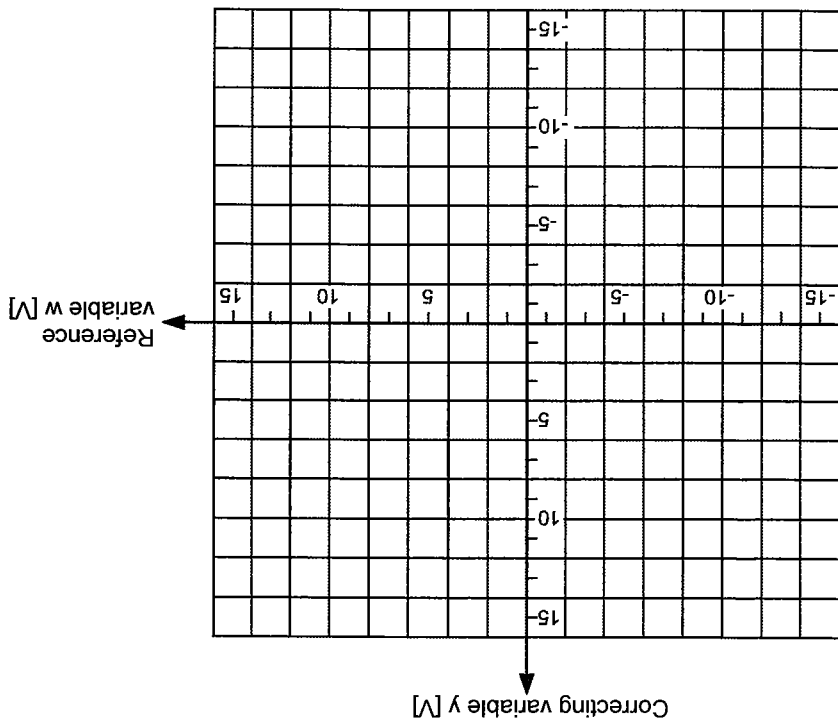
8.4 Plotting the limiter characteristic

Determine the limiter characteristics using the reference variables given in the table.

Table A8.3:

Reference variable w [V]	Correcting variable y (0 ... 10) [V]	Correcting variable y (- 10 ... 10) [V]
- 12		
- 10		
- 5		
2		
0		
- 2		
- 5		
- 10		
- 12		

Fig. A8.13:
Diagram



Subject

Title

Training aims

- To be able to assemble a P control circuit
- To be able to set a control direction
- Familiarization with factors influencing the control direction

Pneumatic post system

Closed-loop pneumatics

Control direction

Technical knowledge

A closed control loop fulfils its purpose only if the controller helps to reduce the system deviation. We then speak of a "correctly-set control direction". The control direction is also referred to as the direction of action.

This will be explained by taking the example of a closed-loop pressure control system:

The air pressure in a reservoir must be kept to a constant 4 ar. A malfunction then causes a step increase of the controlled variable to 5 ar. There are now two possibilities:

- Correct control direction: The dynamic valve blows air off and the pressure falls.
- Incorrect control direction: The dynamic valve feeds further air into the reservoir and the pressure rises.

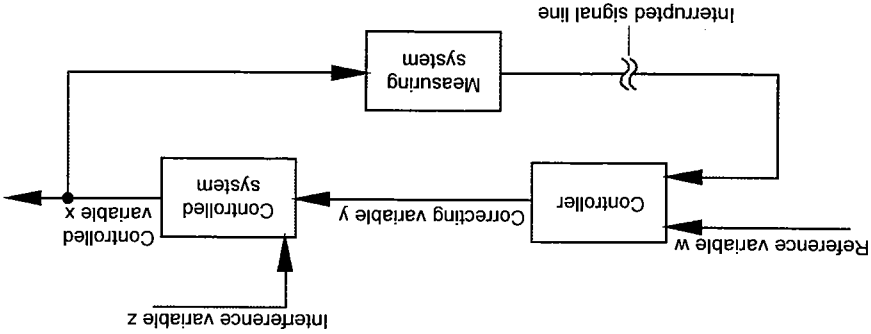
The control direction depends on the polarity of the signal and power lines. If, for example, the connections to the working ports of the valve are reversed, the control direction will also be reversed.

In order to set the control direction, the closed control loop is interrupted downstream of the measuring system. The result is an open-loop control circuit.

The open-loop control circuit starts at the reference variable input and ends at the output signal of the measuring system (see Fig. 9.1).

With the control direction set correctly, an increase in the reference variable will lead to an increase in the controlled variable.

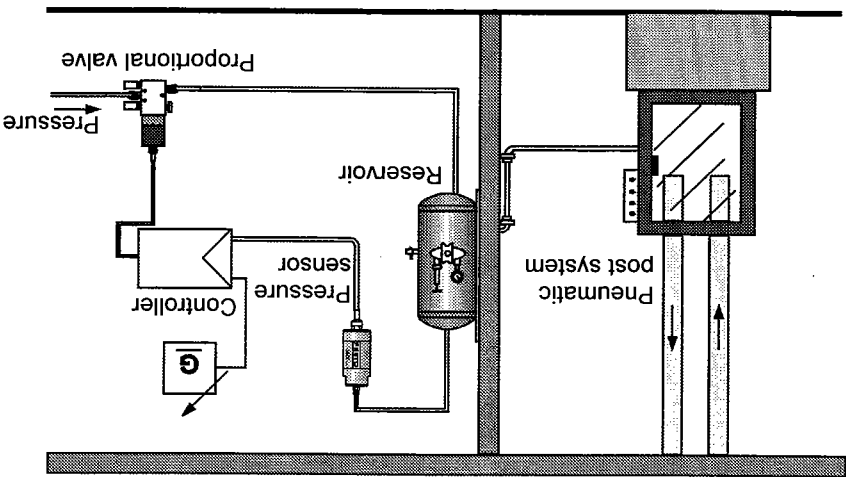
Fig. A9.1:
Closed control loop
interrupted for setting of
control direction



Problem description

A pneumatic post system is supplied with compressed air from a reservoir. The reservoir is filled by a dynamic closed-loop pressure control system. In order to ensure trouble-free operation of the pneumatic post system, the internal pressure of the reservoir must be maintained at a constant 3 ar. This is achieved with the above-mentioned pressure control system.

Fig. A9.2:
Positional sketch



- Exercise
- The pneumatic post system should be commissioned as follows:
1. Assembly of the closed-loop control circuit
 2. Check that control direction is correct
 3. Investigation of closed-loop control circuit
 4. Investigation of factors influencing the control direction

Execution

9.1 Assembly of closed-loop control circuit

The following equipment is used to assemble the circuit:

- A voltage generator as the reference variable source
- The PID controller card as the controller
- The dynamic valve as the final control element
- A compressed air reservoir as the controlled system
- A pressure gauge as an indicator
- A signal input unit to help in making connections
- The pressure sensor as a measuring system

A 2-channel storage oscilloscope will be used to display the result of the measurements.

- The valve ports should be connected up as follows:
- Working port 2 of the dynamic valve should be blanked off.
- Working port 4 of the dynamic valve should be connected to the compressed air reservoir via a piece of tubing.

The controller should be initialised as follows:

- Controller parameters: Zero or switched off
- Correcting variable offset: 0 V
- Range selector switch: [0..10 V]

Do not switch on the electrical power supply and compressed air until you have completed the assembly and have checked the settings on the controller card.

9.2 Check that control direction is correct

In order to check the control direction, proceed as follows:

- Set a proportional coefficient $K_P = 1$. Leave the other coefficients at zero.
- Apply a signal of approx. 0 V to the reference variable input.
- Interrupt the closed-loop control circuit by disconnecting the signal line of the pressure sensor from the controlled variable input of the controller card.
- Display the reference variable and voltage signal of the pressure sensor (controlled variable) on the oscilloscope (connection via signal input plate).

- Increase the reference variable and observe the effect on the controlled variable.
- Determine whether the controlled variable rises or falls and judge the control direction based on this.
- If the control direction is incorrect, check the circuit.

9.3 Investigation of closed-loop control circuit

- Restore the closed-loop control circuit by reconnecting the signal lines of the pressure sensor to the controlled variable input.
- Display the reference variable and controlled variable on the oscilloscope.
- Apply a constant voltage of 3 V to the reference variable input of the controller card.
- Set a proportional coefficient of $K_P = 20$.
- Switch on the electrical power supply and compressed air. If assembly has been carried out correctly, the reference variable and controlled variable should be at 3 V. If significant deviations are present, check the assembly of the circuit.
- Make the modification described in the worksheet and record your observations.
- Explain your observations.

9.4 Investigation of factors influencing the control direction

We will now investigate the effect of crossed signal and energy lines on the control direction.



First switch off the compressed air supply, then change over the lines.

- First set the following parameters:

P = 20

KI = 0

KD = 0

Correcting variable offset = 0

- Change the polarities as described on the worksheet.

- Briefly describe the effects on the controlled variable of changing over lines.

- Now restore correct polarity.

9.1 Assembly of closed-loop control circuit

Assemble the closed-loop control circuit in accordance with the circuit diagrams.

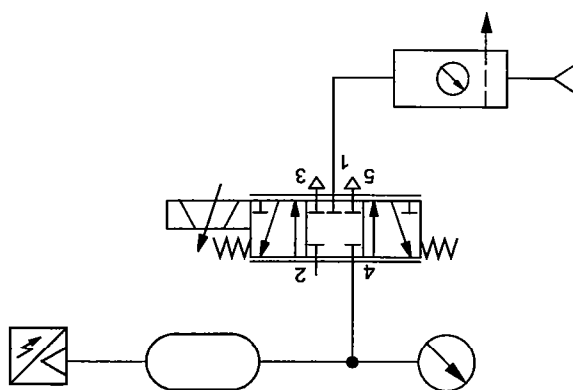


Fig. A9.3:
Pneumatic circuit diagram

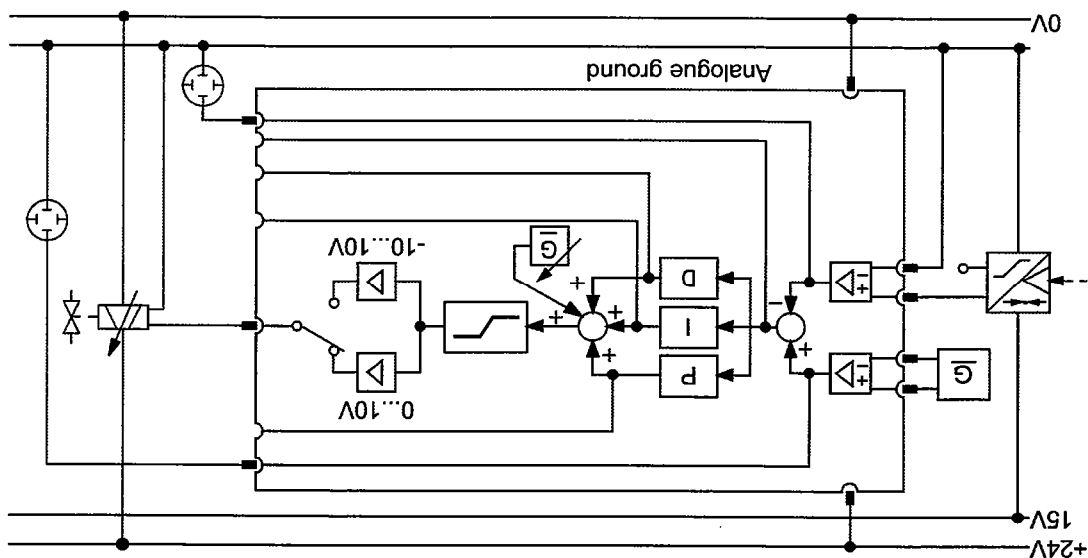


Fig. A9.4:
Electrical circuit diagram

9.2 Check that control direction is correct

Table A9.1:

Input signal	Output signal	Effect on controlled variable	Assessment of control direction
Increase reference variable	Controlled variable	Controlled variable	Control direction
		☐ rises ☐ falls	☐ correct ☐ incorrect

9.3 Investigation of closed-loop control circuit

Table A9.2:

Changes	Observations	Explanation
Increase the reference variable to 4 V	The controlled variable ☐ increases ☐ stays the same ☐ decreases	
Set $K_P = 2$	The controlled variable ☐ increases ☐ stays the same ☐ decreases	
Turn the correcting variable offset as far as possible to the right	The controlled variable ☐ increases ☐ stays the same ☐ decreases	

WORKSHEET

9.4 Investigation of factors influencing the control direction

Type of incorrect polarity	Effect on controlled variable	Table A9.3: Factors influencing the control direction				
Reference variable signal						
Correcting variable signal						
Valve ports 2 and 4						
Output signal of measuring system						
Reference and controlled variables						

Subject

Title

Training aims

- To be able to name the criteria for control quality
- To be able to set the parameters for a P control circuit
- To be able to determine the limit of stability

Clamping device

Closed-loop pneumatics

Control quality

Technical knowledge

The controlled system and controller operate in constant interaction. The matching of these two components has a decisive influence on the quality of the closed-loop control function. This is known as control quality.

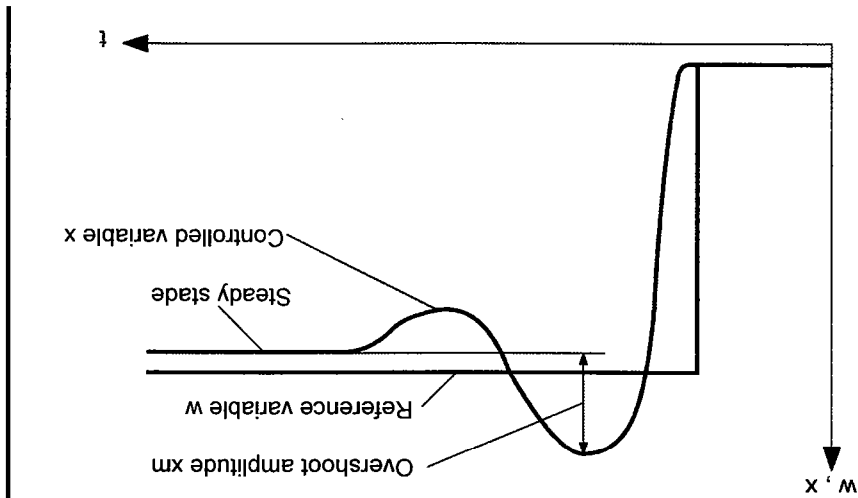
Control quality is assessed on the basis of the transient response of the controlled variable after a step-change in the reference variable. The following characteristic data are generally used for this purpose:

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

A good transient response is obtained when the values of these characteristic data are low.

The *overshoot amplitude* x_m of the controlled variable is the greatest temporary system deviation after a step-change in the reference variable. The overshoot amplitude is measured relative to the steady state.

Fig. A10.1:
Graph of
overshoot amplitude x_m



The steady-state system deviation e_{stat} is the difference between the reference variable w and the controlled variable x which results in a steady state.

$$e_{stat} = w - x$$

DIN 19226 does not specify a designation for the steady-state system deviation. Here, we shall use the designation e_{stat} .

■ DIN 19226 describes the measured value of the controlled variable as the feedback variable r . In the following, however, we shall use only the term "controlled variable" x .

■ The settling time T_s is measured as follows: It starts when the controlled variable leaves its steady state after a step-change in the reference variable. It ends when the controlled variable assumes a new steady state.

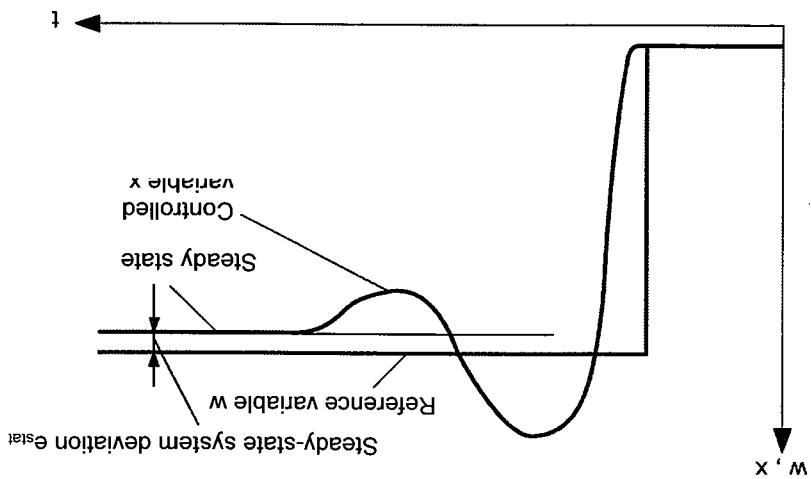


Fig. A10.2:
Graph of steady-state
system deviation e_{stat}

The settling time T_s is measured as follows: It starts when the controlled variable leaves its steady state after a step-change in the reference variable. It ends when the controlled variable assumes a new steady state.

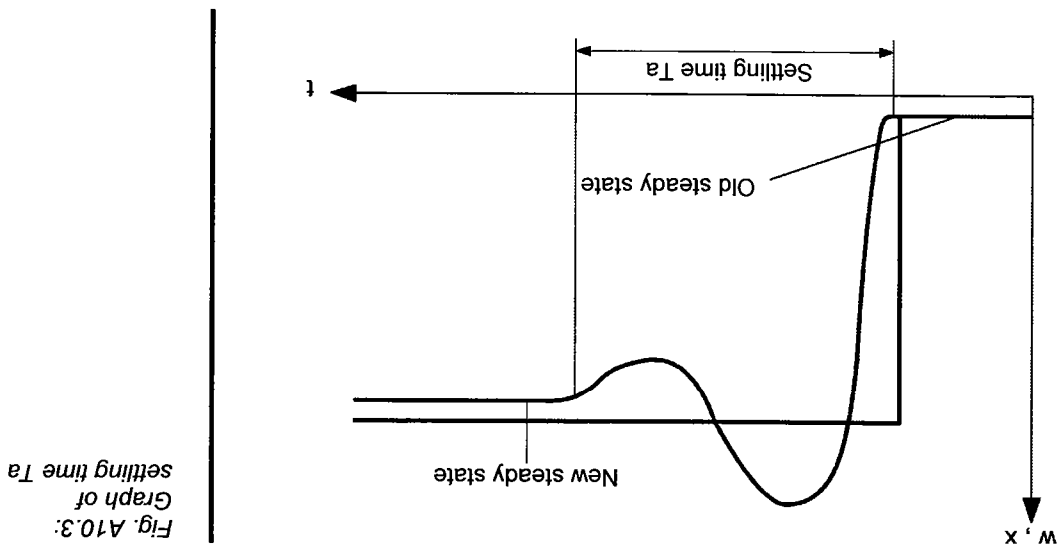


Fig. A10.3:
Graph of
settling time T_s

A closed-loop control circuit operates *stably* if the controlled variable assumes a new constant value after a change in the reference variable. A closed-loop control circuit operates *unstable* if the controlled variable is subject to persistent oscillations. The stability of a closed-loop control circuit depends on the coefficients and time constants of the closed-loop control circuit components.

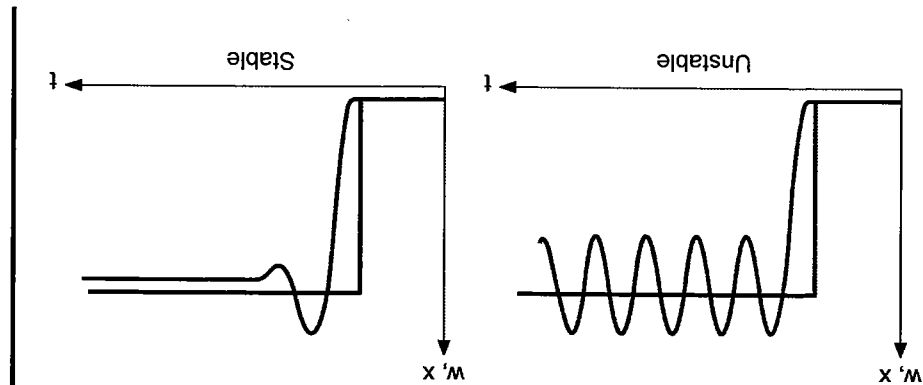


Fig. A10.4:
Step responses of stable
and unstable
closed-loop control circuits

In order to determine the *limit of stability* of a closed-loop control circuit, the coefficients are increased until the closed-loop control circuit oscillates.

In the case of many closed-loop control circuits, the limit of stability depends on the reference variable. It may occur that, with the same controller gain, the controlled variable exhibits steady-state oscillation for one value of the reference variable but not for another value.

The limit of stability is determined with a step-change reference variable.

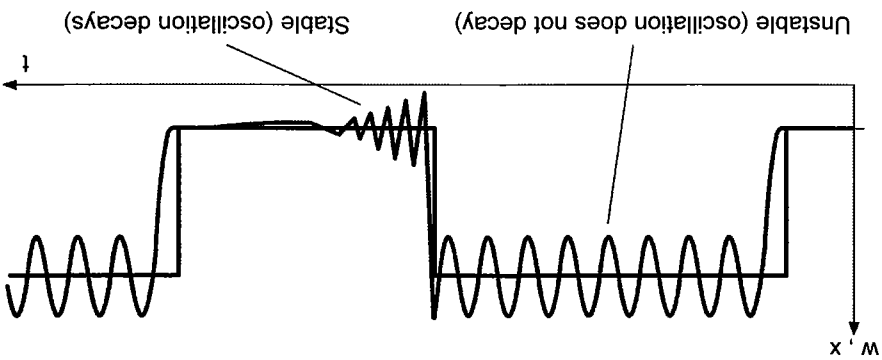


Fig. A10.5:
Example of
dependency of
stability limit
on reference variable

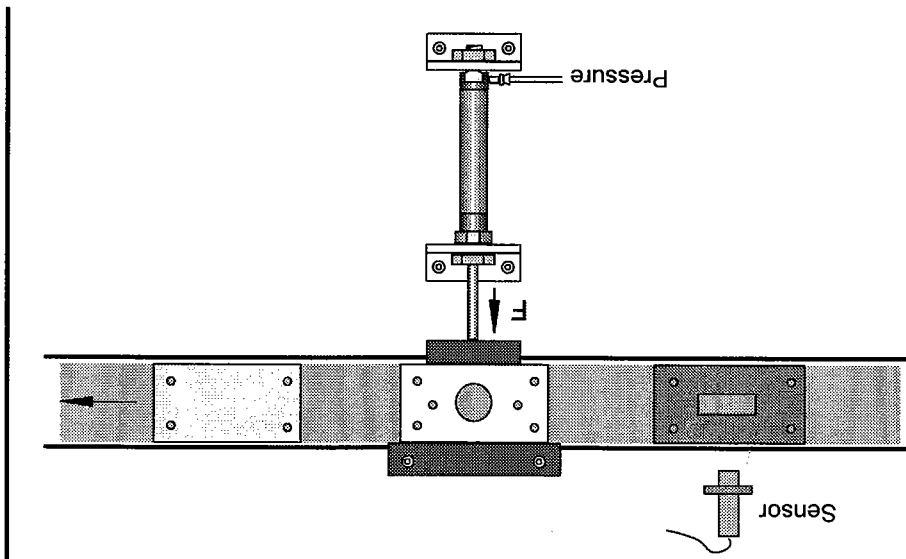
In order to reach a conclusion regarding critical gain, it is necessary to specify different reference variable step changes in such a way that the complete value range of the reference variable is covered.

Various workpieces are to be clamped in a clamping device. Due to the varying strengths of the workpieces, they cannot all be subjected to the same clamping force.

The working sequence for the clamping device is as follows:

- The workpieces are detected by a master controller by means of sensors.
- The master controller outputs the correct reference variable for the clamping pressure.
- The closed-loop pressure controller provides the desired clamping pressure.
- The clamped workpiece is processed.
- The clamping device is opened by the application of a reference variable of 0 bar clamping pressure.
- The master controller restarts the conveyor belt.

Fig. A10.6:
Positional sketch



The following work must be carried out in order to commission the clamping device:

1. Assembly of closed-loop control circuit
2. Determination of characteristic data for control quality
3. Determination of limit of stability.

10.1 Assembly of closed-loop control circuit

Execution

The following equipment is required in order to carry out the exercise:

- A voltage generator as a reference variable source
- The PID controller card as a controller
- The dynamic valve as a final control element
- A reservoir as a controlled system
- A pressure gauge as an indicator
- The pressure sensor as a measuring system.

The volume of the clamping cylinder is simulated in this exercise by the volume of the reservoir.

A storage oscilloscope is used to display the measured results.

Ensure when assembling the electrical circuit that polarity and supply voltages are correct.

Do not switch on the electrical power supply and compressed air until you have completed the assembly and have checked the settings on the controller card:

- Controller parameters: Zero or switched off
- Correcting variable offset: 0 V
- Range selector switch: [0..10 V].

10.2 Plotting characteristic data for control quality

- Set the voltages specified in the worksheet for the reference variable and proportional coefficients.
- Determine the appropriate characteristic data for the control quality (e_{stat} , x_m) and enter these values into the prepared table.
- Enter the measured values for the steady-state system deviation on the graph.
- Evaluate the measurements by answering the question.

10.3 Determining the limit of stability

- Set one at a time the step-changes for the reference variable specified in the worksheet. The frequency should be approx. 0.5 Hz.
- Determine the limit of stability $K_{P\text{crit}}$ by increasing the proportional coefficient K_P , using a supply pressure of 6 bar, until oscillations occur. The limit of stability may be different for the upper and lower values of the correcting variable. Always note the lower value.
- Discuss your observations on the basis of the questions in the worksheet.

10.1 Assembly of closed-loop control circuit

Fig. A10.7:
Pneumatic circuit diagram

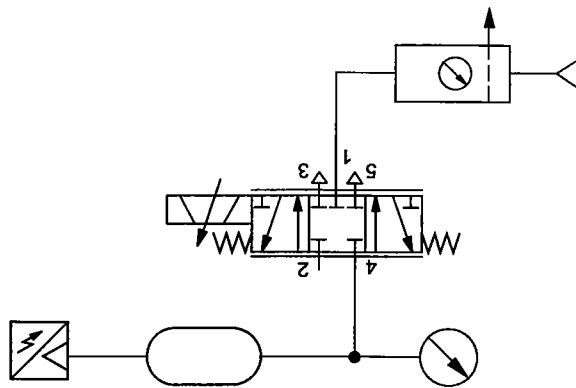


Fig. A10.7:

Pneumatic circuit diagram

Fig. A10.8:

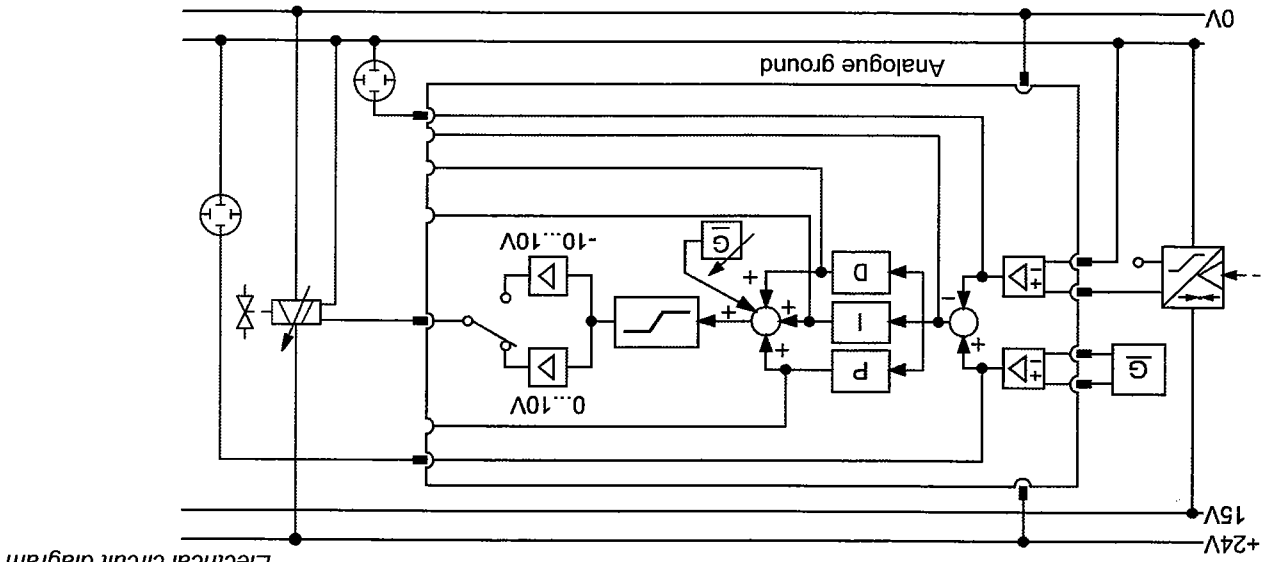
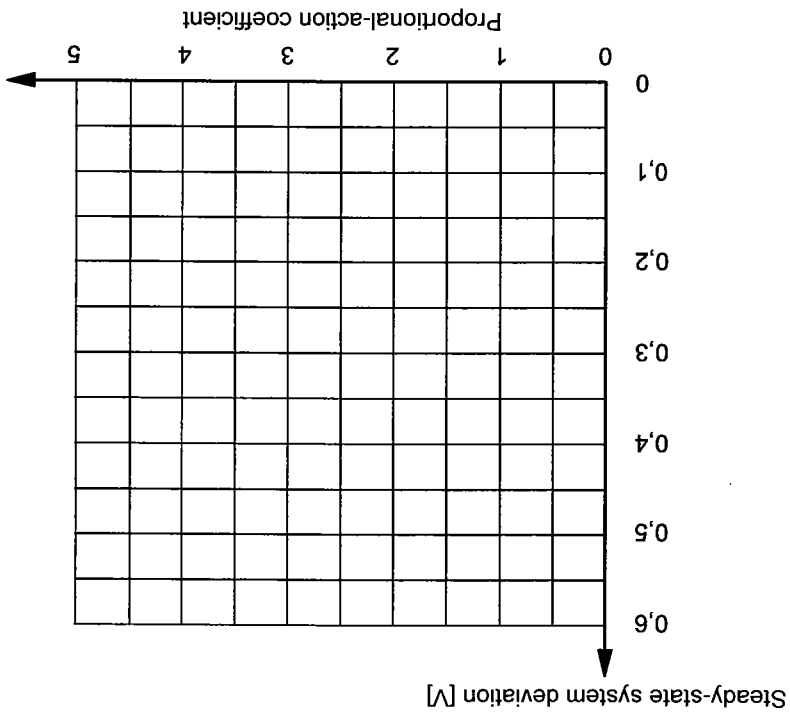


Table A10.1:
Plotting the
characteristic data for
control quality

Prop.-action coefficient K_P	Reference variable w [V]	Controlled variable x [V]	Steady state- system dev. e_{stat} [V]	Overshoot amplitude x_m [mV]
0.1	3 V			
0.5	3 V			
1	3 V			
5	3 V			

Enter the values from the table for the steady-state system deviation and proportional coefficients into the graph and join up the points to form a curve.

Fig. A10.9:
Diagram



How does the steady-state system deviation change as a function of the proportional coefficient?

WORKSHEET

10.3 Determining the limit of stability

Determine the limit of stability for the specified reference variable step changes.

Step range of reference variable	Critical proportional-action coefficient K_{Pcrit}
1 V – 1.5 V	
2 V – 2.5 V	
3 V – 3.5 V	
4 V – 4.5 V	
5 V – 5.5 V	

Table A10.2:
Limit of stability

Which step range has the lowest critical proportional coefficient?

Which step range has the highest critical proportional coefficient?

Which critical proportional coefficient is most important for the design of a closed-loop control circuit?

- ☐ Lowest critical proportional coefficient
- ☐ Highest critical proportional coefficient

Give reasons for your answer.

Subject Title

Training aims

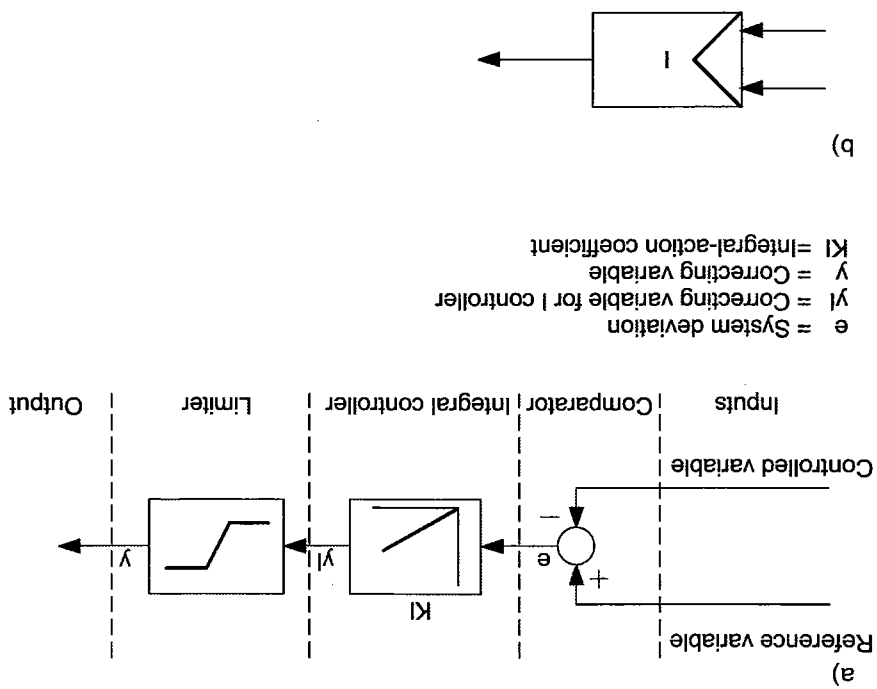
- To be able to explain the design of an integral controller
- To be able to produce and assess a transition function of an integral controller
- To be able to explain the design of a proportional plus integral controller
- To be able to produce a transition function of a proportional plus integral controller

Integral controller (I controller)

Technical knowledge

- An integral controller is made up of the following modules:
- The reference variable and controlled variable are fed to the *differential inputs*.
 - The *comparator* uses the reference variable and controlled variable to produce a system deviation e .
 - The integral controller sums the system deviation as a function of the time t and amplifies it by the factor K_I . This means: The longer a positive system deviation is present, the larger the integral correcting variable y_I becomes. With a constant system deviation, the following relationship applies:
- $$y_I = K_I \cdot e \cdot t$$
- The *limiter* has the task of limiting the correcting variable to within the energisation range of the final control element. The correcting variable y is the output signal of the limiter.
 - The correcting signal y is available at the *output*.

Fig. A11.1:
Schematic representation
and symbol for
integral-action controller



An I controller converts step-change input signals into ramp-shaped output signals by means of continuous summation (integration). This means that the changes in the correcting variable are stepless and occur considerably more slowly than in the case of a P controller. The *integration time* T_I can be determined from the integral-action coefficient K_I . Assuming that the controlled-variable range and correcting variable range are the same, the following applies:

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

A long integration time means a small integral coefficient K_I and a slow rate of rise for the transition function. A short integration time means a large integral coefficient K_I and a fast rate of rise for the transition function.

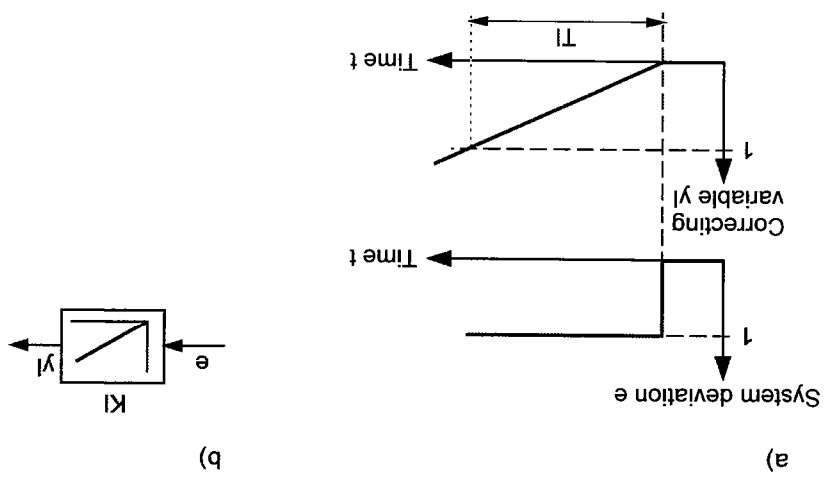


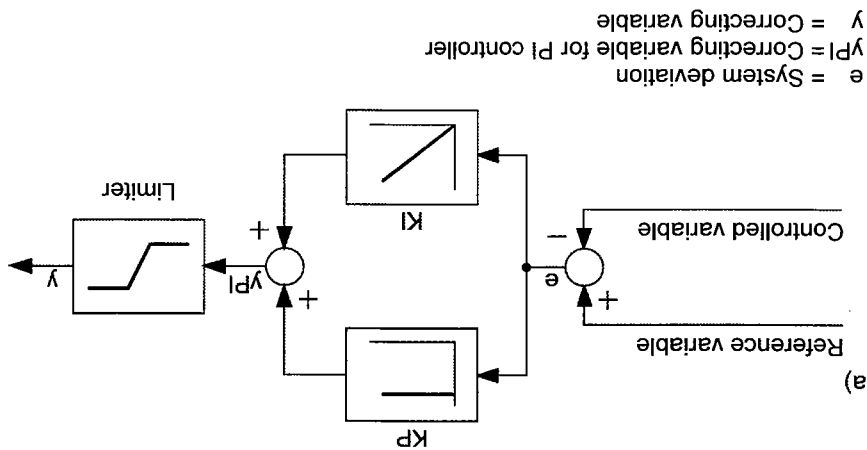
Fig. A11.2:
Transition function and
symbol for I controller

I controllers react only slowly to changes in reference variables and are thus rarely used alone. They are, however, able to reduce system deviations to zero. This ability is exploited in PI controllers.

Proportional plus integral controller (PI controller)

A PI controller is formed by the parallel connection of a proportional and an integral controller. It combines the advantages of the two types of controllers, giving a controller which is able both to react quickly and eliminate system deviations completely.

Fig. A11.3:
Schematic representation
and symbol for
a PI controller



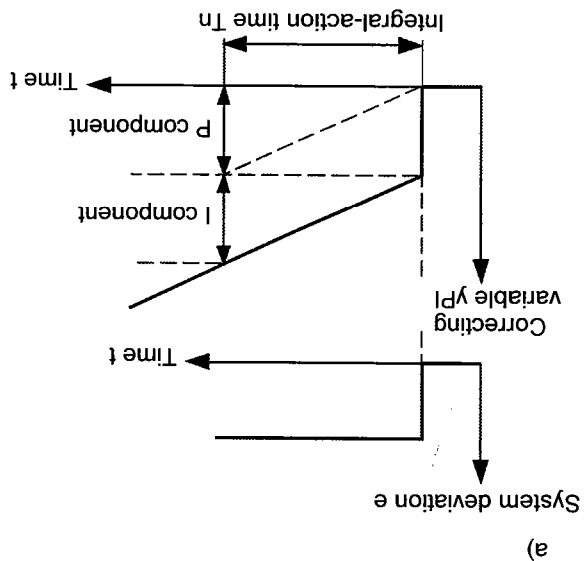
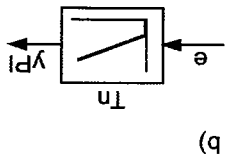
With a constant system deviation, a PI controller operates in accordance with the following equation:

$$y_{PI} = K_P \cdot e \cdot (1 + t/T_n) \quad \text{with } T_n = K_P/K_I \quad (T_n = \text{integral-action time})$$

T_n is known as the *integral-action time* and is the time required by the I controller to produce the same correcting variable component as the P controller with a constant input signal.

The characteristic variables for a PI controller are: K_P and K_I , or K_P and T_n .

Fig. A11.4:
Transition function
and symbol
for PI controller



The table below compares the advantages and disadvantages of P, I and PI controllers:

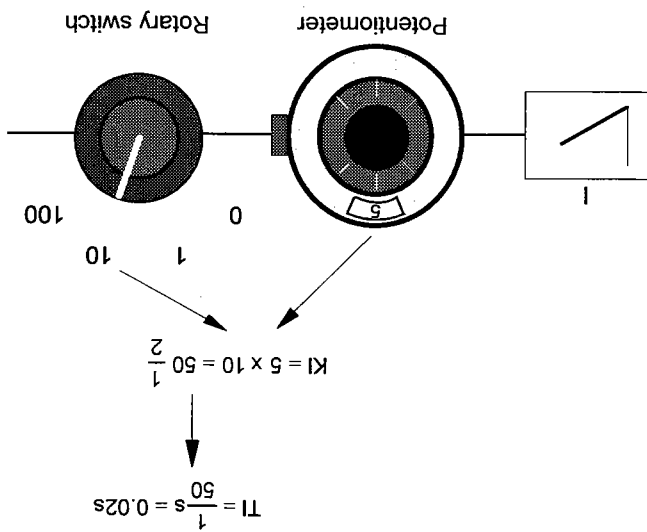
Controller type	Advantage	Disadvantage
P controller	Fast	Inaccurate
I controller	Accurate	Slow, tendency to oscillation
PI controller	Fast and accurate	Tendency to oscillation

Advantages and disadvantages of P, I, and PI controllers
Table A11.1:

I controller on controller card

A rotary switch and a potentiometer are provided on the controller card to allow setting of the integral-action coefficient K_I of the I controller. The rotary switch has a multi-step scale from 0 to 100, while the potentiometer has a infinite scale from 0 to 10. The product of these two values gives the integral-action coefficient K_I in the unit $[1/s]$. The integration time T_I can then be calculated as the reciprocal of this.

Fig. A11.5:
Example of setting of
integral-action coefficient K_I



PI controller on controller card

A PI controller can be created on the controller card by adding the output signals of the P and I controllers. The correcting variable produced in this way is available at the controller card output. The *integral-action time* T_n is the quotient of the proportional coefficient setting and the integral-action coefficient:

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

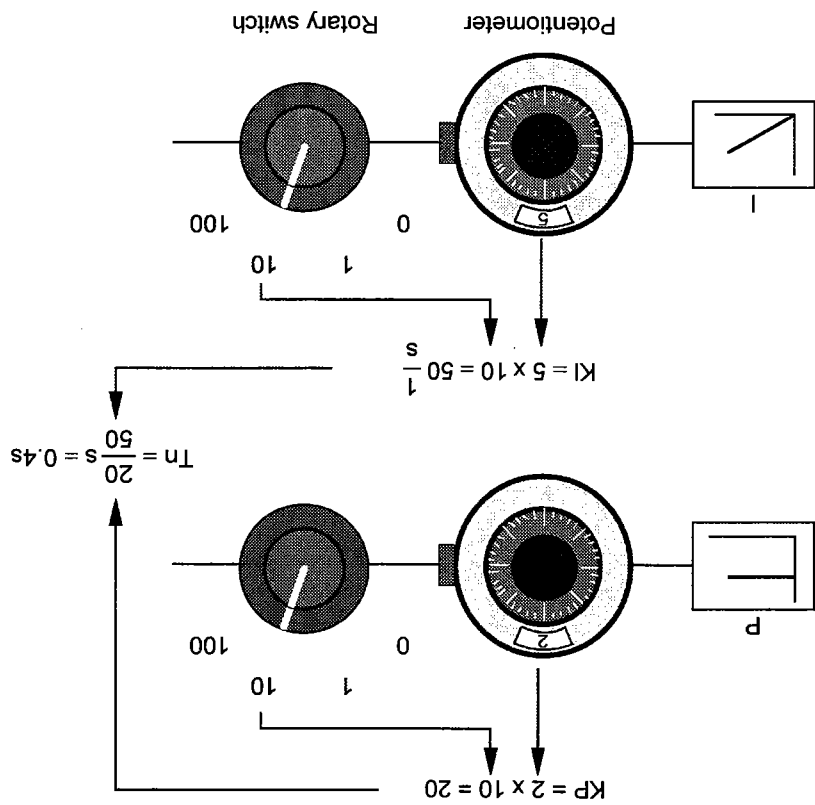


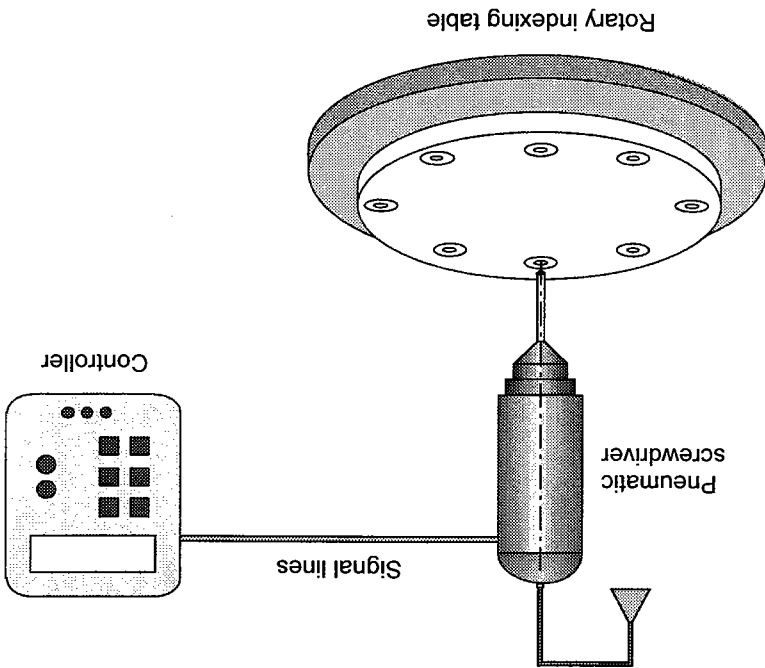
Fig. A11.6:
Example of calculation of
integral-action time T_n

Problem description

A pneumatic screwdriver is equipped with a torque control system using a P controller. In order to improve the accuracy of the torque control, the P controller is to be supplemented by an I controller. In order to reduce costs, a new controller will not be developed; instead, an existing controller card will be used.

The technical data for this controller must be determined during the planning phase.

Fig. A11.7:
Positional sketch



Exercise

The process of determining the technical data consists of the following steps:

1. Production of a transition function with the I controller
2. Measurement of the integration time T_I and calculation of the integral-action coefficient
3. Determination of the minimum and maximum integration times which can be set
4. Production of a transition function with the PI controller
5. Measurement of the integral-action time T_n and comparison of this with the values set
6. Determination of the minimum and maximum integral-action times which can be set
7. Comparison of P, I and PI controllers.

Execution

11.1 Plotting the transition function with the I controller

Note the following regarding the display of the transition function of an I controller:

An input signal located only in the positive or negative voltage range will cause the integrated output signal to rise or fall to its limit and remain at this value. The output signal cannot thus be displayed in this case.

If an integral transition function is to be displayed, a square-wave input signal is thus required which oscillates symmetrically about the zero point. The use of a signal of this kind (e.g. ± 10 V) allows a triangular wave output signal to be produced, with a gradient which is alternately positive and negative. With this form of display, the measured values for the integration time and integral-action time should be halved!

In order to record the transition function, proceed as follows:

- Assemble the circuit in accordance with the electrical circuit diagram provided.
- Set all the controller parameters and the correcting variable offset to zero.
- Set the range selector switch to $[-10 \dots 10 \text{ V}]$.
- Specify a fixed value for the integral-action coefficient (e.g. $K_I = 5 [1/s]$).
- The amplitude of the input signal (offset = 0 V) should be matched to the voltage range of the controller card output (approx. 10 V). The output signal frequency should be selected in such a way that the integrated output signal has enough time to rise to its limit (approx. 0.5 Hz).
- Draw the transition function of the I controller on the worksheet.
- Enter the amplitude A, the period of oscillation T and the integration time T_I.

11.2 Measurement of the integration time T_I and calculation of the integral-action coefficient

- Leave the test assembly and the signals unchanged.
- Specify an integral-action coefficient of $K_I = 10$.
- Measure the time (integration time) which the output signal takes for the reference variable step-change from 0 V to the limit (approx. 10 V).
- Calculate the actual integration time setting from the reciprocal of the integral-action coefficient.
- Determine the deviation between the integration times by comparing the measured and calculated integration times.

11.3 Determining the minimum and maximum integration times which can be set

In order to measure the maximum and minimum possible integration times, the potentiometer and rotary switch of the I controller should be turned to their end positions. The extreme values can be read from the resulting transition functions.



The output signal of the integrator reacts with a delay to a step-change in the input signal. This can be seen particularly clearly with high frequencies and large integral-action coefficients. This time component is not added to the integration time and can be determined by means of a tangent construction as an intersection between the transition function and the time axis.

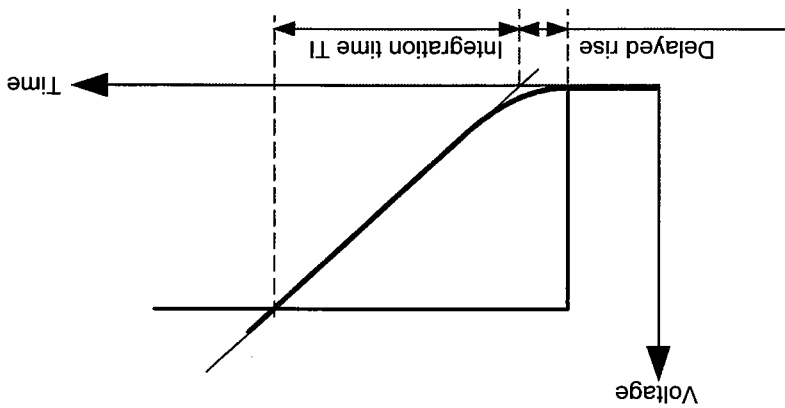


Fig. A11.8:
Integration time T_I

11.4 Plotting transition function with the PI controller

- Use the same test assembly as for step 1.
 - Set the correcting variable potentiometer and the controller parameters to zero and the range selector switch to [-10...+10 V].
 - The PI correcting variable is available at the output of the controller card at the correcting variable measuring sockets.
- Carry out the measurements using the following settings:

KP potentiometer:	0.5
KI potentiometer:	0.6
KI switch	10 1/s
Reference variable frequency:	2 Hz
Oscilloscope time division:	0.1 s/div
Oscilloscope amplitude:	5 V/div
Reference variable amplitude:	approx. 10 V

11.5 Measurement of the integral-action time T_n and comparison of this with the values set

- Do not change the transition-function settings used for step 4.
- The transition function must not run into the limiter, since this would falsify the measured results. The transition function must have the signal curve shown in the worksheet. If necessary, carry out fine adjustment using the integral-action coefficient.*



- Measure and record the integral-action time T_n . Please note that, due to the special nature (alternating) of the reference variable (negative and positive values: -10 V ... +10 V), the integral-action time is equal to half the measured value (see signal curve in worksheet).

- Calculate the integral-action time using this formula: $T_n = \frac{K_I}{K_P}$

- Compare the measured integral-action time with the calculated value and determine the deviation.

11.6 Determining the minimum and maximum integral-action times which can be set

In order to measure the maximum integral-action time of the PI controller, it is necessary to set the greatest possible proportional-action coefficient and the smallest possible integral-action coefficient. The opposite settings should be used to measure the minimum integral-action time.

11.7 Comparison of P, I and PI controllers

Assess and draw a distinction between the three types of controllers by filling out the table in the worksheet.

WORKSHEET

11.1 Plotting the transition function with the I controller

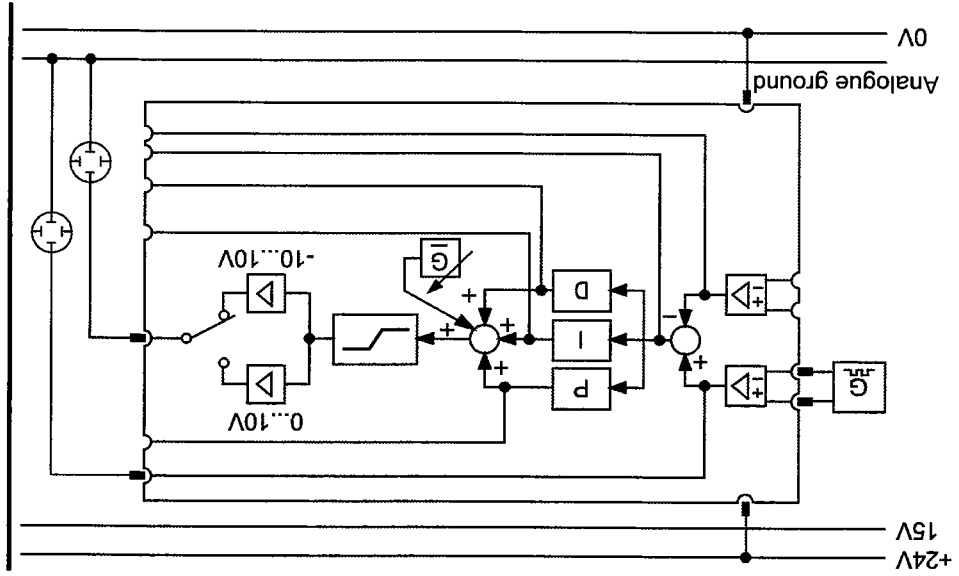


Fig. A11.9:
Electrical circuit diagram

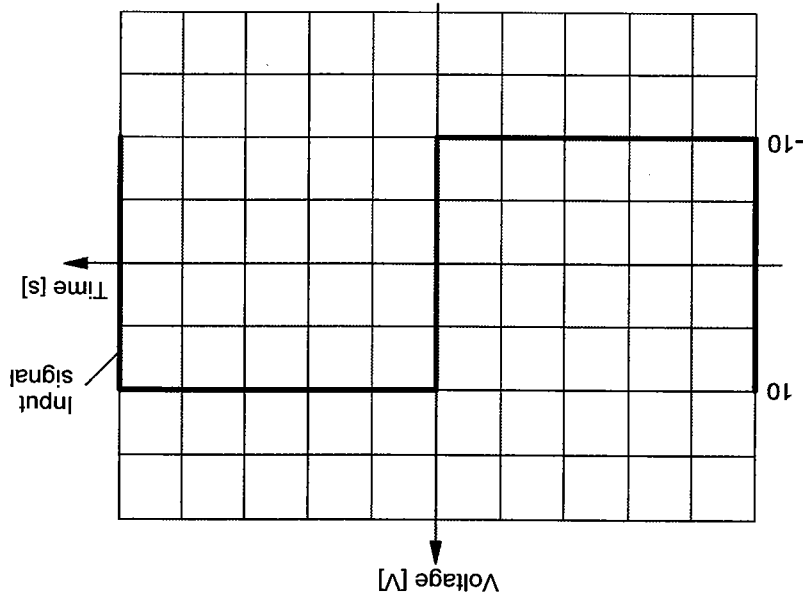


Fig. A11.10:
Transition function
I controller

11.2 Measurement of the integration time TI and calculation of the integral-action coefficient

Measured integration time $T_I =$ _____ ms

Integral-action coefficient setting $K_I =$ _____ 1/s

Calculated integration time: $T_I =$ _____ ms

Deviation =
Measured integration time – Calculated integration time = _____ ms

What percentage setting accuracy results in this case?

$$\text{Percentage deviation} = \frac{\text{Deviation}}{\text{Calculated } T_I} \cdot 100 \%$$

11.3 Determining the minimum and maximum integration times which can be set

Minimum integration time T_{Imin} (with $K_I = 1000$ 1/s) = _____ ms

Maximum integration time T_{Imax} (with $K_I = 0$ 1/s) = _____ ms

WORKSHEET

11.4 Plotting the transition function with the PI controller

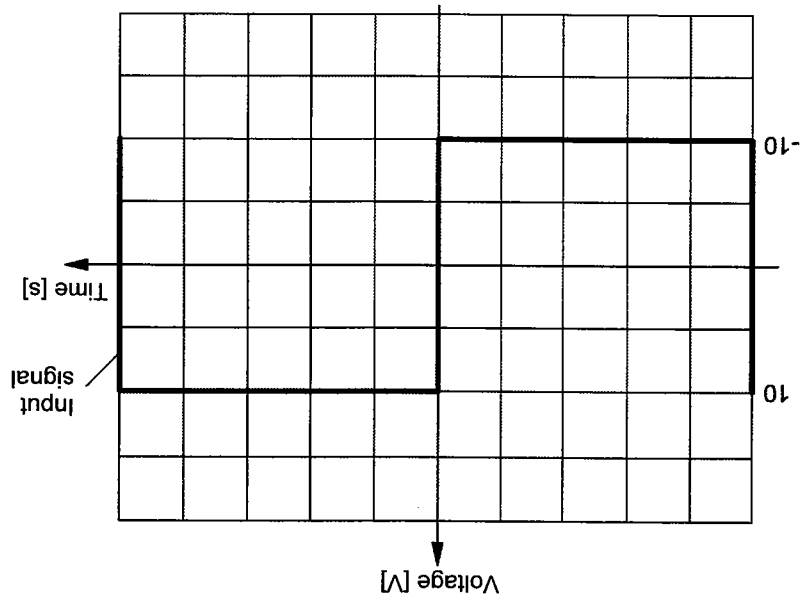
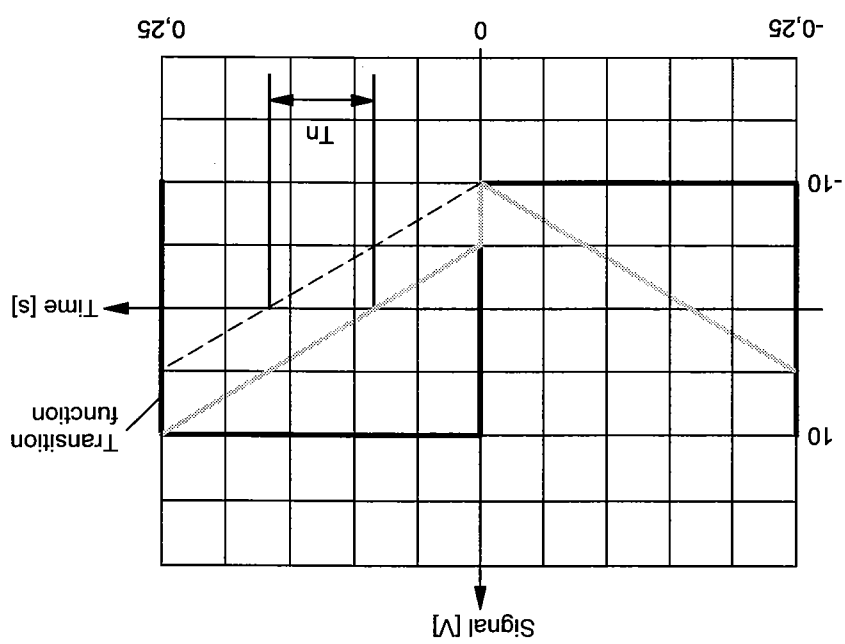


Fig. A11.11:
Transition function
PI controller

11.5 Measurement of the integral-action time T_n and comparison of this with the values set

The transition function should be displayed on the oscilloscope as follows:

Fig. A11.12:
Diagram



Parameter settings $K_P = 0.5$ and $K_I = 6 \text{ 1/s}$:
 Measured integral-action time $T_n =$ _____ ms
 Calculated integral-action time $T_n =$ _____ ms
 Deviation = Measured T_n – Calculated $T_n =$ _____ ms

WORKSHEET

11.6 Determining the minimum and maximum integral-action times which can be set

Minimum integral-action time $T_{n \min}$ (with $K_P = 0$; $K_I = 1000$): _____ ms
Maximum integral-action time $T_{n \max}$ (with $K_P = 1000$; $K_I = 0$): _____ ms

11.7 Comparison of P, I and PI controllers

Draw a distinction between the properties of the various types of controllers:

Criteria	Controller types		
	P	I	PI
Speed			
Steady state system deviation			

Table A11.2:
Comparison of different controller types

Subject

Injection-moulding machine

Title

Training aims

- To be able to determine the limit of stability of a closed-loop pressure control circuit using an I controller
- To be able to parametrise a PI controller using the empirical method

Technical knowledge

Setting criteria for a PI controller

The operation of a controller depends on, among other things, how well its coefficients are matched to the runtime performance of the controlled system in question. The setting of coefficients is known as parametrisation.

There are two methods of matching a controller to a controlled system and carrying out settings:

- Mathematical (using formulae)
- Empirically (by trial and error)

With the mathematical method, the controlled system is expressed as a mathematical model. Parameters for the controller are derived from this model. The disadvantage of this method is that it requires the laborious determination of controlled-system data.

The empirical method is used whenever the data for the controlled system are not precisely known.

Preparatory work

■ Assemble the closed-loop control circuit

■ Check the circuit

■ Switch on the electrical power supply

■ Switch on the compressed air

■ Check the control direction and change if necessary

■ Initialise the controller

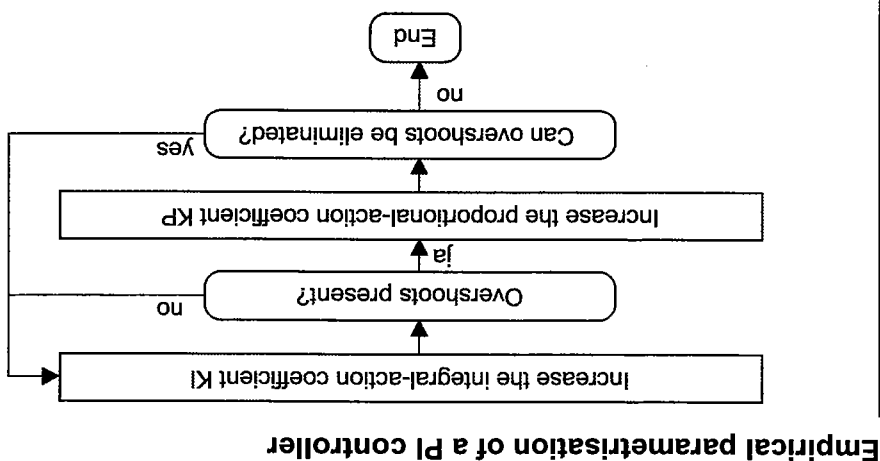
(set all parameters and the correcting variable offset to zero)

■ Set the range selector switch (-10 ... +10 V or 0 ... +10 V

■ Apply a step-change reference variable signal

■ Adjust the correcting variable offset to compensate for asymmetries

Fig. A12.1:
Flow diagram for
empirical parametrisation of
a PI controller

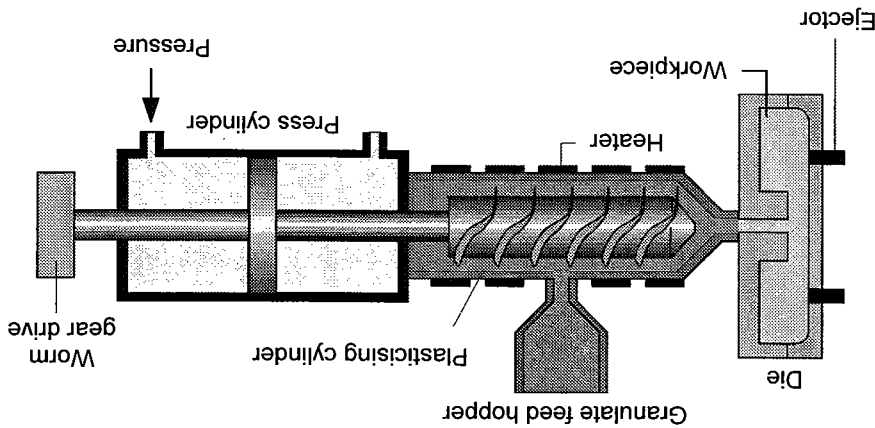


Always try to set the highest possible value for K_P . This gives a short settling time.

Problem description

Granulate passes via the granulate feed hopper of an injection-moulding machine into a plasticising cylinder. The rotary motion of the worm gear and the application of heat compress, degasify and thus plasticise the granulate. Once this process is complete and the hollow die has been closed, the injection stroke begins. During this stroke, the cylinder advances the worm drive; this in turn forces the plasticised material into the die. The pressure in the cylinder must remain constant during the cooling phase. The pressure to be applied to the plastic material depends on the workpiece to be produced and the strength of the die. A closed-loop pressure control system must be used for the cooling phase.

Fig. A12.2
Cross-section of an
injection-moulding machine



The commissioning of the circuit is carried out in the following steps:

Exercise

1. Assembly of the pneumatic and electrical circuits
2. Determination of the limit of stability of the closed-loop control circuit with the I controller
3. Parametrisation of the PI controller.

12.1 Assembly of the pneumatic and electrical circuits

Execution

The closed-loop control circuit for the injection-moulding machine is to consist of the following components:

- Voltage generator
- PID controller card
- Proportional directional control valve
- Compressed-air reservoir
- Pressure gauge
- Pressure sensor

In the interests of simplicity, the cylinder will be omitted from the circuit. A storage oscilloscope is recommended for the measurement and display of the signals.

- Assemble the closed-loop control circuit in accordance with the circuit diagrams provided and set the correct control direction.

12.2 Determining the limit of stability of the closed-loop control circuit with the I controller

- Set all the coefficients to zero and the correcting variable offset to approx. 0 V.
- Set the range selector switch of the limiter to [0 ... 10 V].
- Select a reference variable step change with an offset of 3 V and an amplitude of 1 V. The frequency selected should be as low as possible (approx. 0.1 Hz).
- Set the integral-action coefficients specified in the worksheet.
- Measure and note the maximum overshoot amplitude x_m in each case. Note that the overshoot amplitude is different in the upper and lower amplitude range. Furthermore, the first overshoot after a step change may have a greater amplitude than the subsequent overshoots.



Very long settling times occur, with the result that the settling process cannot in certain cases be concluded at the selected frequency of 0.1 Hz. This does not, however, have any influence on the overshoot amplitude.

- Record in the table provided the integral-action coefficients for which the closed-loop control circuit is stable. The stability limit has been reached as soon as steady-state oscillations are observed. These can be recognised on the oscilloscope, by the oscillation of the pointer of the pressure gauge or by an oscillating exhaust-air noise.

12.3 Parametrisation of the PI controller

- Increase the frequency of the reference variable to 1 Hz while leaving the signal otherwise unchanged.
- Commission the PI controller after carrying out empirical parametrisation.
- Optimise the controller parameters with a view to obtaining the smallest possible overshoot and the shortest possible settling time.
- Note the optimum controller values for K_P and K_I .
- Then evaluate the result by answering the following questions.

Assemble the circuits.

Assemble the circuits.

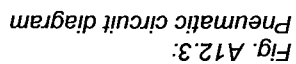


Fig. A12.3:
Pneumatic circuit diagram

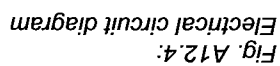


Fig. A12.4:
Electrical circuit diagram

12.2 Determining the limit of stability of the closed-loop control circuit with the I controller

Table A12.1:
Limit of stability of the
closed-loop control circuit

Integral-action coefficient K_I [1/s]	Stable?	Maximum overshoot amplitude x_m [V]	
		Upper value	Lower value
0.5			
1			
5			
10			
20			
50			
100			

At what K_I value do steady-state oscillations first occur (limit of stability)?

How does the overshoot amplitude change when K_I increases?
Consider only those K_I values at which the closed-loop control circuit is stable.

- The overshoot amplitude
- ☐ becomes larger
 - ☐ becomes smaller
 - ☐ stays the same

WORKSHEET

12.3 Parametrisation of the PI controller

Coefficients	Optimum values	
	KP	KI
	PI controller	

Can the values for KP and KI in this closed-loop control circuit be increased to any desired value?

How do the characteristic data overshoot amplitude, settling time and steady-state system deviation vary if KI is set to zero with KP unchanged?

- The characteristic data
- ☐ become noticeably larger
 - ☐ become noticeably smaller
 - ☐ stay roughly the same

Subject

Title

Training aims

- To be able to explain the design of a derivative-action controller
- To be able to produce transition functions with D, PD and PID controllers

Forming of moulded packaging

Closed-loop pneumatics

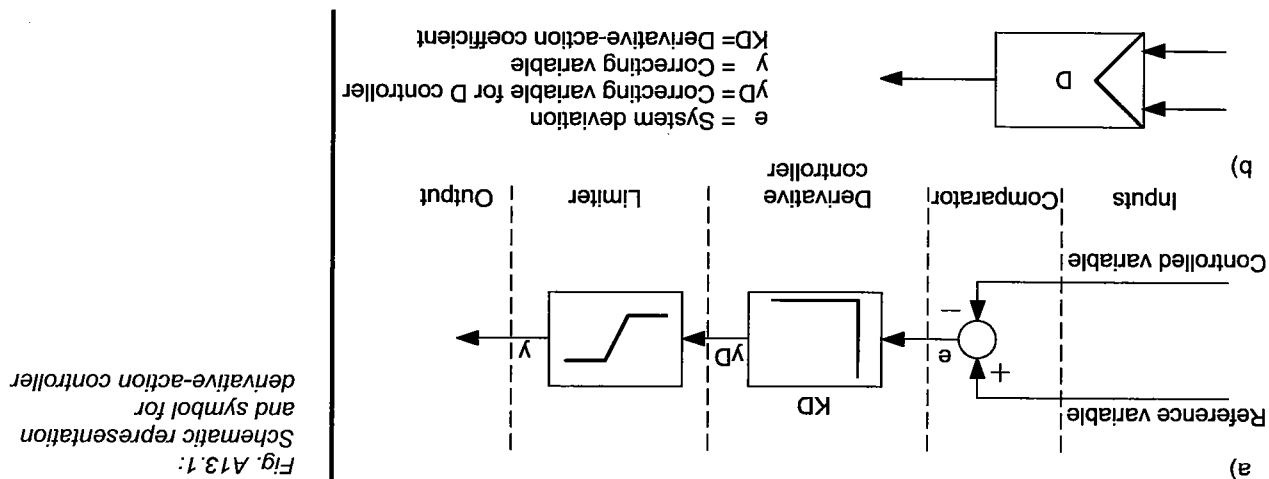
Derivative-action controller (D controller)

Technical knowledge

- A derivative-action controller is made up of the following function areas:
 - The reference variable and controlled variable are fed to the inputs.
 - The comparator uses the reference variable and controlled variable to produce a system deviation e .
 - The derivative-action controller amplifies the change in the system deviation de/dt . The magnitude of the gain depends on the derivative-action coefficient KD which has been set. The relationship between the system deviation change and the differentiated correcting variable yD is described by the following equation:

$$yD = KD \cdot \frac{de}{dt}$$

- The limiter has the task of limiting the correcting variable yD to within a range which is matched to the actuating range of the downstream control element.
- The correcting signal y is available at the output.



The *transition function* (Fig. A13.2) shows that, when a step-change occurs in the input signal, the correcting variable exhibits a brief step increase and then returns to zero.

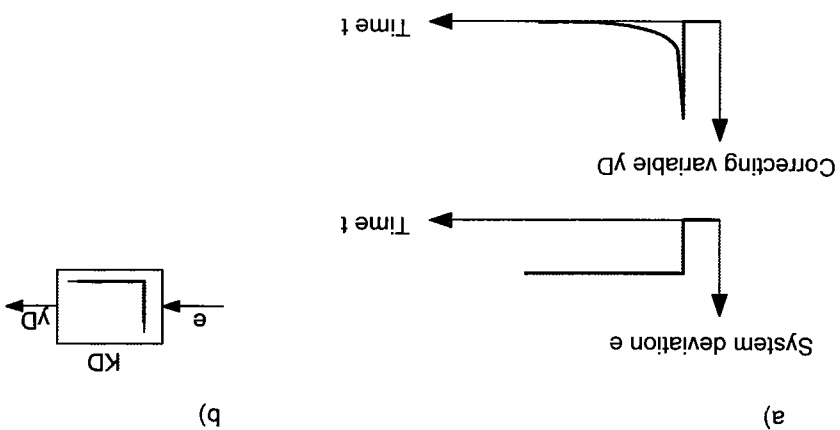


Fig. A13.2:
Transition function and
symbol for D controller

The D controller responds to changes in the system deviation. It therefore reacts faster than the P controller. A D controller is, however, not able to compensate for a steady-state system deviation. A derivative-action controller is used in combination with a proportional or a proportional plus integral controller. With a D controller, we consider not only the transition function (step response) but also the ramp response, i.e. we apply an input signal with a slow rise (triangular-wave signal). A step-change signal (square-wave) is then obtained as an output signal.

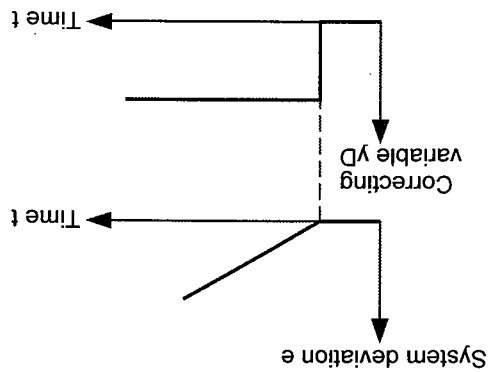
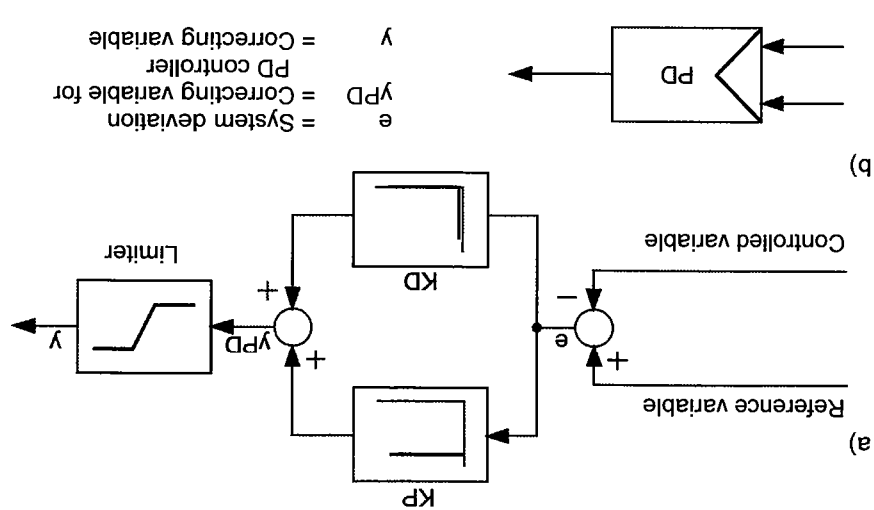


Fig. A13.3:
Ramp response
of D controller

PD controller

In the case of a PD controller, a proportional-action and a derivative-action controller are connected in parallel.

Fig. A13.4:
Schematic representation
and symbol for
PD controller



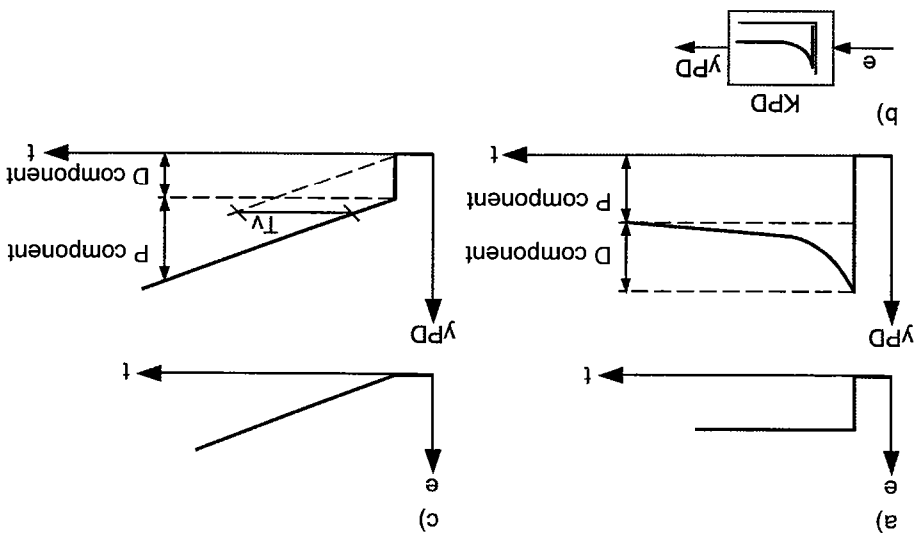
With a constant system deviation change, a PD controller operates in accordance with the following equation:

$$y_{PD} = K_P \cdot (e + T_v \cdot \frac{de}{dt}) \quad \text{where } T_v = K_D / K_P$$

(T_v = derivative-action time)

The characteristic data of a PD controller are as follows: K_P and K_D or K_P and T_v . The derivative-action time T_v specifies the time difference by which the ramp response of the PD controller reaches a specified value sooner than a P controller. The derivative-action time T_v of a PD controller is the quotient of the derivative-action coefficient K_D and the proportional-action coefficient K_P and can be determined from the ramp response using a graph.

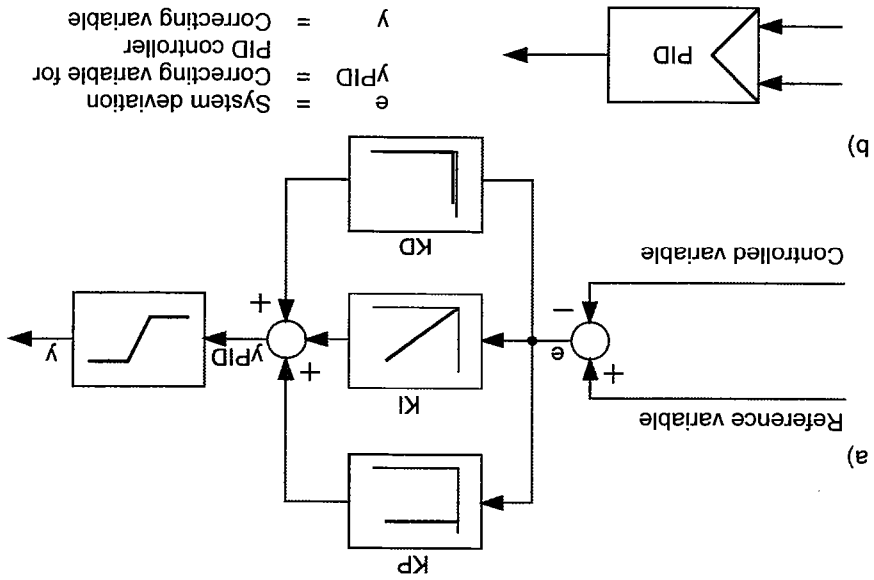
Fig. A13.5:
Transition function,
symbol and ramp response
of PD controller



PID controller

A PID controller combines all three types of controllers.

Fig. A13.6:
Schematic representation
and symbol for
PID controller



e = System deviation
 y_{PID} = Correcting variable for
 PID controller
 y = Correcting variable

The characteristic data of a PID controller are the coefficients K_P , K_I and K_D and the times T_n and T_v . The integral-action time can be determined from the transition function using a tangent construction (see Fig. A13.7).

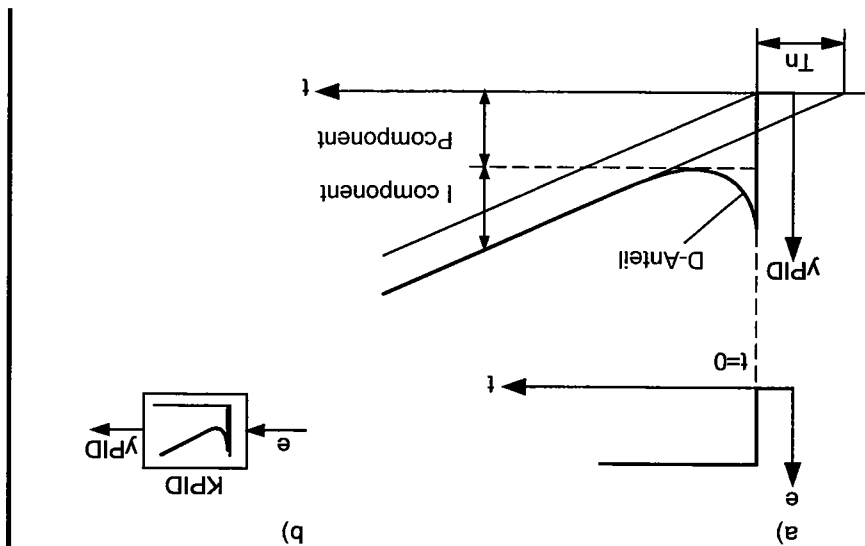


Fig. A13.7:

Transition function and symbol for PID controller

Table A13.1 compares the advantages and disadvantages of the various types of controllers.

Controller type	Advantages	Disadvantages
P controller	Fast	Steady state system deviation
I controller	No steady state system deviation	Slow, tendency to oscillation
PI controller	Fast, no steady state system deviation	Tendency to oscillation
PD controller	Very fast	Steady state system deviation
PID controller	Very fast, no steady state system deviation	—

Table A13.1:

Advantages and disadvantages of controller types

D controller on controller card

The derivative-action branch of the controller card has two adjustment devices, a potentiometer and a multi-step rotary switch. The product of these two settings is the derivative-action coefficient KD with the unit [ms].

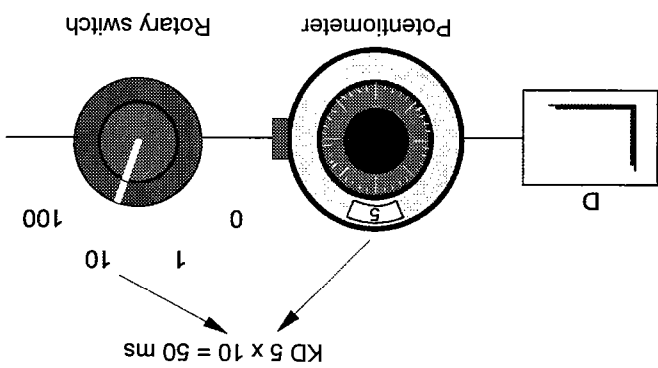


Fig. A13.8:
Examples of setting of
derivative-action
coefficient and
controller card

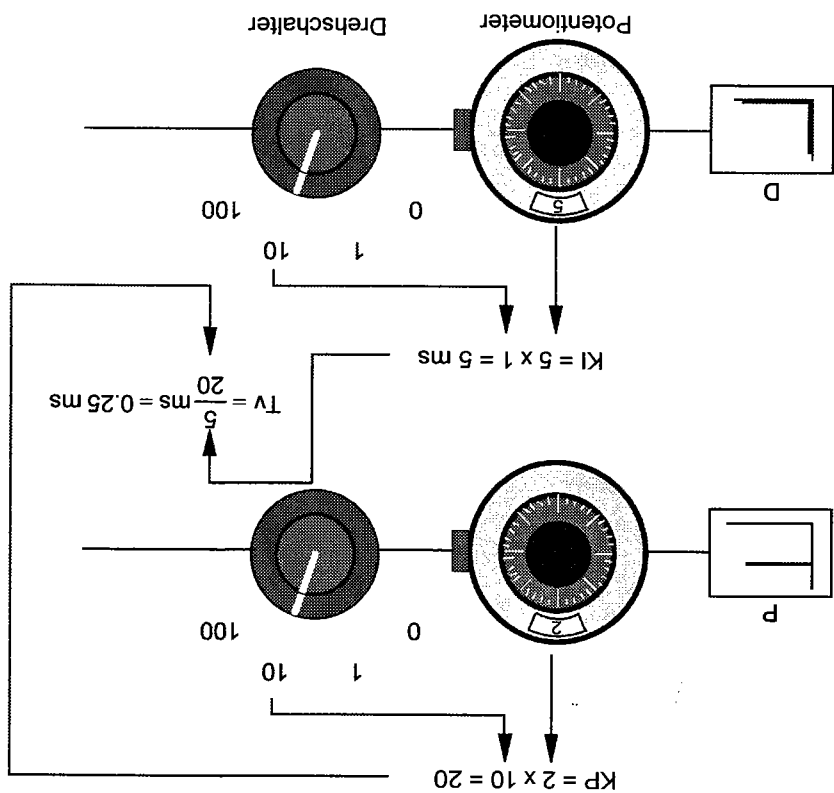
PD controller on controller card

In the case of the PD controller, the two correcting signals from the proportional-action and derivative-action controllers are added together at the summation point. This signal is then available for measurement at the controller card output.

The derivative-action time T_v is the quotient of the settings for the derivative-action and proportional-action coefficients:

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

Fig. A13.9:
Example of
setting of derivative-action
time on controller card



PID controller on controller card

With the PID controller, the three correcting signals of the proportional-action, integral-action and derivative-action controllers are added together at the summation point. Signals are generated in a similar way to those of a PI or PD controller.

The parameters of industrial PID controllers can be set in two different ways:

1. Setting of the coefficients K_P , K_I and K_D .

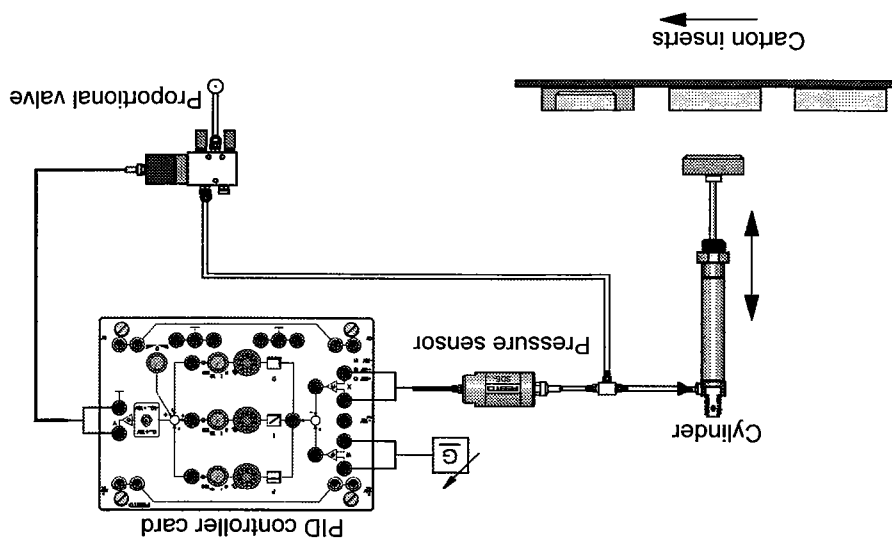
2. Setting of the integral-action time T_n and derivative-action time T_v .

Both methods have both advantages and disadvantages. The first method will be used to adjust the PID controller in the present case. This has the advantage that the effect of the coefficients can be investigated selectively.

Problem description

In a packaging plant, a pneumatically-driven feed device is used to form depressions in carton inserts. The actual pressing operation is carried out using a pressure control system. Inspection of the finished work-pieces reveals that "chatter" is taking place during the pressing operation. Re-adjustment of the controller parameters does not produce any improvement. We will now investigate the D element of the PID controller.

Fig. A13.10:
Positional sketch



Exercise

The D controller will be checked in the following steps:

1. Drawing of the transition and ramp responses of the D controller.
2. Drawing of the ramp response of the PD controller and determination of TV.
3. Drawing of the transition function of the PID controller.

Execution

13.1 Drawing the transition and ramp responses of the

D controller

- Assemble the electrical circuit in accordance with the circuit diagram.
- Set all coefficients and the correcting variable offset to zero. Set the range selector switch to [-10 ... 10 V].
- Display the controller input and output variables on the oscilloscope.
- Apply a square-wave signal to the reference variable input of the controller. Amplitude 10 V, offset 0 V and frequency 5 Hz.
- Select the following oscilloscope setting: Time/div. 20 ms, amplitude/div. 5 V.
- Set a derivative-action coefficient $K_D = 25$ ms.
- Draw the output signal on the worksheet.
- Input a triangular-wave signal in order to display the ramp response. Amplitude, offset and frequency should remain as before.
- Display the ramp response on the oscilloscope and draw this on the worksheet.
- Calculate the correcting variable for the ramp response, using the formula:

$$y = K_D \cdot \frac{de}{dt}$$
- Compare the calculated correcting variable and the measured variable (amplitude of ramp function).

13.2 Drawing the ramp response of the PD controller and determining the T_v

- Use the triangular-wave signal from step 1 and leave the test assembly unchanged.
- Set a proportional-action coefficient of $K_P = 0.5$ and a derivative-action coefficient of $K_D = 25 \text{ ms}$ on the controller card.
- Plot the ramp function in the coordinate system on the worksheet.
- Now measure the derivative-action time T_v from your drawing and enter the value into the worksheet. Note that, due to the alternating reference variable signal, the derivative-action time is equal to half the measured value.
- Calculate the derivative-action time T_v using the formula:

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

and compare this with the measured value.

13.3 Drawing the transition function of the PID controller

- As in step 1, input a step-change symmetrical reference variable signal
 - amplitude = 10 V
 - offset = 0 V
 - frequency = 5 Hz
- Set the following values on the controller card:
 - K_P = 0.5
 - K_I = 25 1/s
 - K_D = 25 ms
- Draw the transition function of the PID controller on the worksheet.
- Explain the curve for the transition function by dividing this into P, I and D components.

WORKSHEET

13.1 Drawing the transition and ramp responses of the D controller

The measuring circuit is as follows:

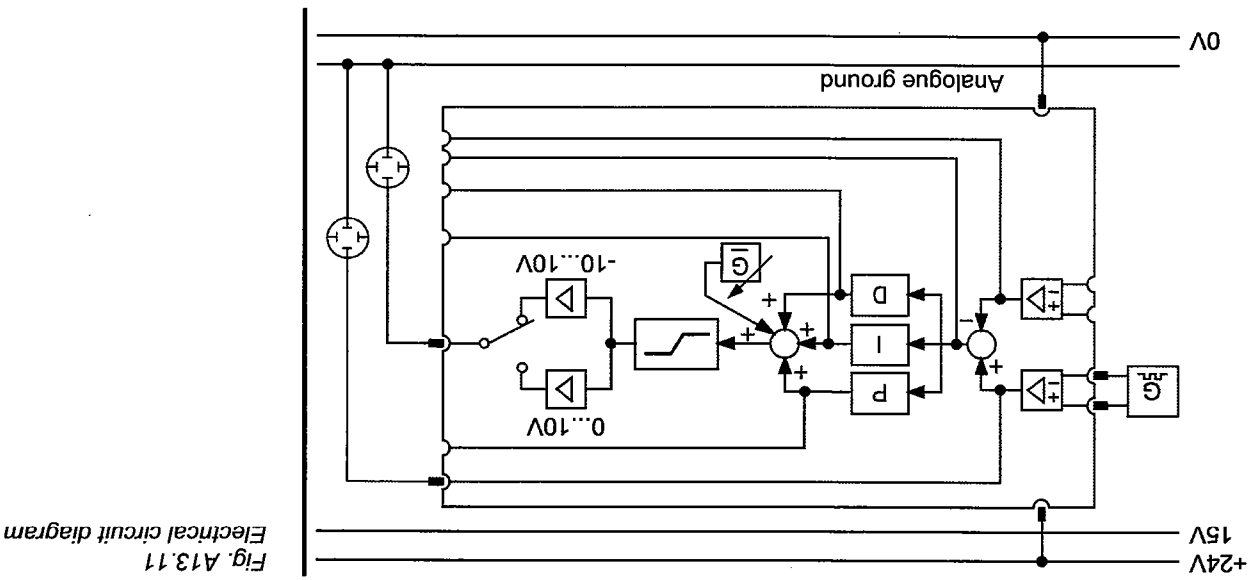
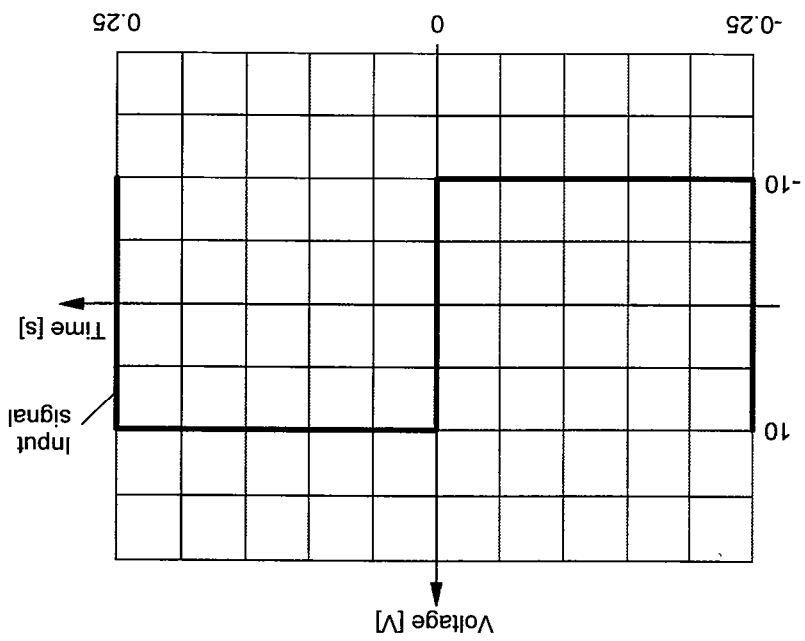


Fig. A13.11

Electrical circuit diagram

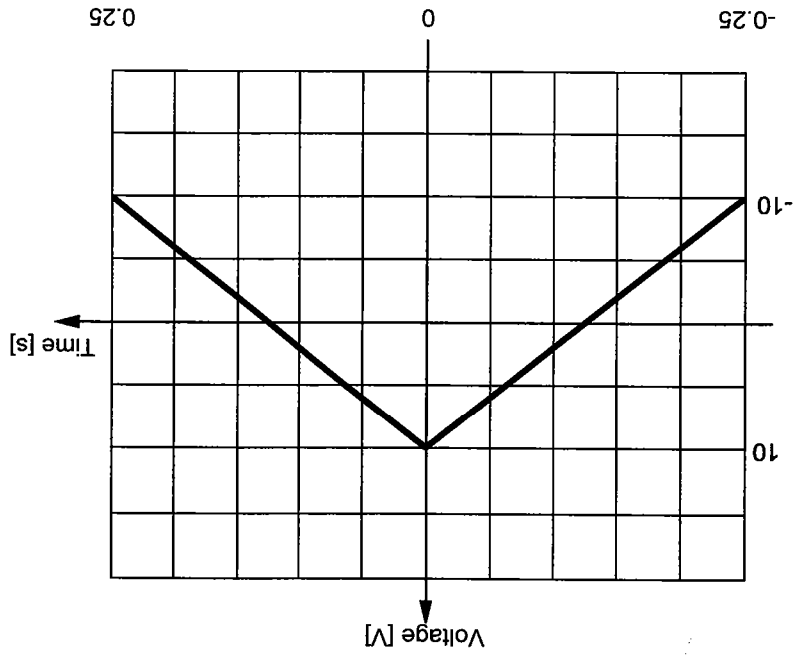
Fig. A13.12:
Transition function of
D controller



How can you explain the shape of the curve for the transition function?

WORKSHEET

Fig. A13.13
Ramp function of
D controller



The gradient $\frac{de}{dt}$ of the reference variable signal gives the following:

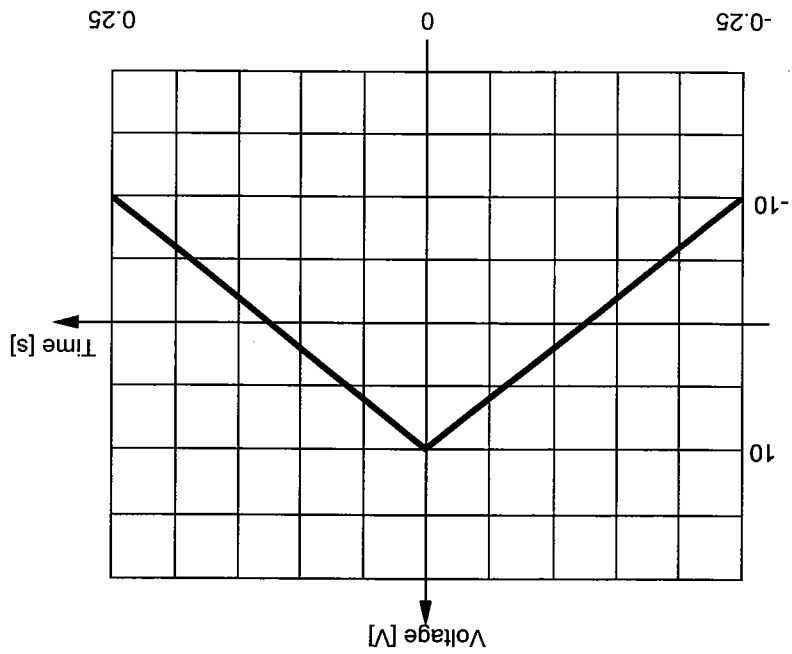
$$\frac{de}{dt} = 4 \cdot \text{Amplitude} \cdot \text{Frequency} \left[\frac{V}{s} \right]$$

Formula: $y = K_D \cdot \frac{de}{dt}$

$y =$ _____

13.2 Drawing the ramp response of the PD controller and determining the T_v

Fig. A13.14:
Ramp response of the
PD controller



Measured derivative-action time $T_v =$ _____ ms

Calculated derivative-action time $T_v =$ _____ ms

Deviation between measured and calculated derivative-action times:

_____ ms

Explain the shape of the curve for the transition function:

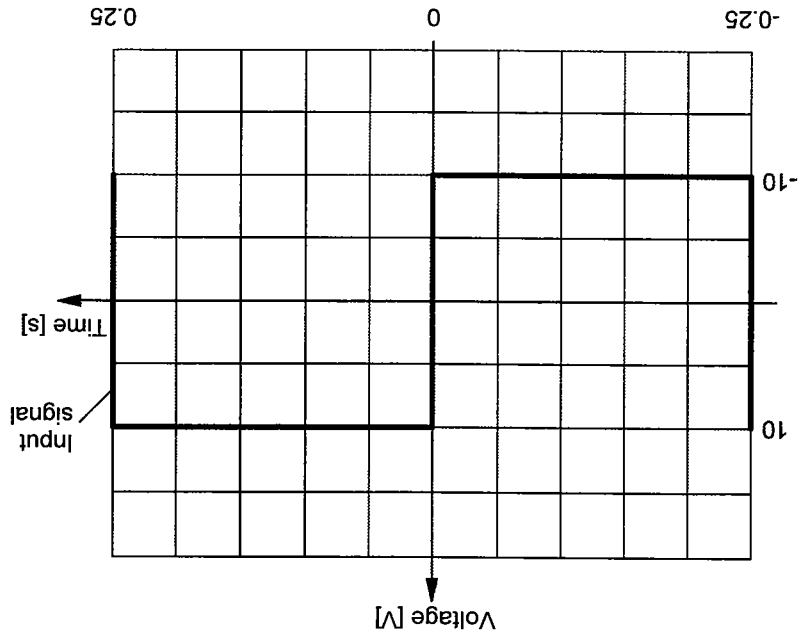


Fig. A13.15:
Transition function
of the PID controller

13.3 Drawing the transition function of the PID controller

WORKSHEET

Subject

Title

Training aims

- To be able to set the parameters of a PID controller using an empirical method
- To be able to assess the transient response of a closed-loop control circuit with a PID controller

Empirical parametrisation of a PID controller

Technical knowledge

The setting of a PID controller requires experience of commissioning. In order to make this work easier, a well-proven method for the parametrisation of a PID controller is described below.

Preparatory work

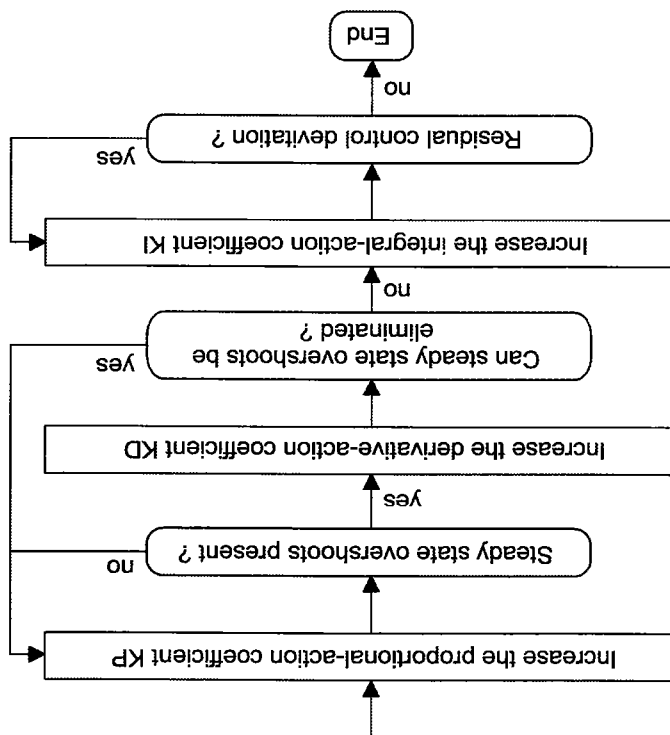
- Assemble the closed-loop control circuit
- Check the circuit
- Switch on the electrical power supply
- Switch on the compressed air
- Check the control direction and change if necessary
- Initialise the controller (set all parameters and the correcting variable offset to zero)
- Set the range selector switch (-10 ... +10 V or 0 ... +10 V)
- Apply a step-change reference variable signal
- Adjust the correcting variable offset to compensate for asymmetries

Closed-loop pneumatics

Bending machine

Empirical parametrisation of a PID controller

Fig. A14.1:
Flow diagram for
empirical parametrisation of
a PID controller



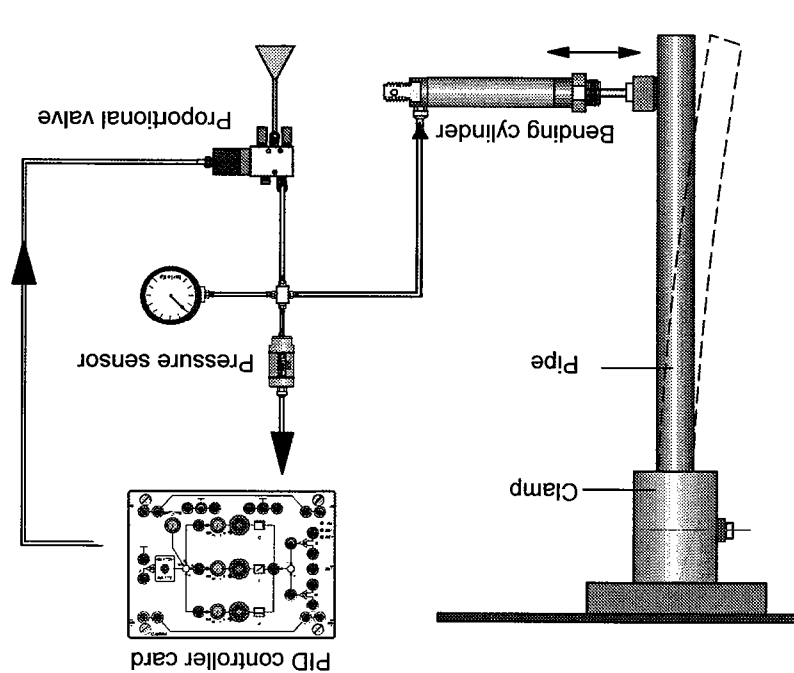
The procedure shown in the flow chart can be used only in cases where it is permissible to bring a closed-loop control circuit into oscillation during the setting operation.

Problem description

A bending machine is used to bend metal pipes of various diameters. The angle to which the clamped pipe is bent is determined by the stroke of the bending cylinder. The bending operation is matched to the characteristic data for the metal pipe (diameter, wall thickness, material). A bending force (or in other words cylinder pressure) is then used which is suitable for these data. A defined pressure must be present in the cylinder chamber during the advance stroke of the bending cylinder. This is ensured through the use of a closed-loop pressure control system.

The bending machine is to be operated with a closed-loop pressure control circuit incorporating a PID controller.

Fig. A14:2
Positional sketch



Exercise

- The execution of the experiment is made up of the following steps:
1. Assembly and commissioning of the closed-loop control circuit
 2. Investigation of the transient response of the closed-loop control circuit with a PD controller
 3. Investigation of the transient response of the closed-loop control circuit with a PID controller

14.1 Assembly and commissioning of the closed-loop control circuit

The closed-loop control circuit consists of the following components:

- Voltage generator
- PID controller card
- Proportional valve
- Two compressed-air reservoirs connected in series
- A one-way flow control valve (flow control valve fully open) fitted between the two reservoirs
- Pressure gauge
- Pressure sensor

A 2-channel storage oscilloscope should be used to measure the signals. Assemble the closed-loop control circuit in accordance with the prepared circuit diagrams and check the control direction.

14.2 Investigation of the transient response of the closed-loop control circuit with a PD controller

Commission the closed-loop control circuit with PD controller. Proceed in accordance with the flow chart shown in Fig. A14.1. Note the following additional instructions:

- Set the range selector switch to [0 ... 10 V].
 - Select a square-wave reference variable signal.
 - Offset 3 V, amplitude 1 V. The frequency should be approx. 0.1 Hz.
 - Display the reference variable and the controlled variable on the oscilloscope.
 - Note the optimised controller coefficients.
 - Enter the optimised controller coefficients and the characteristic data into the prepared table.
 - Now set the derivative-action coefficient K_D to zero.
 - Once again measure and record the characteristic data.
 - Compare the parameters and characteristic data of the P and PD controllers.
- In your measurements, consider only the upper range of the reference variable (4 V).*



14.3 Investigation of the transient response of the closed-loop control circuit with a PID controller

- The control system will now be optimised by adding an I controller.
- Use the optimised PD coefficients from step 2.
- Increase the integral-action coefficient K_I .
- Measure the characteristic data. Compare these with the data for the PD controller.
- Draw the controlled variable curve for the case in which K_I is increased to considerably above the optimised value ($K_I = \text{approx. } 40$).

WORKSHEET

14.1 Assembly and commissioning of the closed-loop control circuit

Fig. A14.3:
Pneumatic circuit diagram

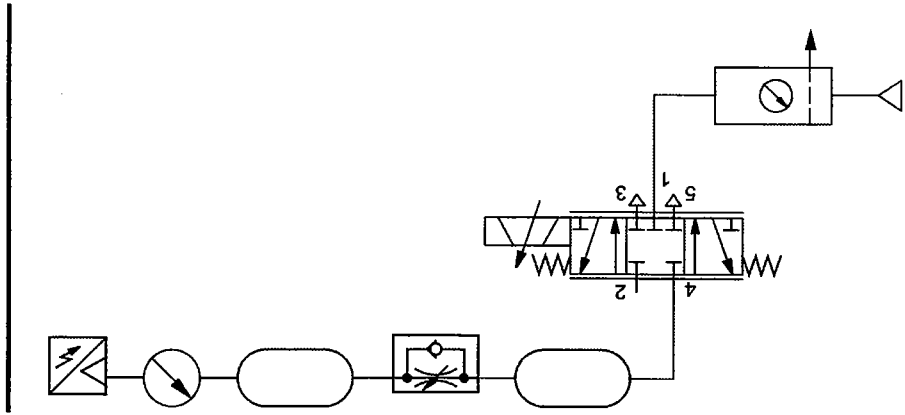
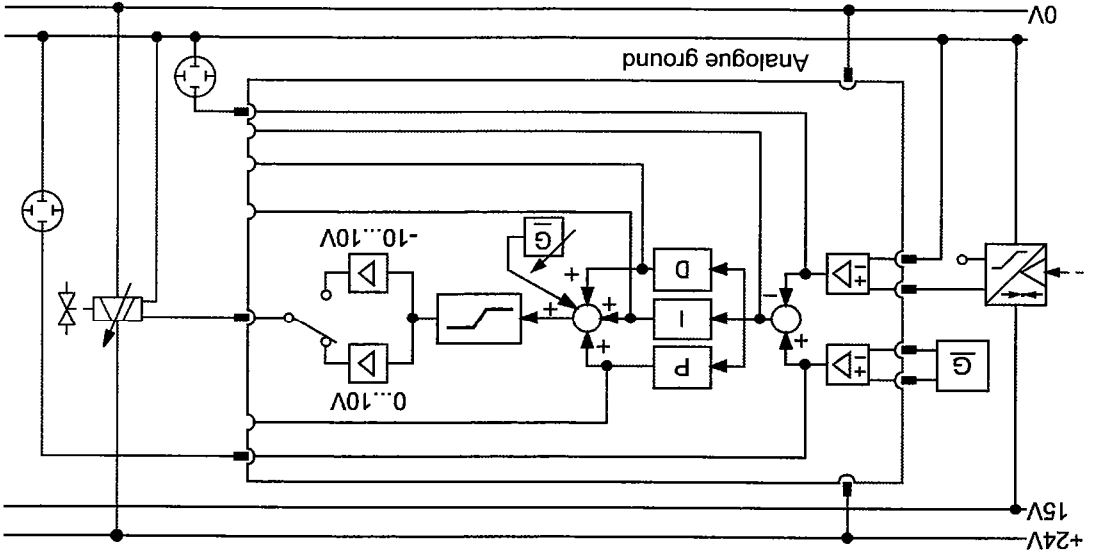


Fig. A14.4:
Electrical circuit diagram



14.2 Investigation of the transient response of the closed-loop control circuit with a PD controller

Table A14.1:

Characteristic data		Controller	
Proportional-action coefficient K_P		PD	
Derivative-action coefficient K_D [ms]		0	
Settling time T_a [ms]			
Overshoot amplitude x_m [mV]			
Steady state system deviation $e_{stat.}$ [mV]			

Is the closed-loop control circuit still stable after the derivative-action coefficient K_D is switched off?

Which type of controller gives a smaller overshoot amplitude?

WORKSHEET

14.3 Investigation of the transient response of the closed-loop control circuit with a PID controller

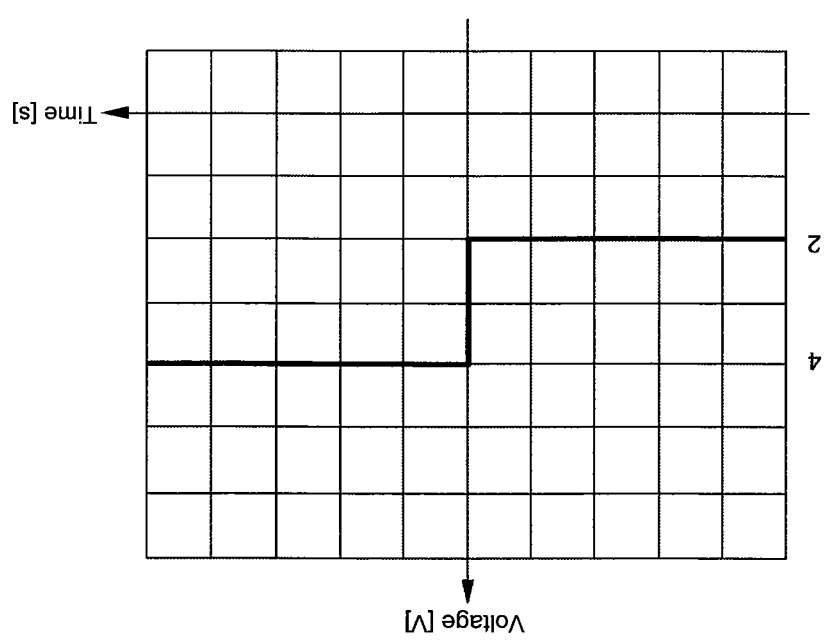
Enter the measured values from step 2 into the table.

Table A14.2:

Characteristic data		Controller PD (step 2) P
Proportional-action coefficient K_P		
Integral-action coefficient K_I [1/s]	0	
Derivative-action coefficient K_D [ms]		
Settling time T_a [ms]		
Overshoot amplitude x_m [mV]		
Steady state system deviation e_{stat} . [mV]		

Can the steady-state system deviation be reduced by increasing K_I ?

Fig. A14:5
Diagram



Describe the controlled variable curve for the case in which the value selected for K_I is too high.

Subject

Title

Training aim

Technical knowledge

Papermaking machine

Regelpneumatik

- Familiarization with the influence of interference variables

Interference variables are all the unwanted variables which act on a closed-loop control circuit and impair the closed-loop control action. Table A15.1 shows examples of interference variables and their effects on control behaviour.

Table A15.1:
Examples of interference
variables and their effects

Type of interference	Effect on control behaviour
Radiated noise signals	Unscreened electrical signal lines act as antennae for interference signal from adjacent electrical devices
Hysteresis	The hysteresis of closed-loop control circuit components leads to asymmetrical transmission behaviour. For example, a dynamic valve subject to hysteresis has different flow characteristics for its two flow directions.
Offset	Offsets shift the operating points of closed-loop control circuit components. This can lead to steady state system deviations.
Supply networks	Under-sizing of compressed air or electrical supply networks leads to fluctuations in the transmission lines. This impairs the follower behaviour of the closed-loop control circuit.
Leaks	Leaks in compressed air supply lines or within closed-loop control circuit components can reduce the line pressure.
Forces, moments	External forces or moments acting on the closed-loop control circuit cause changes in the runtime performance of closed-loop control circuit components.
Measuring errors	Incorrectly-installed or unsuitable measuring devices lead to falsified signals. Signal delays may result which impair the stability of the closed-loop control circuit.

Interference variables not only act on individual components, such as a dynamic valve, but can also act simultaneously on several components in a closed-loop control circuit. The variables may amplify each other or cancel each other out. Interference variable signals are designated as z .

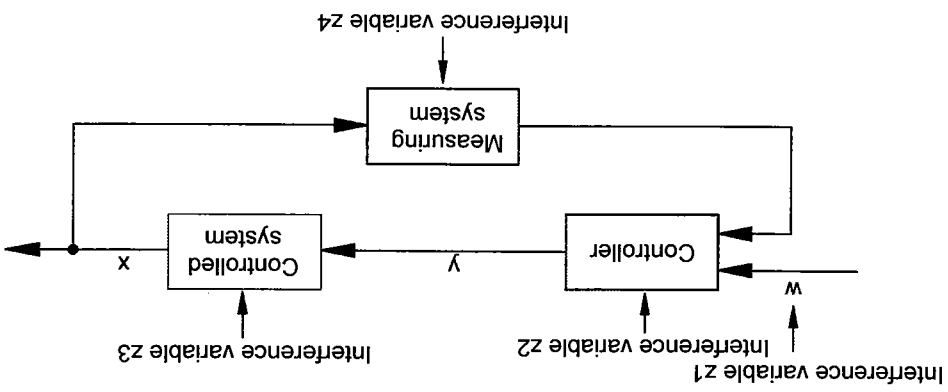


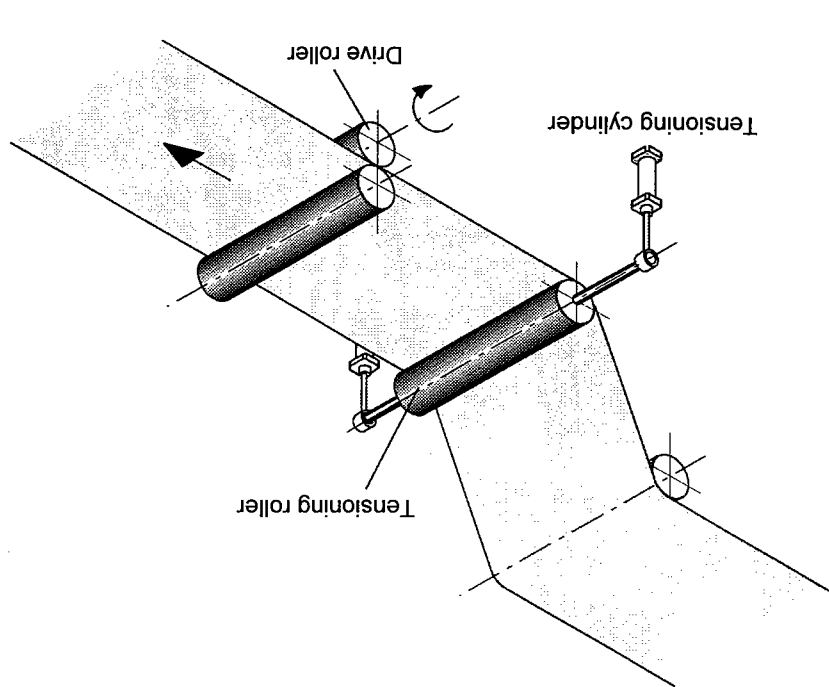
Fig. A15.1:
Points of attack of
interference variables

Problem description In a papermaking machine, strips of paper are transported through several pairs of rollers. The drive rollers are driven continuously by pneumatic vane motors.

Tensioning rollers are used to keep the paper taut. The tensile stress under which the paper is transported must not exceed the paper's tear strength.

In order to ensure that interference variables, caused for example by oscillations in the motion of the paper strip, are quickly brought under control, the pressure of the tensioning cylinder is controlled by a PID controller.

Fig. A15.2:
Positional sketch



The procedure for the investigation of the influence of various interference variables is as follows:

1. Assembly and commissioning of the closed-loop control circuit
2. Investigation of the influence of leaks
3. Investigation of the influence of the compressed-air supply pressure
4. Investigation of the influence of the measuring point

Execution

15.1 Assembly and commissioning of the closed-loop control circuit

The closed-loop control circuit used in the experiment is made up of the following components:

- Voltage generator
- PID controller card
- Proportional valve
- Two compressed-air reservoirs connected in series
- One-way flow control valve (1V2) between the reservoirs (flow control valve fully open)
- Pressure sensor
- Pressure gauge
- 3/2-way solenoid valve
- One-way flow control valve (1V3) upstream of solenoid valve
- Signal input plate

A storage oscilloscope should be used to measure the signals.

The solenoid valve should be connected up in such a way that it can be energised via a pushbutton on the signal input plate.

The series circuit consisting of the solenoid valve and one-way flow control valve (1V3) can be used to create a leakage interference variable. The flow control valve should be roughly half-open in order to control the flow of exhaust air.

Assemble the closed-loop control circuit in accordance with the prepared circuit diagrams and set the control direction.

First connect the pressure sensor to the measuring point identified as 2.

15.2 Investigation of the influence of leaks

The influence of a leak on control behaviour should be investigated as follows:

- Input a square-wave reference variable signal with an offset of 3 V and an amplitude of 1 V. The frequency should be set to roughly 0.1 Hz.
- Display the reference variable and controlled variable on the oscilloscope.
- Initialise the controller (set all parameters to zero).
- Parametrise the PID controller, using the empirical method and with the solenoid valve not actuated (no leakage).
- Measure and record the characteristic data.
- Activate the leak and record the characteristic data. Leave the controller settings unchanged.
- Discuss the result.

In your measurements, consider only the upper range of the reference variable (4 V).



15.3 Investigation of the influence of the compressed-air supply pressure

The influence of the supply pressure on control behaviour should be investigated as follows:

- Input a square-wave reference variable signal as in step 2.
- Display the reference variable and controlled variable on the oscilloscope.
- Initialise the controller (set all parameters to zero).
- Parametrise the PID controller, using the empirical method, for a pressure of 6 bar at measuring point 2 (you can also use the parameters from step 2).
- Measure and record the characteristic data.
- Reduce the pressure to 5 bar and then to 4 bar.
- Record the characteristic data.
- Assess the results by answering the following question.

15.4 Investigation of the influence of the measuring point

The influence of the measuring point on control behaviour should be investigated as follows:

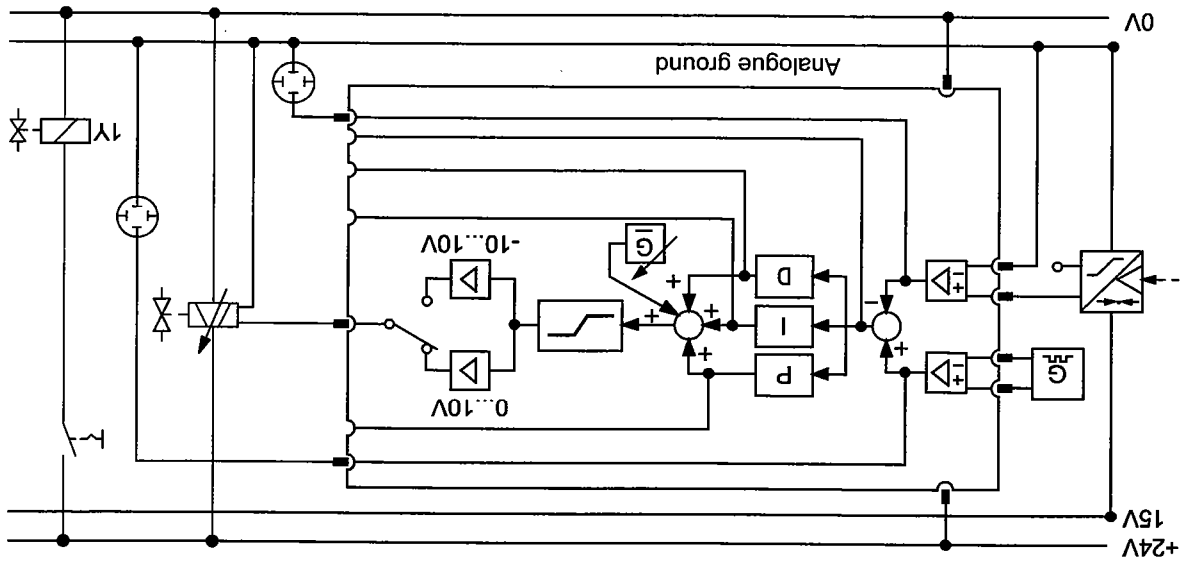
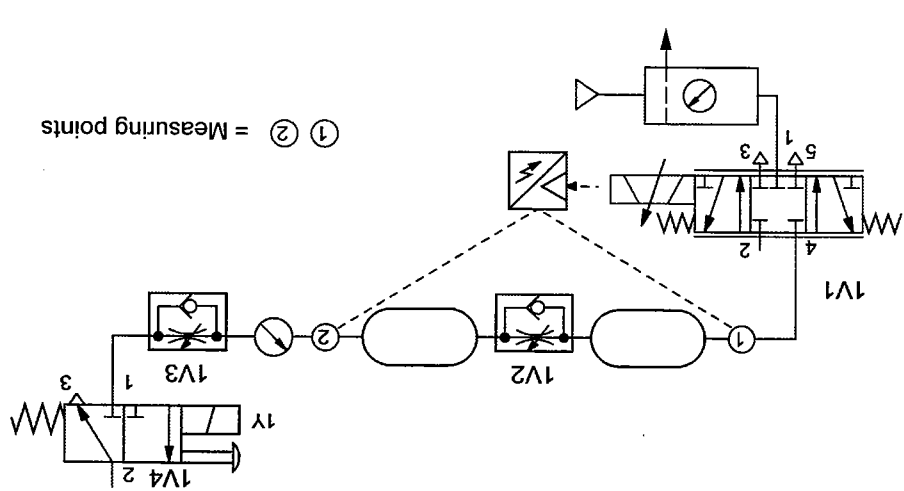
- Input a square-wave reference variable signal as in step 3.
- Display the reference variable and controlled variable on the oscilloscope.
- Initialise the controller (set all parameters to zero).
- Parametrise the PID controller, using the empirical method for two different measuring points within the measuring system (see pneumatic circuit diagram).
- Measuring point 2: Pressure sensor downstream of the controlled system
- Measuring point 1: Pressure sensor within the controlled system

The results from step 2 can be taken for measuring point 2.

- Measure and record the characteristic data in each case.
- Discuss the result.

WORKSHEET

15.1 Assembly and commissioning of the closed-loop control circuit



15.2 Investigation of the influence of leaks

Table A15.2:

Characteristic data		
Proportional-action coefficient KP		Without leaks
Integral-action coefficient KI [1/s]		Without leaks
Derivative-action coefficient KD [ms]		Without leaks
Settling time Ta [ms]		Without leaks
Overshoot amplitude xm [mV]		Without leaks
Steady state system deviation es _{stat} [mV]		Without leaks
		With leak

What is the influence of the leak on the settling time?

WORKSHEET

15.3 Investigation of the influence of the compressed-air supply pressure

Table A15.3:

Characteristic data			
Proportional-action coefficient KP			
Integral-action coefficient KI [1/s]			
Derivative-action coefficient KD [ms]			
Settling time Ta [ms]			
Overshoot amplitude xm [mV]			
Steady state system deviation es _{stat} [mV]			

What influence does the pressure level have on the settling time with a constant proportional-action coefficient?

15.4 Investigation of the influence of the measuring point

Table A15.4:

Characteristic data		
Measuring point 1	Measuring point 2	Proportional-action coefficient KP
		Integral-action coefficient KI [1/s]
		Derivative-action coefficient KD [ms]
		Settling time T_s [ms]
		Overshoot amplitude x_m [mV]
		Steady state system deviation e_{stat} [mV]

Which measuring point allows a higher proportional-action coefficient KP?

At which measuring point can a lower steady-state system deviation be achieved?

Subject

Title

Training aims

Technical knowledge

Setting parameters using the Ziegler-Nichols method

As a complement to empirical parametrisation, a number of standard methods have been developed. One method which uses objective criteria to produce suitable controller parametrisation is the "Ziegler-Nichols method".

The flow chart below explains the procedure for the parametrisation of a controller using the Ziegler-Nichols method:

Parametrisation using the Ziegler-Nichols method

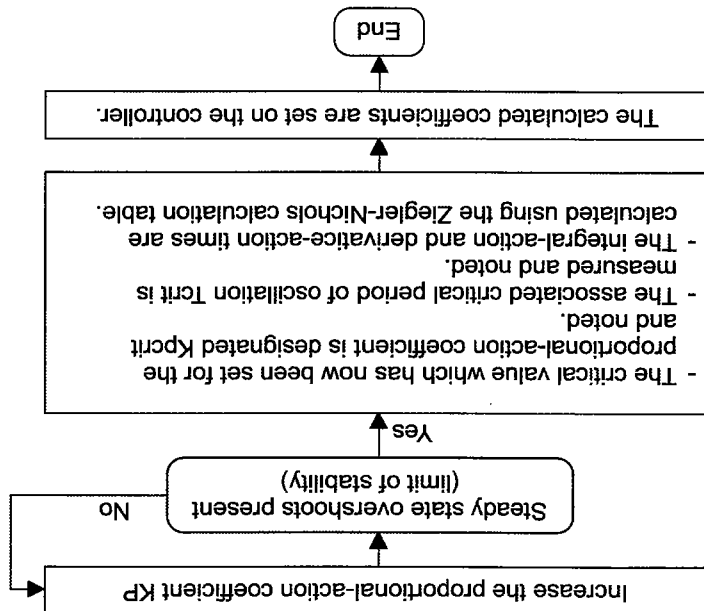


Fig. A16.1:
Flow diagram for
parametrisation using
the Ziegler-Nichols method

Closed-loop pneumatics

Testing machine

■ To be able to set the parameters of a PID controller using the Ziegler-

Nichols method

Preparatory work

- Assemble the closed-loop control circuit
- Check the circuit
- Switch on the electrical power supply
- Switch on the compressed air
- Check the control direction and change if necessary
- Initialise the controller (set all parameters and the correcting variable offset to zero)
- Set the range selector switch (-10 ... +10 V or 0 ... +10 V)
- Apply a step-change reference variable signal
- Adjust the correcting variable offset to compensate for asymmetries

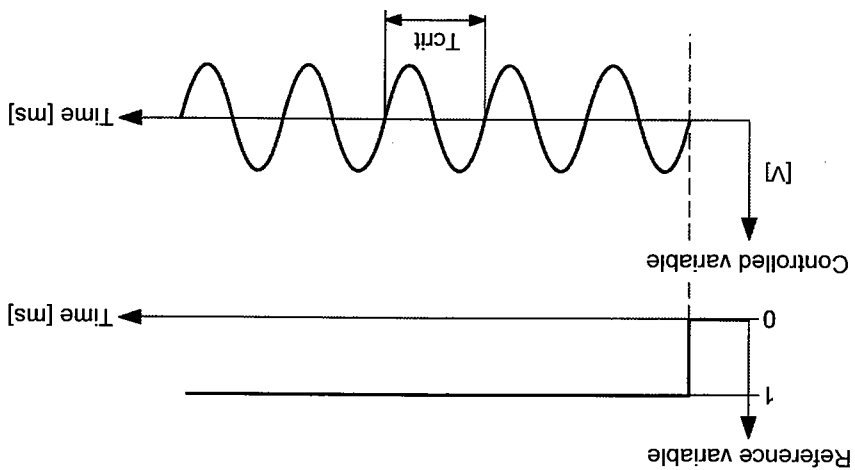


Fig. A16.2:
Representation of critical
period of oscillation T_{crit}

Table A16.1 shows a calculation table for the Ziegler-Nichols method. This can be used to calculate the characteristic data (K_P , T_n , T_v) for various types of controllers.

Controller type	Calculation of characteristic data				
	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	$0.45 \cdot K_{Pcrit}$	$0.85 \cdot T_{crit}$	—	$\frac{K_P}{T_n}$	—
PID	$0.6 \cdot K_{Pcrit}$	$0.5 \cdot T_{crit}$	$0.12 \cdot T_{crit}$	$\frac{K_P}{T_n}$	$K_P \cdot T_v$

Table A16.1:
Ziegler-Nichols
calculation table

Example of calculation:
The following critical values have been determined for a closed-loop control circuit with a PID controller

$$-K_{Pcrit} = 20$$

$$-T_{crit} = 100 \text{ ms}$$

The characteristic data for the controller are calculated as follows:

$$K_P = 0.6 \cdot K_{Pcrit} = 0.6 \cdot 20 = 12$$

$$T_n = 0.5 \cdot T_{crit} = 0.5 \cdot 100 \text{ ms} = 50 \text{ ms}$$

$$T_v = 0.12 \cdot T_{crit} = 0.12 \cdot 100 \text{ ms} = 12 \text{ ms}$$

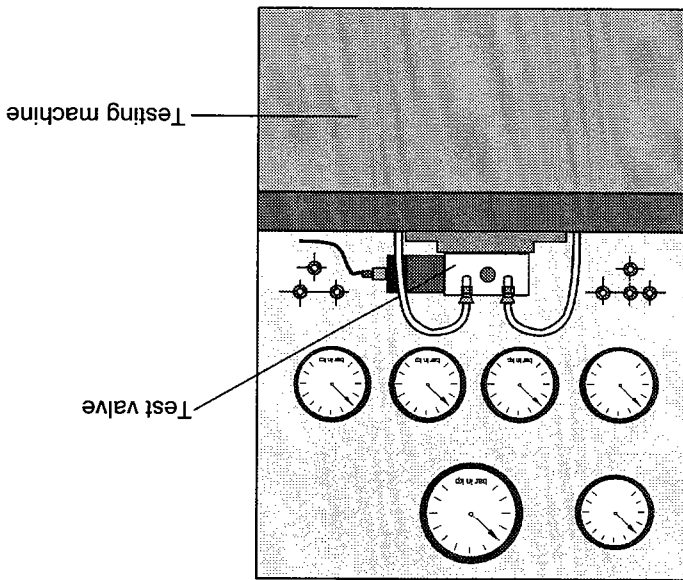
$$K_I = \frac{K_P}{T_n} = \frac{12}{0.05 \text{ s}} = 240 \frac{1}{\text{s}}$$

$$K_D = K_P \cdot T_v = 12 \cdot 12 \text{ ms} = 144 \text{ ms}$$

Problem description

The flow rate of pneumatic valves is to be tested. For this purpose, test valves are clamped into a testing machine and fed with compressed air. The valve flow rate and leakage rates represent controlled systems with different runtime performance which influence the test pressure. A PID control system is used to maintain the test pressure at a constant value during the measurement.

Fig. A16.3:
Positional sketch



Exercise Measurements should be taken on the testing machine in the following order:

1. Assembly of the closed-loop control circuit
2. Setting the controller for a controlled system without a delay
3. Setting the controller for a controlled system with a delay
4. Setting the controller for a controlled system with a leak

Execution

16.1 Assembly of the closed-loop control circuit

The assembly for the testing machine consists of the following closed-loop control circuit components:

- Voltage generator
- PID controller card
- Proportional valve
- One-way flow control valve (1V3)
- Solenoid valve
- Pressure gauge
- Signal input unit
- Pressure sensor

The test valves are simulated by two different controlled systems. The controlled systems differ in their time constants:

- A short piece of tubing (length approx. 100 mm) as a low-delay controlled system
- Two compressed-air reservoirs connected in series and separated by a one-way flow control valve (1V2) to act as a controlled system with a delay.

A storage oscilloscope should be used to measure the voltage signals.

The one-way flow control valve (1V3) is used to simulate a variable fault. The valve must be switchable. It is therefore connected in series with the solenoid valve.

- First assemble a circuit incorporating the short piece of tubing and set the control direction.
- Set a pressure of 6 bar.

16.2 Setting the controller for a controlled system without a delay

- Input a square-wave reference variable with an offset of 3 V and an amplitude of 1 V. A low frequency should be selected (approx. 0.1 Hz).

Use the Ziegler-Nichols method to commission a P controller. Proceed as follows:

- Determine the critical gain K_{Pcrit} and the period of oscillation T_{crit} which results. Select a suitable small time base on the oscilloscope (e.g. 10 ms).

- Use the settings table to calculate the coefficient K_P for a P controller.

- Set this value on the controller.

- Then use the step response to determine the characteristic data.



In your measurements, always consider the higher value for the reference variable (4 V).

- Use the settings table to calculate the proportional coefficient K_P and the integral-action time T_n for a PI controller.
- Use these to calculate the integral-action coefficient K_I :

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

- Set this value on the controller.

- Then use the step response to determine the characteristic data T_a , x_m and ε_{stat} for the PI controller.

16.4 Setting the controller for a controlled system with a leak

- An interference variable will now be applied to the closed-loop pressure control circuit (twin-reservoir system).
- Set the flow control valve to approximately half open. Open the solenoid valve.
- Use the Ziegler-Nichols method to commission the PID closed-loop control circuit.
- Determine the characteristic data.

16.3 Setting the controller for a controlled system with a delay

- Assemble the closed-loop pressure control circuit incorporating a controlled system subject to a delay (twin-reservoir system).
- Do not actuate the solenoid valve for the time being.
- Set the parameters of the P controller as described in step 2. Due to the lower oscillation amplitude, a larger division (0.5 V/division) should be selected on the oscilloscope.
- Then calculate the parameters for a PID controller.

$$K_D = K_P \cdot T_v$$

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

WORKSHEET

16.1 Assembly of the closed-loop control circuit

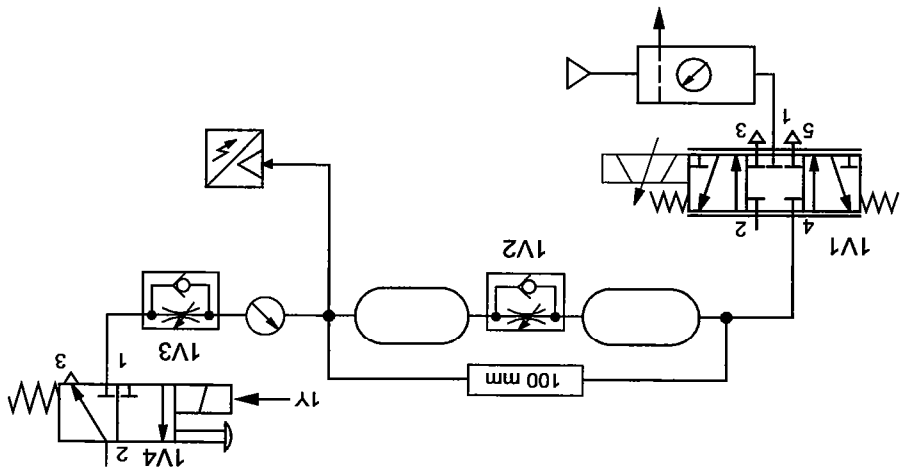


Fig. A16.4:
Pneumatic circuit diagram

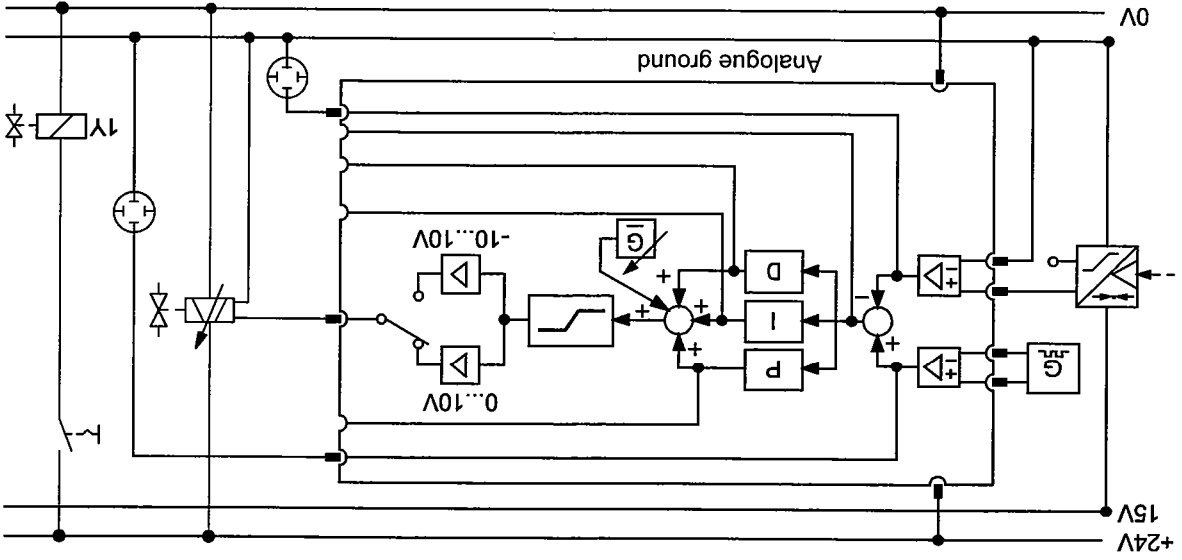


Fig. A16.5:
Electrical circuit diagram

16.2 Setting the controller for a controlled system without a delay

Table A16.2:

Characteristic data		
	P controller	PI controller
Crit. proportional-action coefficient K_{Pcrit}		
Crit. period of oscillation T_{crit} [ms]		
Proportional-action coefficient K_P		
Integral-action time T_n [ms]		
Integral-action coefficient $K_I = \frac{K_P}{T_n} \left[\frac{1}{s} \right]$		
Settling time T_a [ms]		
Overshoot amplitude x_m [mV]		
Steady state system deviation e_{stat} [mV]		

Have the two setting procedures using the Ziegler-Nichols method produced a stable closed-loop control circuit?

☐ Yes
☐ No, the _____ controller was not stable.

Which controller gave the better results?
☐ P controller
☐

☐ Both the same

WORKSHEET

16.3 Setting the controller for a controlled system with a delay

Table A16.3:

Characteristic data		
	P controller	PID controller
Crit. proportional-action coefficient K_{Pcrit}		
Crit. period of oscillation T_{crit} [ms]		
Proportional-action coefficient K_P		
Integral-action time T_n [ms]		
Derivative-action time T_v [ms]		
Integral-action coefficient $K_I = \frac{K_P}{T_n} \left[\frac{1}{s} \right]$		
Derivative-action coefficient K_D [ms]		
Settling time T_a [ms]		
Overshoot amplitude x_m [mV]		
Steady state system deviation e_{stat} [mV]		

Have the two setting procedures using the Ziegler-Nichols method produced a stable closed-loop control circuit?

- ☐ Yes
- ☐ No, the _____ controller was not stable.

Which controller gave the better results?

- ☐ P controller
- ☐
- ☐ Both the same

16.4 Setting the controller for a controlled system with a leak

Table A16.4:

Characteristic data	PID controller
Crit. proportional-action coefficient K_{Pcrit}	
Crit. period of oscillation T_{crit} [ms]	
Proportional-action coefficient $K_P = 0.6 \cdot K_{Pcrit}$	
Integral-action time $T_n = 0.5 \cdot T_{crit}$ [ms]	
Derivative-action time $T_v = 0.12 \cdot T_{crit}$ [ms]	
Integral-action coefficient $K_I = \frac{K_P}{T_n} \left[\frac{1}{s} \right]$	
Derivative-action coefficient $K_D = K_P \cdot T_v$ [ms]	
Settling time T_a [ms]	
Overshoot amplitude x_m [mV]	
Steady state system deviation e_{stat} [mV]	

Has the setting procedure produced a stable closed-loop control circuit?

☐ Yes

☐ No

What is the difference between the settling times here and in step 3? Briefly describe the reason for this difference.

Subject Title

Stamping machine

- To understand the design and mode of operation of a linear potentiometer
- To be able to explain the design and mode of operation of a linear axis
- To become familiar with a controlled system without compensation
- To be able to approach positions
- To be able to produce and assess potentiometer characteristics

Linear potentiometer

A linear potentiometer can be used to measure lengths and distances. The potentiometer converts the physical variable "position" into an electrical voltage. This is carried out using the principle of a voltage divider. With this principle, an input voltage U_e is applied to a total resistance R_{total} . The output voltage U_a of the potentiometer can be calculated using the voltage divider formula:

$$U_o = U_i \cdot \frac{R}{R_{total}}$$

Since the resistance component R is proportional to the wiper position l , the voltage divider formula can be replaced by the expression

$$U_o = U_i \cdot \frac{l_{total}}{l}$$

The motion of the wiper produces a change in the resistance component R . The output voltage U_a varies in proportion to the resistance component.

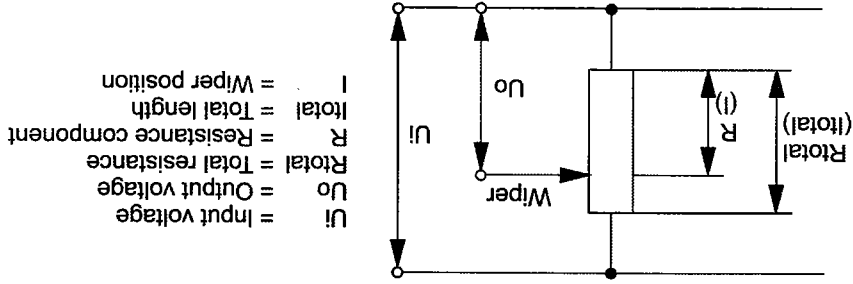


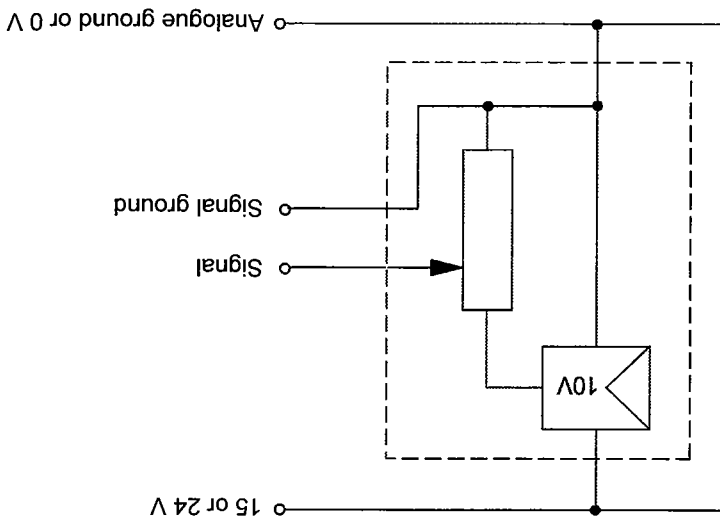
Fig. A17.1:
Schematic representation of
linear potentiometer

The linear potentiometer used here is connected in series with additional electronic circuitry to prevent damage to the potentiometer by crossed connections.

The potentiometer has an electrical length of 450 mm. A voltage of between 0 and 10 V appears at the sensor output, depending on the wiper position. The supply voltage must be between 15 and 24 V. The additional electronics converts this voltage into a constant supply voltage of 10 V for the potentiometer.

- The potentiometer has four electrical connections:
- Power supply 24 V (or 15 V)
 - Power supply ground 0 V (or analogue ground)
 - Signal voltage
 - Signal ground

Fig. A17.2:
Electrical connection
diagram for linear
potentiometer



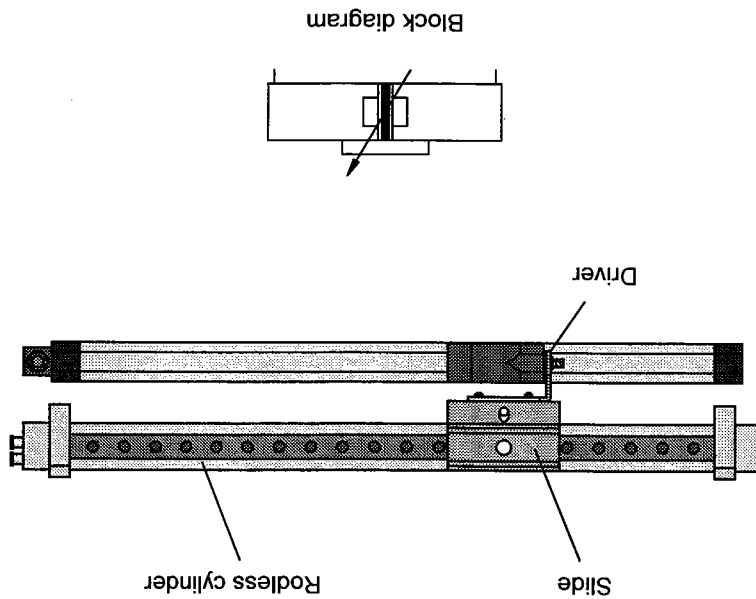
Within the closed-loop control circuit, the potentiometer should always be connected to the 15 V power supply and the analogue ground of the controller card. Only in this way can it be ensured that electrical interference is kept to a minimum.

Linear axis

The linear actuator used here consists of a rodless cylinder which acts via an interlocking connection between piston and carrier to drive a slide with through guide rods. The axis has a stroke of 450 mm. The piston diameter D of the cylinder is 25 mm.

The slide is fitted with a driver which actuates the wiper of the linear potentiometer.

Fig. A17.3:
Schematic representation of
pneumatic linear axis



In controlled systems, it is a disadvantage if pneumatic cylinders are fitted with end-position cushioning, since this impairs the control behaviour of the system.

The stroke of the linear potentiometer should be greater than that of the cylinder in order to prevent mechanical overload of the potentiometer in the end positions. The mechanical stroke of the potentiometer used here is approx. 450 mm.

Controlled systems without compensation

With controlled systems without compensation, the output variable changes dramatically after a step-change in the input variable. Systems of this kind are also known as I systems (integral-action systems). If a switching valve is used to control a pneumatic cylinder, the distance travelled by the piston, which corresponds to the controlled variable x , increases continuously. This controlled system therefore exhibits integral-action system behaviour.

The transition function of a pneumatic cylinder is shown in Fig. A17.4.

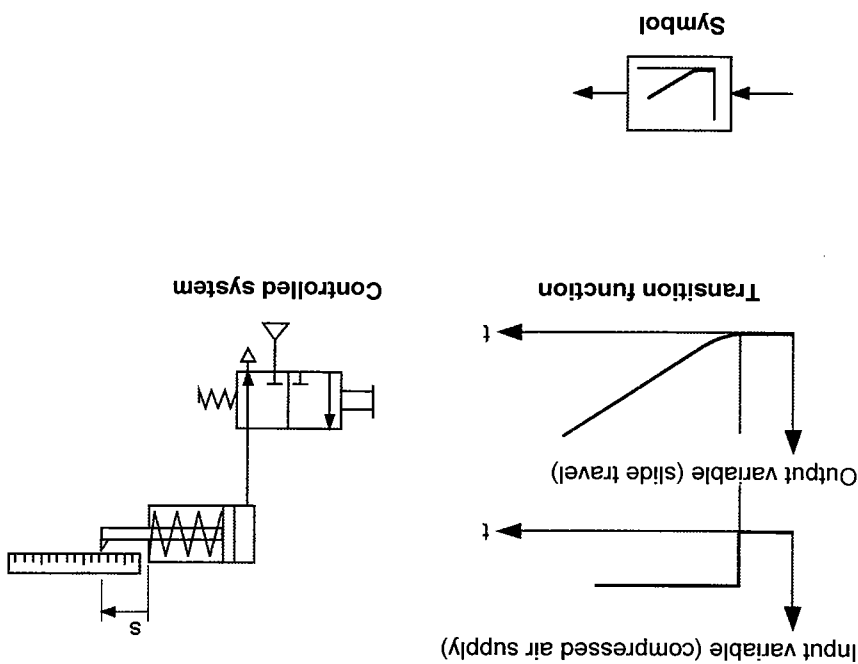
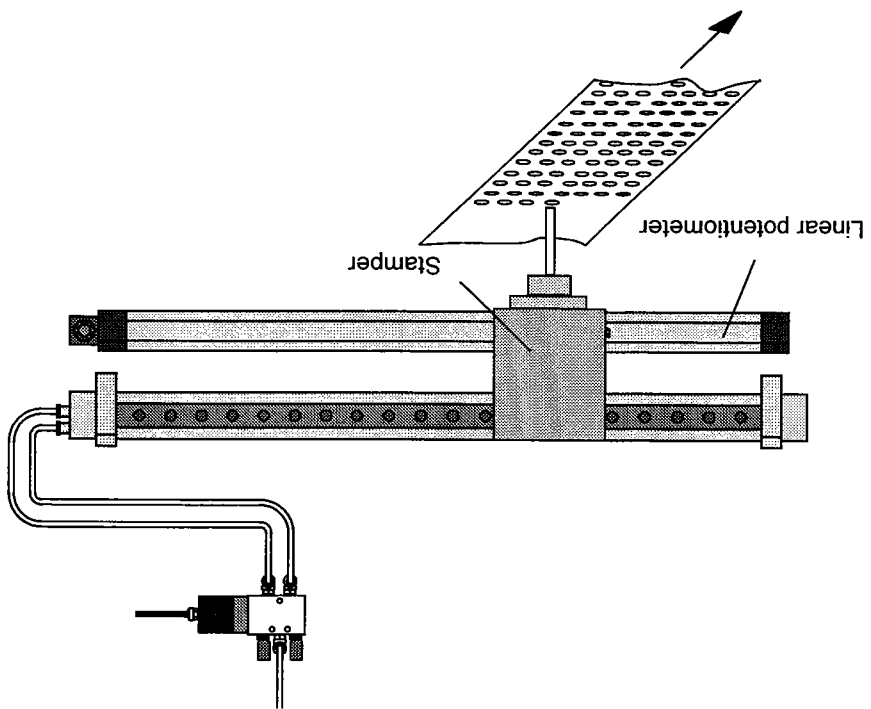


Fig. A17.4:
Transition function of a
controlled system without
compensation (cylinder)

A stamping machine is used to stamp circular workpieces out of sheet metal. In order to do this, the machine table must approach closely-adjacent positions in a defined sequence. A pneumatic linear axis is used for this purpose. Before the linear axis is installed, its functions must be tested on a test stand.

Fig. A17.5:
Positional sketch



Exercise

The test should be carried out in the following steps:

1. Assembly of test circuit
2. Approach of positions and calculation of voltage values
3. Plotting of potentiometer characteristic

Execution

17.1 Assembly of test circuit

The pneumatic and electrical circuit diagrams for the test assembly are given in the worksheet:

- The input signals for the proportional valve are produced with a voltage generator.

- The output voltage of the linear potentiometer is displayed by means of a multimeter connected to the wiper output. Use the signal input to connect up the proportional valve and linear potentiometer.

- Fit the scale at the side of the linear axis on the profile plate.



Follow the fitting instructions supplied when fitting the linear potentiometer to the linear axis for the first time.



- It may occur that the slide impacts abruptly against the stop when the compressed air supply is switched on. Always therefore keep a safe distance away from the slide when switching on the compressed air and operating the linear axis.

17.2 Approach of positions and calculation of voltage values

- Switch on the electrical power supply.
- Switch on the compressed air supply (6 bar).
- Approach 7 positions chosen at random but spaced equally along the linear axis by energising the proportional valve with the voltage generator. As soon as the slide has come to rest in a position, note the potentiometer voltage and position. Also record the voltages at the two end positions (20 mm, 420 mm).
- Then calculate the voltage values for the positions you have approached, using the voltage divider formula.

17.3 Plotting of potentiometer characteristic

Use the selected positions and the voltages measured for these to plot the potentiometer characteristic. Also plot the calculated voltages as a characteristic in the prepared graph.

WORKSHEET

17.1 Assembly of test circuit

Assemble the test circuit in accordance with the pneumatic and electrical circuit diagrams.

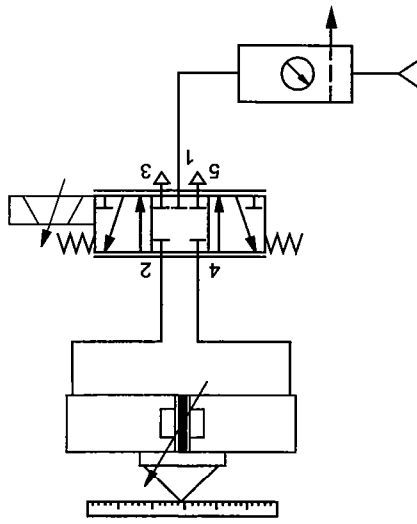


Fig. A17.6:

Pneumatic circuit diagram

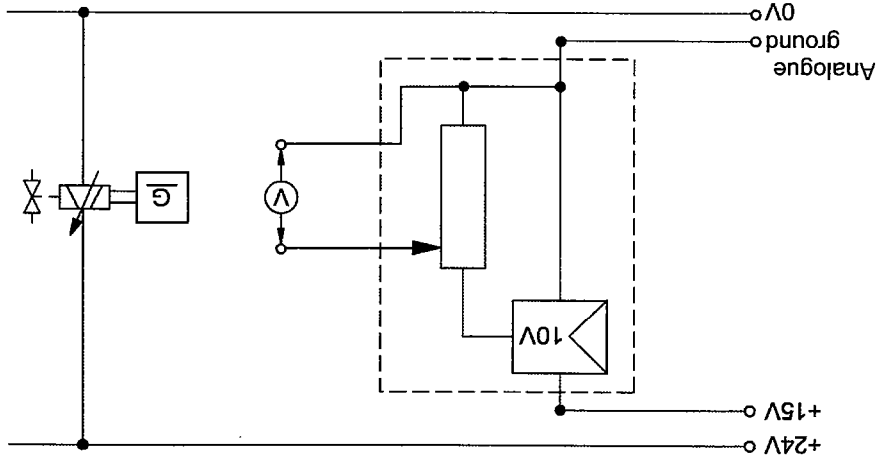


Fig. A17.7:

Electrical circuit diagram

17.2 Approach of positions and calculation of voltage values

Use the following formulae to calculate the data:

Total electrical length: $l_{\text{total}} = 450 \text{ mm}$

Selected position (rule) l

Input voltage: $U_i = 10 \text{ V}$

Calculated voltage: $U_o = U_i \cdot \frac{l_{\text{total}}}{l}$

$$= 10 \text{ V} \cdot \frac{450}{l} \text{ mm}$$

Table A17.1:
Results table

Number	Position l [mm]	Measured voltage [V]	Calculated voltage [V]
1	20 mm		
2			
3			
4			
5			
6			
7	430 mm		

mV

How large is the zero-point deviation (offset) of the potentiometer?

What shape do the characteristics have?

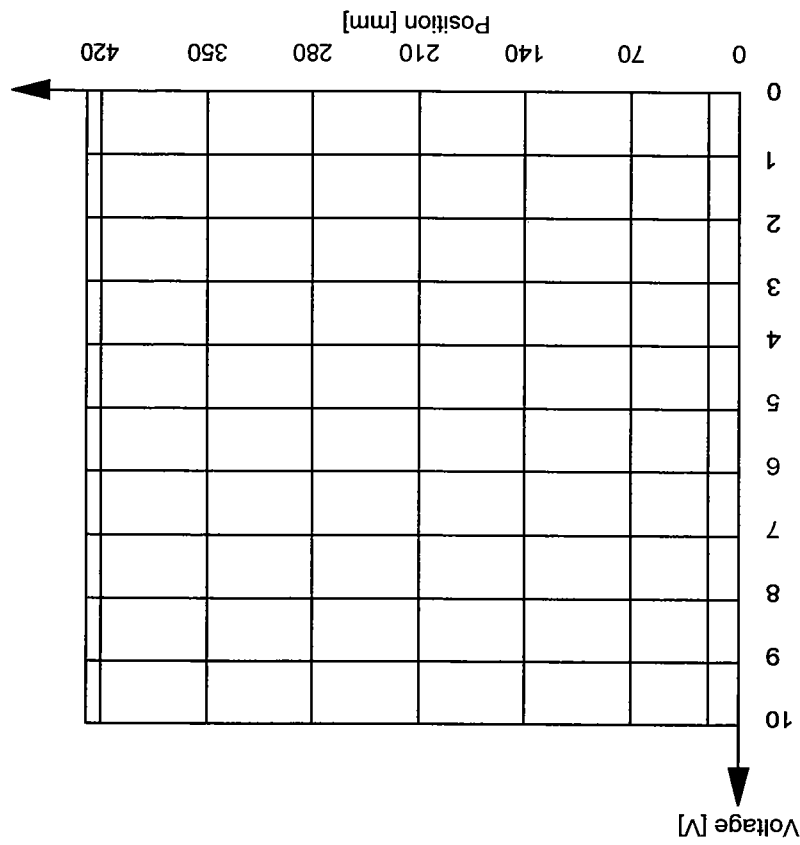


Fig. A17.8:
Potentiometer characteristic

17.3 Plotting of potentiometer characteristic

WORKSHEET

Subject

Title

Training aims

- To be able to explain the design of a status controller
- To be able to produce transition and ramp functions with position, speed and acceleration controllers

Status controller

Technical knowledge

Status controllers have proved extremely useful for the closed-loop control of pneumatic linear axes.

The status controller used here processes three status variables:

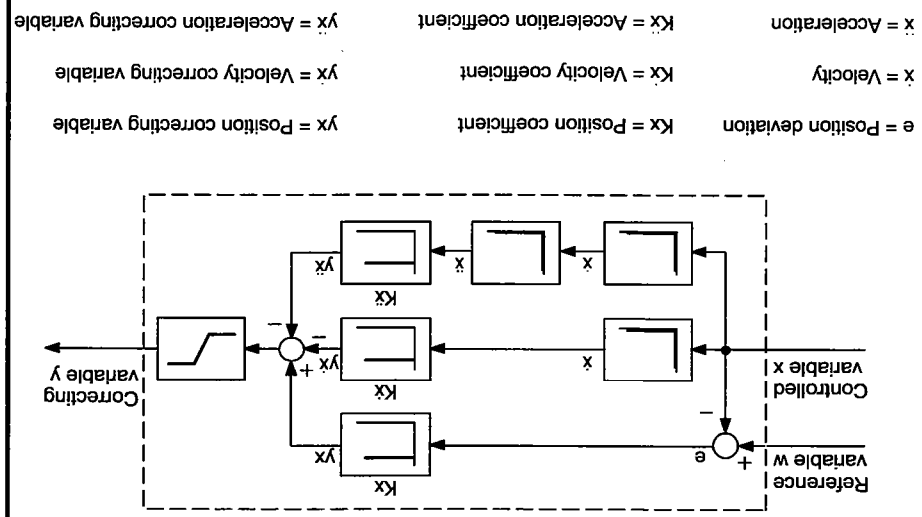
- The system deviation e (also known as the position deviation)
- The velocity $\dot{x}$ and
- The acceleration $\ddot{x}$

of the slide.

Since it is extremely complex in hardware terms to measure all three status variables with sensors, only the position is measured. The velocity and acceleration are generated from the position variable using derivative-action controllers.

Fig. A18.1 shows the block diagram for the status controller used here.

Fig. A18.1:
Block diagram for
status controller



Mode of operation of a status controller

The status controller has a separate controller branch for each status variable. Status controllers for pneumatic actuators thus have a triple-loop controller structure:

Position controller

The reference variable and controlled variable are fed to a summation point and subtracted from each other. The resulting position difference e is multiplied by the position coefficient K_X . The position correcting variable y_X is calculated as follows:

$$y_X = K_X \cdot e$$



The position controller is identical to the P controller.

Velocity controller

The velocity controller consists of a derivative-action controller which converts the controlled variable x into the velocity value $\dot{x}$ and multiplies it by the velocity coefficient K_X .

$$y_X = K_X \cdot \dot{x}$$

Acceleration controller

The acceleration controller consists of two derivative-action controllers which convert the controlled variable x into the acceleration value $\ddot{x}$ and multiplies this by the acceleration coefficient K_X .

$$y_X = K_X \cdot \ddot{x}$$

The correcting signal components of these controller branches are added at a summation point. The velocity and acceleration signals are incorporated into this operation with a negative sign. The correcting signal thus produced then passes through a limiter circuit.

Design of status controller card

The status controller card has a similar design to the PID controller card. Figs. 18.2a and b show the front panel and the electrical connection diagram for the status controller.

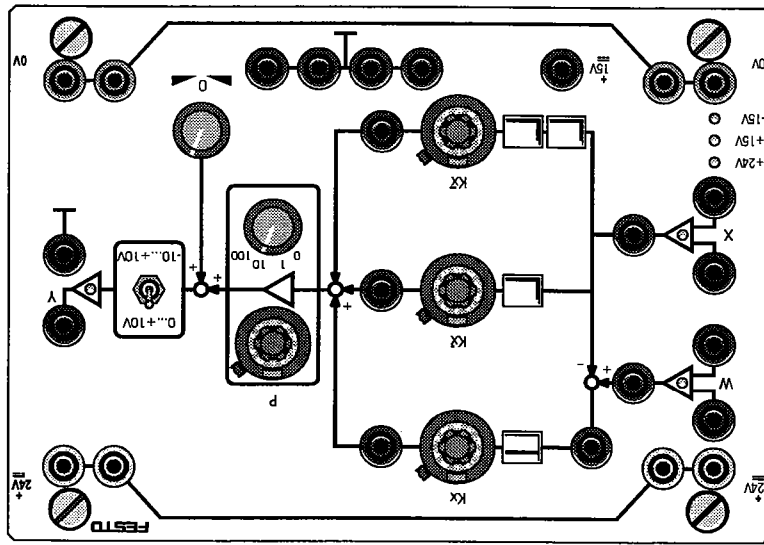


Fig. A18.2a:
Front panel of
status controller card

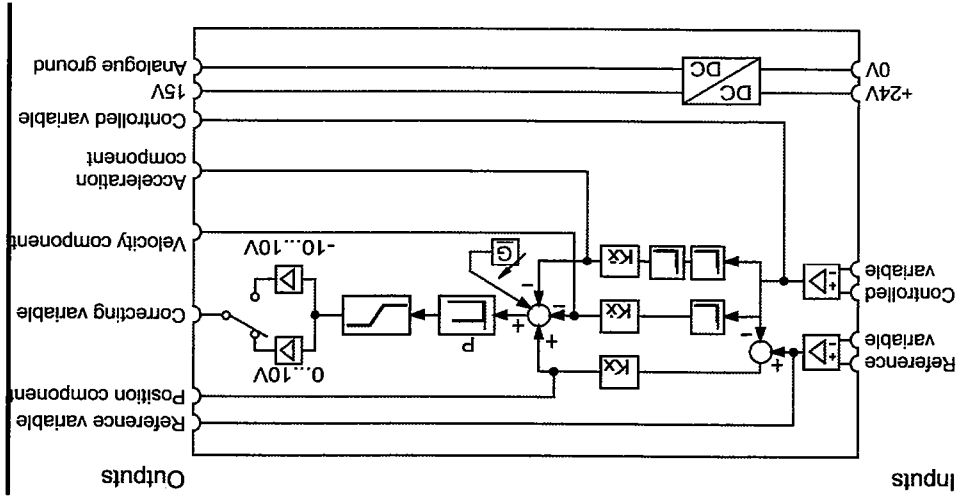


Fig. A18.2b:
Electrical connection
diagram for status
controller card

In contrast to the PID controller card, the status controller card has a rotary potentiometer and a rotary switch which allow adjustment of an overall gain coefficient P for the correcting signal.

Problem description

In a pneumatic sorting device, the desired positions are no longer reached correctly. Adjustment of the controller coefficients has not produced any improvement, with the result that it is necessary to check the status controller.

Measuring and test station

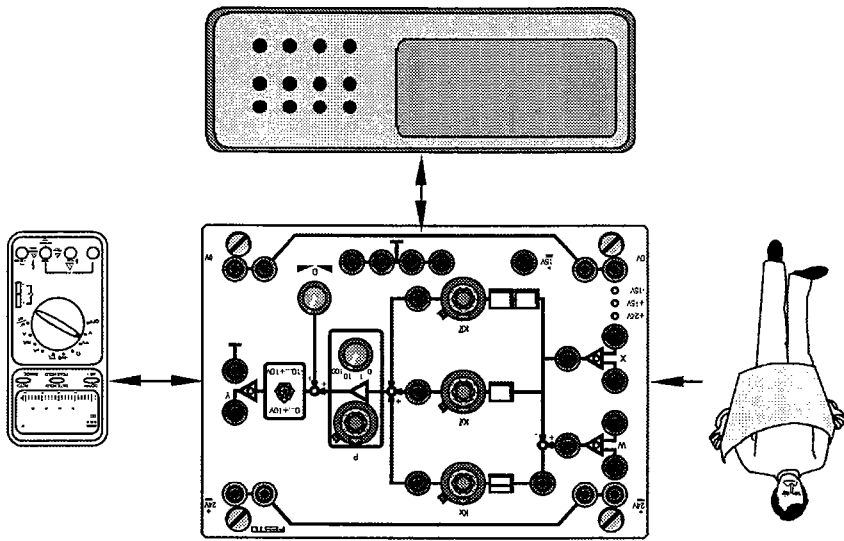


Fig. A18.3:
Positional sketch

Exercise

In order to check the operation of the status controller, the following steps must be carried out:

1. Production of transition and ramp functions for the position controller
2. Production of transition and ramp functions for the velocity controller
3. Production of transition and ramp functions for the acceleration controller

Execution

18.1 Production of transition and ramp functions for the position controller

The procedure for the production of transition and ramp functions for the position controller is as follows:

- Assemble the measuring circuit in accordance with the circuit diagram provided and switch on the electrical power supply.
- Set all potentiometers to zero and the range selector switch to [-10 ... 10 V].

- Use the voltage generator to input a square-wave signal (offset: 2 V, amplitude: 2 V, frequency: 2 Hz) as a reference variable. Display the reference variable and correcting variable on an oscilloscope.

- Set an overall gain of $P = 3.5$.

- Set a position coefficient of $K_x = 1$ and draw the transition function on the worksheet.

- Input a triangular-wave signal (offset: 2 V, amplitude: 2 V, frequency: 2 Hz). Leave the controller coefficients unchanged. Draw the ramp response of the position controller on the worksheet.

18.2 Production of transition and ramp functions for the velocity controller

The procedure for the production of transition and ramp functions for the velocity controller differs from the procedure described above in the following points:

- The position coefficient should be set to zero.
- The square-wave or triangular-wave signal should be fed to the controlled variable input of the controller card (see circuit diagram).
- The velocity coefficient should be set to $K_x = 7$.



Note that the voltage signals are output at the test sockets in negative form (minus sign at the summation point). In order to display the signals correctly, they must be inverted about the x axis. Switch the oscilloscope output to INV. (inverted) or swap over the signal line and ground line.

18.3 Production of transition and ramp functions for the acceleration controller

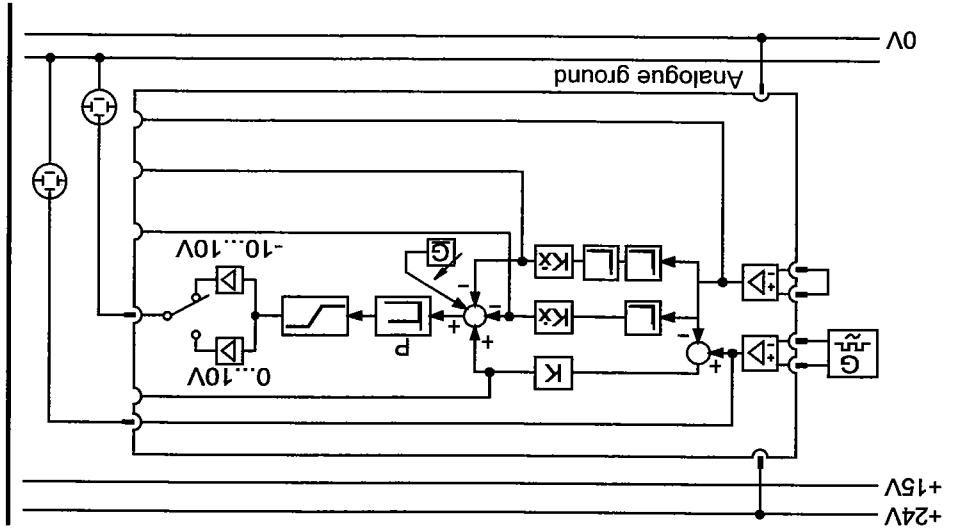
In order to produce the transition and ramp functions for the acceleration controller, proceed as for step 2. Set an acceleration coefficient of $Kx = 2$. The position and velocity coefficients should be set to zero. Note that the voltage signals are output at the test sockets in negative form.



WORKSHEET

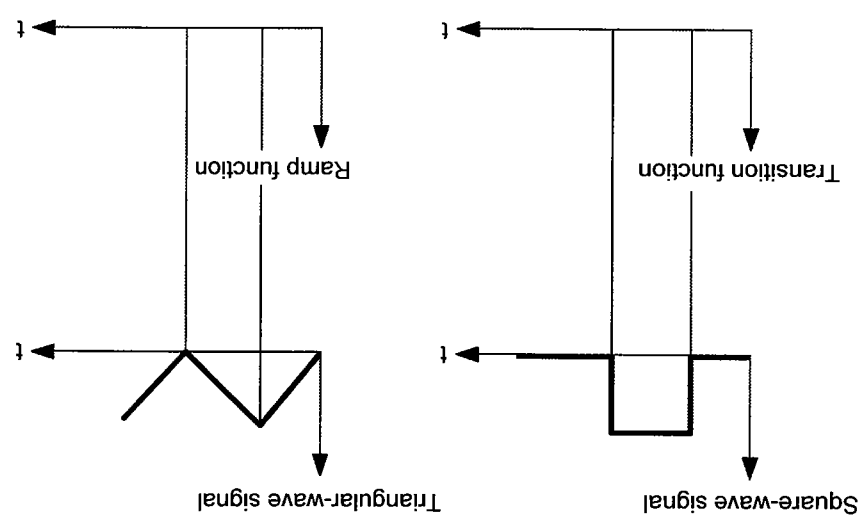
18.1 Production of transition and ramp functions for the position controller

Fig. A18.4:
Electrical circuit diagram



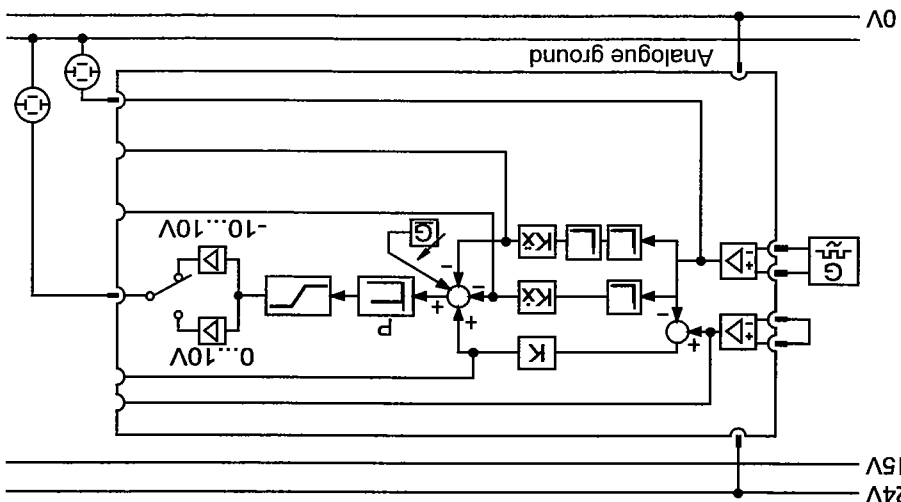
Draw-in the transition and ramp functions of the position controller.

Fig. A18.5:
Transition and
ramp functions of the
position controller



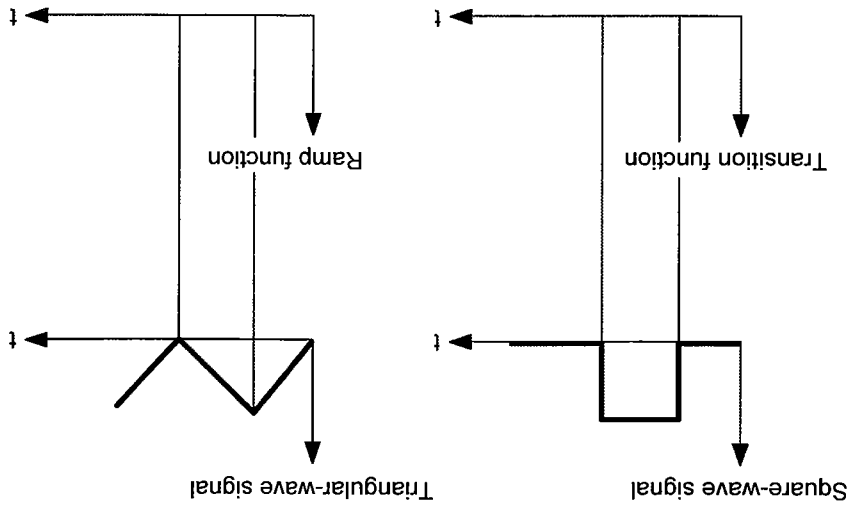
controller

Fig. A18.6:
circuit diagram



Draw-in the transition and ramp functions of the velocity controller.

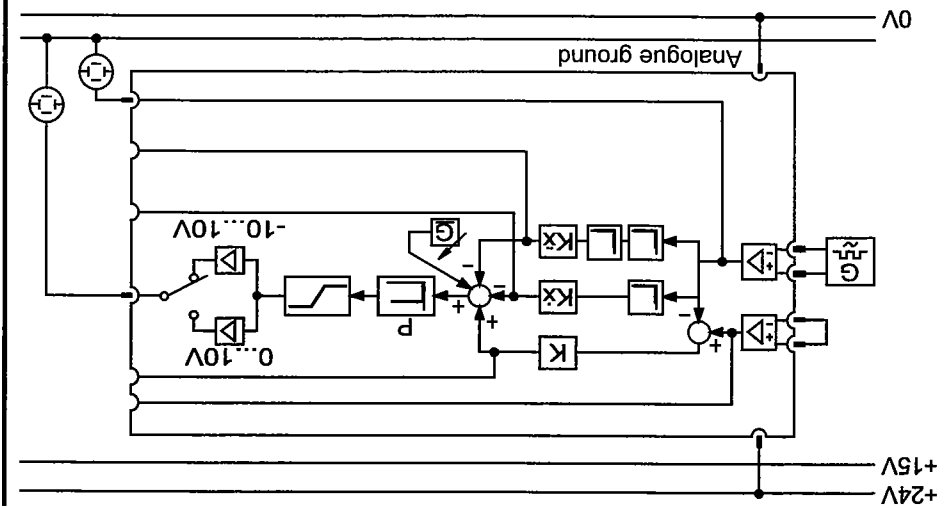
Fig. A18.7: Transition and ramp functions of the velocity controller



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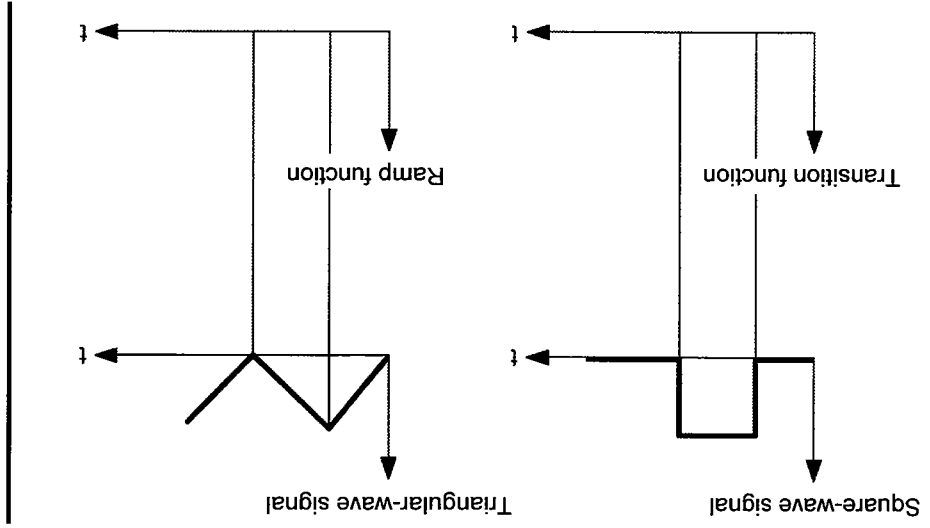
18.3 Production of transition and ramp functions for the acceleration controller

Fig. A18.8:
Electrical circuit diagram



Draw-in the transition and ramp functions of the acceleration controller.

Fig. A18.9:
Transition and ramp functions of the acceleration controller



Subject

Title

Training aims

- To be able to set the parameters of a status controller
- Familiarization with the influence of controller coefficients

Deburring an engine block

Status controller in a closed-loop position control circuit

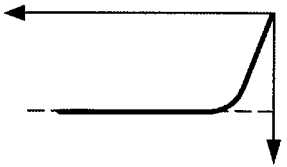
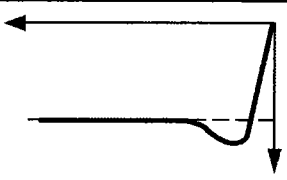
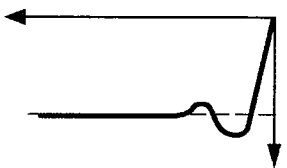
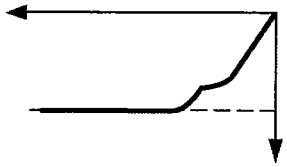
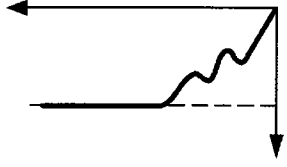
Technical knowledge

The parameters of a status controller are set in accordance with the same quality criteria as for a PID controller:

- Short settling time T_a
- No or only small overshoot amplitude x_m
- Small steady-state system deviation ϵ_{stat}

Table A19.1 shows various transient responses which may be obtained with poor status controller settings. Details are given in each case of how the controller coefficients must be changed in order to obtain a better transient response.

Table A19.1:
Transient response for
various status controller
coefficients

Case	Transient response	Description	Measures
I		Optimum	None
II		Overshoot	Reduce K _x
III		Overshoot with forward swing	Reduce K _x or increase K _x or increase K _̈
IV		One forward swing	Reduce K _x
V		Several forward swings	Reduce K _x or increase K _x

The flow chart below shows the procedure for the empirical parametrisation of a status controller.

Preparatory work

- Assemble the closed-loop control circuit
- Check the circuit
- Switch on the electrical power supply
- Switch on the compressed air
- Check the control direction and change if necessary
- Initialise the controller (set all parameters and the correcting variable offset to zero)
- Set the range selector switch (-10 ... +10 V or 0 ... +10 V)
- Apply a step-change reference variable signal
- Adjust the correcting variable offset to compensate for asymmetries

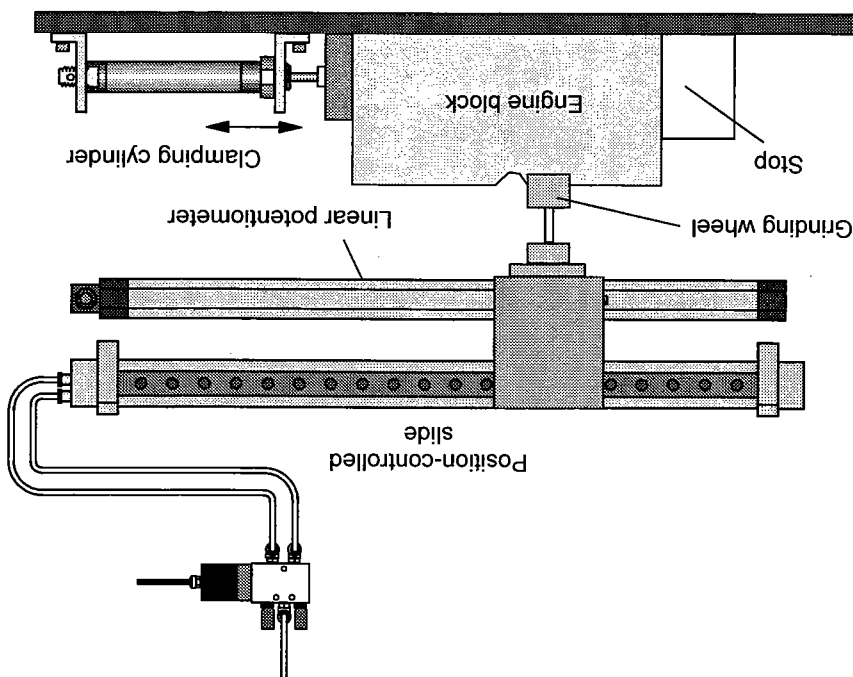
Problem description

Blocks for car engines are produced in a foundry. The blocks are trimmed and deburred after casting. For this purpose, they are fed to a deburring station on a conveyor belt. The blocks are clamped to allow trimming to be carried out.

A grinding wheel is mounted on a slide. This slide is driven by a controlled linear axis. The grinding wheel is guided along the edges of the engine blocks.

The closed-loop control circuit for the linear axis must be assembled, adjusted and then tested.

Fig. A19.2:
Positional sketch



Exercise

The procedure for this is made up of the following steps:

1. Assembly and commissioning of the closed-loop control circuit
2. Investigation of the transient response for various coefficients
3. Parametrisation of the status controller using the empirical method

Execution

19.1 Assembly and commissioning of the closed-loop control circuit

The closed-loop control circuit consists of the status controller, the control valve and the linear axis. A voltage generator is used to produce the reference variable. A storage oscilloscope is recommended for the measurement and display of signals.

In order to commission the closed-loop control circuit, proceed as follows:

- Assemble the circuit in accordance with the circuit diagrams.
- Set all controller coefficients and the correcting variable offset to zero.
- Set the range selector switch to [0 ... 10 V].
- Switch on the electrical power supply.
- Switch on the compressed air.

Keep a safe distance away from the area of travel of the slide when switching the compressed air on.



- Check the control direction and correct this if necessary.

19.2 Investigation of the transient response for various coefficients

- Set a step-change reference variable: frequency: = 0.5 Hz, offset: = 5 V, amplitude: = 1 V.
- Check that the slide oscillates symmetrically about its mid-position.
- If necessary, use the correcting variable offset to reduce the steady-state system deviation.
- Set the specified controller coefficients.
- Relate the transient responses to the cases shown in Fig. A19.1.
- Draw the curves for the reference and controlled variables. Use the prepared graph for this purpose.

19.3 Parametrisation of the status controller using the empirical method

Parametrise the status controller as follows:

- Set a step-change reference variable: frequency: = 0.5 Hz, offset: = 5 V, amplitude: = 1 V.
- Initialise the controller (all values set to zero).
- Set a position coefficient $K_x = 1$.
- Set the velocity coefficient K_v and the acceleration coefficient K_a . Proceed as shown in the flow chart (Fig. A19.2). Use the experience which you have gained from step 2.
- Measure and record the characteristic data.

WORKSHEET

19.1 Assembly and commissioning of the closed-loop control circuit

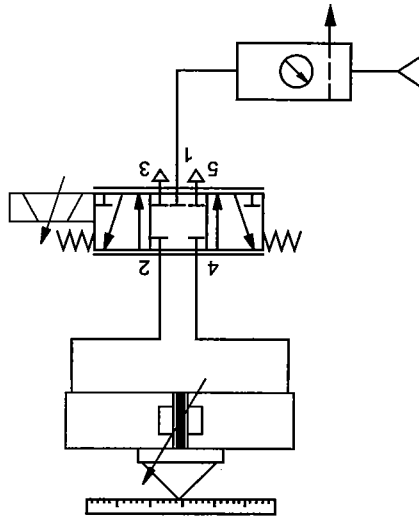


Fig. A19.3:

Pneumatic circuit diagram

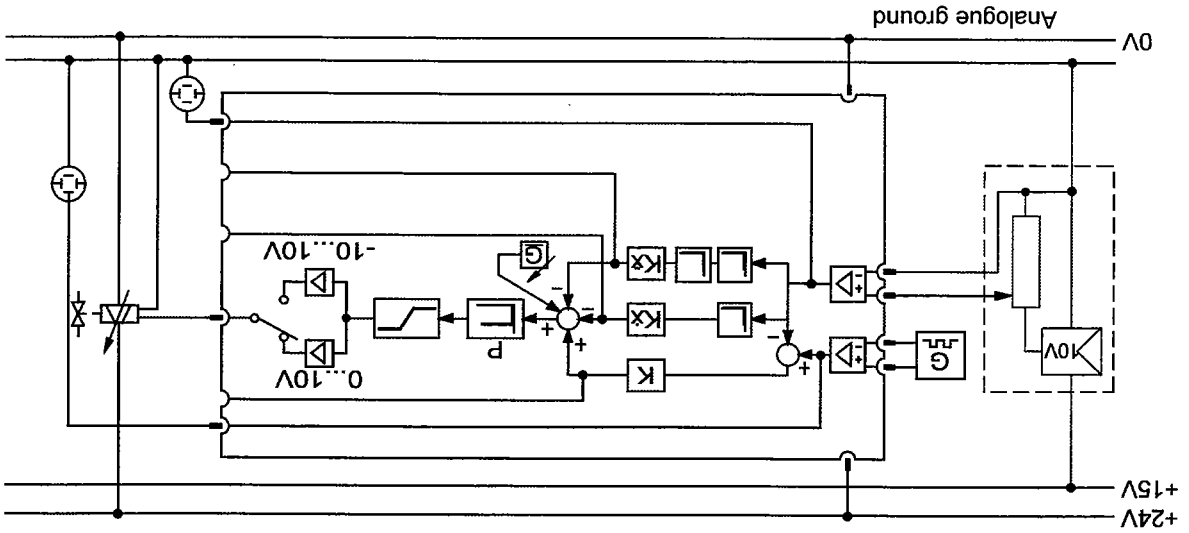


Fig. A19.4:

Electrical circuit diagram

Allocate the relevant variable to the following control technology terms:

Square-wave signal of voltage generator: _____

Voltage values of potentiometer: _____

Input voltage of proportional valve: _____

Status controller card: _____

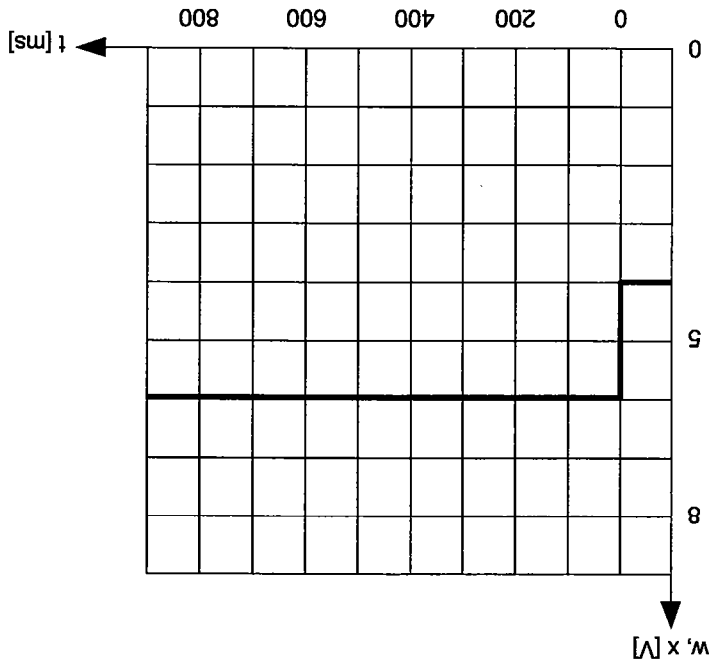
Settings on status controller card: _____

19.2 Investigation of the transient response for various coefficients

Table A19.2:
Influence of
position coefficient K_x :

Controller coefficients				
K_x	$K_{\dot{x}}$	$K_{\ddot{x}}$	p	Case
0.4	0	0	8.5	
0.7	0	0	8.5	

Fig. A19.5:
Graph of controlled
variables (2 curves)



WORKSHEET

Table A19.3:
Influence of
velocity coefficient K_x :

Controller coefficients			
K_x	K_x	K_x	Case
1	2.5	0	
1	7	0	
		8.5	

Fig. A19.6:
Graph of controlled
variables (2 curves)

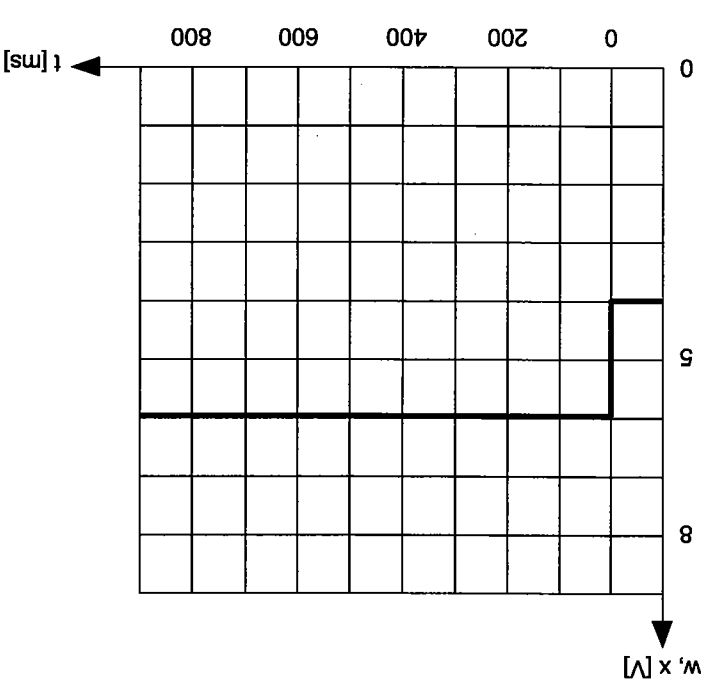
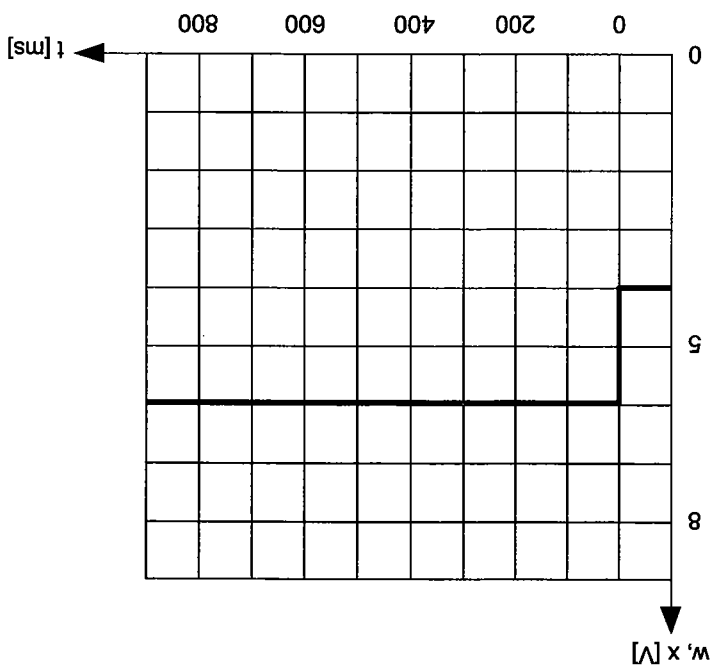


Table A19.4:
Influence of acceleration
coefficient $K\ddot{x}$:

$K\ddot{x}$	0.4	0	10	8.5
Controller coefficients	$K\ddot{x}$	$K\ddot{x}$	$K\ddot{x}$	p
Case				

Fig. A19.7:
Graph of controlled variable
(1 curve)



WORKSHEET

19.3 Parametrisation of the status controller using the empirical method

Note the values which have been set for the characteristic data:

Table A19.5:

Characteristic data	Values
Overall gain P	
Position coefficient K _x	
Velocity coefficient K _v	
Acceleration coefficient K _a	
Settling time T _s [ms]	
Overshoot amplitude x _m [mV]	
Steady state system deviation [mV]	

Subject

Title

Training aims

- Familiarization with a follower control system
- To be able to explain the term "lag error"
- To be able to measure lag error
- To be able to explain the term "closed-loop gain"

Cake production

Closed-loop pneumatics

Follower control system

Technical knowledge

The purpose of a follower control system is to ensure that the controlled variable x follows the time curve of the reference variable w as closely as possible. This type of control system is also known as a servo control system.

Lag error

In a follower control system, the controlled variable x follows the ramp-shaped reference variable w with a certain delay. With regard to this control behaviour, the term "lag error" is used; this is equivalent to the system deviation

$$e = w - x$$

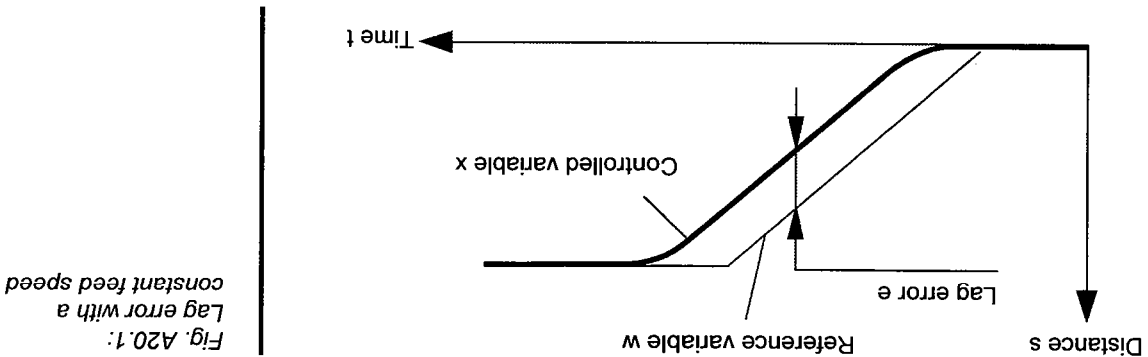


Fig. A20.1:
Lag error with a
constant feed speed

For the linear axis, this means that, with a given constant feed speed, the slide will lag behind the reference variable by a certain amount (the lag error).

The velocity of the axis slide can be calculated using the following formulae:

$$v = \frac{t}{s} \quad \text{or} \quad v = 4 \cdot A \cdot f$$

v = Velocity
s = Position
t = Time
A = Amplitude
f = Frequency

The lag error is influenced by the velocity v and the closed-loop gain Kv. The closed-loop gain is also referred to as the servo gain of the closed-loop control circuit.

Influences acting on the closed-loop gain

The closed-loop gain Kv is the ratio of the feed velocity v to the lag error e:

$$K_v = \frac{v}{e}$$

The closed-loop gain is the product of the gain components in the closed-loop control circuit, such as the controller gain and controlled-system gain.

The controlled-system gain is generally fixed, which means that the closed-loop gain cannot be varied in this way. The controller gain, on the other hand, is adjustable and thus directly affects the closed-loop gain.

Influences acting on the lag error

The lag error is dependent on the velocity v and the closed-loop gain K_v :

$$e = \frac{K_v}{v}$$

- As the velocity increases, the lag error e becomes larger.
- As the closed-loop gain K_v increases, the lag error e is reduced.

There are, however, limits to the value which can be set for the closed-loop gain. If the lag error is too small, the slide will shoot beyond the destination point and will then oscillate as it settles.

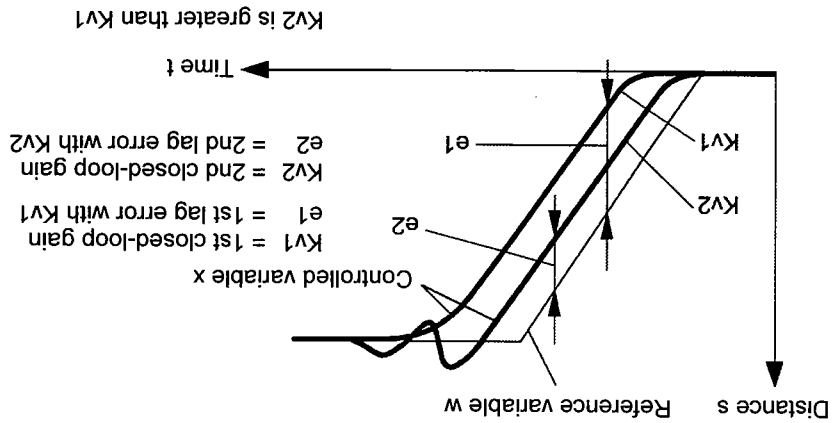


Fig. A20.2:
Influence of closed-loop
gain on lag error

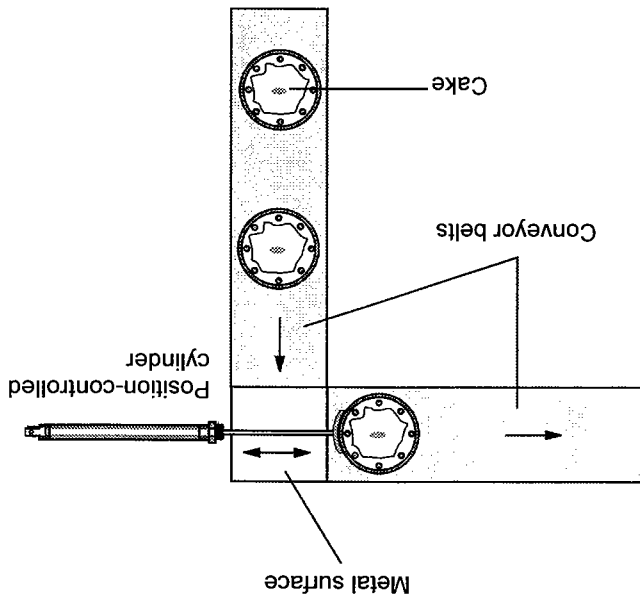
Problem description

In a cake factory, cakes are transported on conveyor belts. At the end of a conveyor section, the cake slides onto a metal surface. From here, the cake is pushed onto a second conveyor belt at right-angles to the first belt.

The transfer to the second conveyor belt is carried out using a closed-loop-controlled pneumatic cylinder. This accelerates the cake up to the speed of the belt. Due to the fragility of the cake, acceleration must be at an even rate.

In order to optimise the controller settings for the actuator, we must investigate the motion characteristics of the linear axis.

Fig. A20.3:
Positional sketch



Exercise

This investigation consists of the following steps:

1. Determination of follower behaviour with a ramp function
2. Determination of the lag error as a function of velocity
3. Determination of the lag error as a function of controller gain

Execution

20.1 Determining the follower behaviour with a ramp function

- Assemble the experiment in accordance with the circuit diagrams provided.
- Use the voltage generator to input a triangular-wave function (offset: 5 V, amplitude: 2 V, frequency: 0.5 Hz).
- Check the control direction and correct this if necessary.
- The correcting variable offset relative to the reference variable should be set so that the slide oscillates in the middle of its stroke.
- Adjust the reference variable and controlled variable signals on the oscilloscope in such a way that they are correctly positioned relative to each other. At least one oscillation period must be visible on the screen.
- Parametrise the controller using the empirical method or set the controller with the coefficients from the previous exercise.
- Draw the curve for the controlled variable in the prepared graph.
- Measure the lag error and convert it into the unit mm.
- Investigate the follower behaviour by varying the settings for the triangular-wave function as specified.
- Assess the follower behaviour by answering the questions on the worksheet.

20.2 Determining the lag error as a function of velocity

- Reduce the frequency of the reference variable to 0.2 Hz.
- Compare the reference variable and controlled variable on the oscilloscope display.
- Vary the frequencies of the reference variable in accordance with the values in the table.
- Measure the lag error e in each case and enter the values into the table.
- Convert the lag error into the unit mm.
- Determine the velocity v of the axis slide in m/s and convert this into mm/s.
- Calculate the closed-loop gain K_v



Different lag errors may result for the advance and return strokes. If this occurs, proceed as follows:

Either

adjust the correcting variable offset (correction of valve zero point) until the lag errors on either side are the same

or

measure both lag errors and calculate the average value.

At low frequencies, the lag error can be determined only approximately, since the follower behaviour has a step-like character. Note the smallest value for the lag error.

20.3 Determining the lag error as a function of controller gain

- Set a triangular-wave function with a frequency of 0.5 Hz and set the voltage amplitude to 1 V. The offset should be left at 5 V.
- Optimise the controller in each case for the specified controller gain.
- Measure the lag error and calculate the associated slide velocities and closed-loop gain values.
- Assess the measured results by answering the questions.

20.1 Determining the follower behaviour with a ramp function

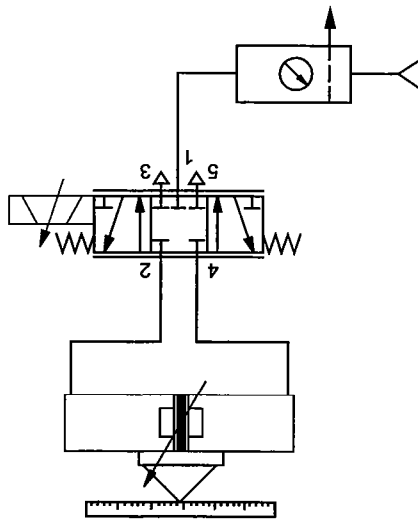


Fig. A20.4:
Pneumatic circuit diagram

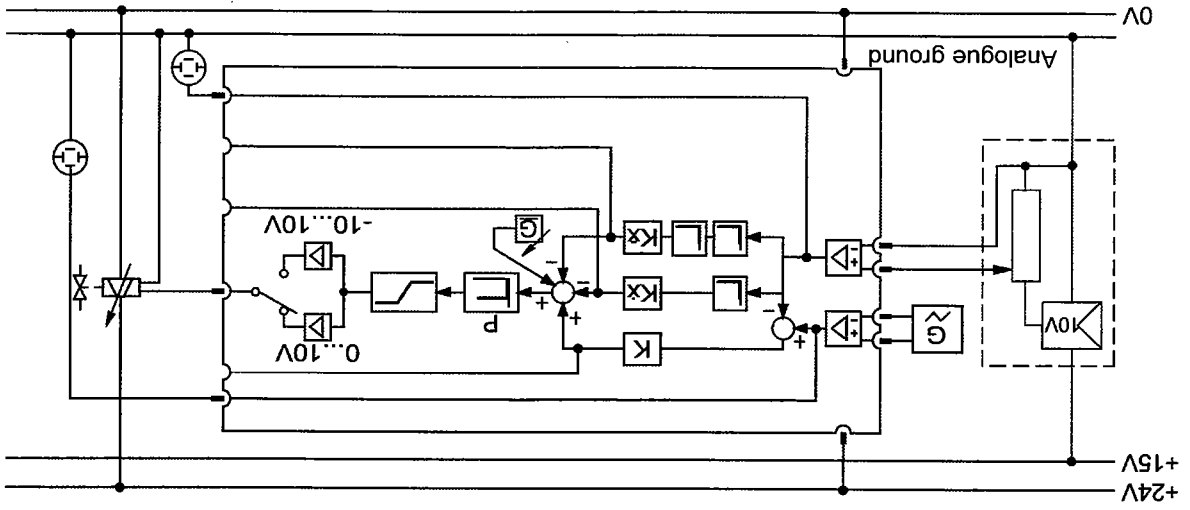


Fig. A20.5:
Electrical circuit diagram

Fig. A20.6:
Diagram



Plot the controlled variable and lag error on the graph.

How large is the measured lag error (value in mV)?

$$e \text{ [mV]} = \underline{\hspace{2cm}}$$

How large is the lag error (value in mm)? Use this formula for conversion:

$$e \text{ [mm]} = e \text{ [mV]} \cdot \frac{450 \text{ [mm]}}{10000 \text{ [mV]}}$$

$$e \text{ [mm]} = e \text{ [mV]} \cdot 0.045 \left[\frac{\text{mm}}{\text{mV}} \right]$$

$$e \text{ [mm]} = \underline{\hspace{2cm}}$$

WORKSHEET

How do the travel velocity and stroke change when the frequency is increased to 1 Hz?

The travel velocity

☐ becomes lower

☐ becomes higher

☐ stays the same

The stroke

☐ becomes smaller

☐ becomes larger

☐ stays the same

How do the travel velocity and stroke change when the voltage amplitude is reduced?

The travel velocity

☐ becomes lower

☐ becomes higher

☐ stays the same

The stroke

☐ becomes smaller

☐ becomes larger

☐ stays the same

20.2 Determining the lag error as a function of velocity

Enter the values you have determined into the table.

Table A20.1:
Determining the lag error

Frequency setting $f \left[\frac{1}{s} \right]$	Amplitude (measured) $A \text{ [mV]}$	Velocity $v1 = 4 \cdot A \cdot f$ $v1 \left[\frac{\text{mV}}{s} \right]$	Velocity $v = v1 \cdot 0.045$ $v \left[\frac{\text{mm}}{s} \right]$	Lag error (measured) $e1 \text{ [mV]}$	Lag error $e = e1 \cdot 0.045$ $e \text{ [mm]}$	Closed-loop gain $Kv = \frac{e}{v}$ $Kv \left[\frac{1}{s} \right]$					
							0.2	0.5	1	2	3

Is the lag error proportional to the velocity? Explain its behaviour.

WORKSHEET

20.3 Determining the lag error as a function of controller gain

Table A20.2
Determining the lag error

Overall gain	Amplitude (measured)	Velocity	Velocity	Lag error (measured)	Lag error	Closed-loop gain
$P[]$	$A \text{ [mV]}$	$v1 = 4 \cdot A \cdot f$ $v1 \left[\frac{\text{mV}}{\text{s}} \right]$	$v = v1 \cdot 0.045$ $v \left[\frac{\text{mm}}{\text{s}} \right]$	$e1 \text{ [mV]}$	$e = e1 \cdot 0.045$ $e \text{ [mm]}$	$Kv = \frac{v}{e}$ $Kv \left[\frac{\text{s}}{\text{mm}} \right]$

How do the lag error and closed-loop gain vary as a function of the control gain (overall gain)?

Subject

Title

Training aims

- Determining the influence of mass load on control behaviour
- Determining the influence of tubing volume on control behaviour

Influence of mass load

Technical knowledge

A mass load produces a change in the runtime performance of the controlled system. In order to maintain good control behaviour, it is therefore necessary to adapt the controller parameters. This is achieved by increasing the velocity and acceleration coefficients.

Even with optimum controller settings, a slide carrying a load has a significantly longer settling time than a slide without a load. This is illustrated in Fig. A21.1.

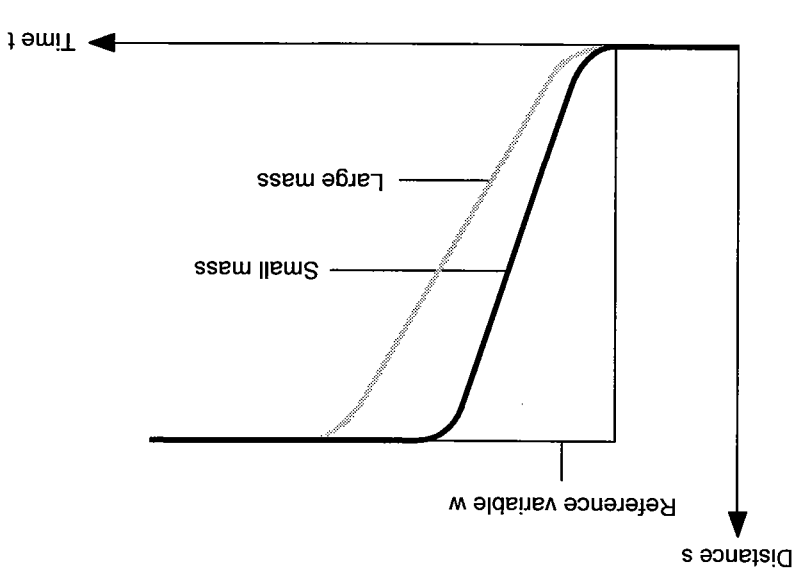


Fig. A21.1:
Effect of mass load on
control behaviour

Influence of tubing volume

Air is a very compressible medium whose volume becomes smaller when acted on by force or pressure. This change in volume is in linear proportion to the change in pressure. For example:

If the supply lines between the proportional valve and the cylinder actuator are made longer, the volume of the air in the tubing will become larger. The air column can be compressed more; it becomes "softer". The rigidity of the controlled system is thus reduced.

The significance of this for control behaviour is that the optimum controller settings must be changed if long supply lines are used between the linear axis and dynamic valve.

Problem description

The palletising station in a ceramic-tile factory is equipped with a 3-axis gantry robot. All three axes (x, y and z axes) are pneumatic axes with closed-loop control. The vertical axis (z axis) travels together with the x and y axes. It carries a vacuum generator unit which is used to pick up the ceramic tiles.

The palletising station stacks the fired tiles in a shipping carton.

The motion sequence is made up of the following steps:

- A ceramic tile is picked up from the conveyor belt by vacuum
- The tile is lifted
- The tile is conveyed to the shipping carton
- The tile is lowered
- The slide executes a return stroke without load

The proportional valves which activate the linear axes are installed at the rear of the machine on a valve terminal. The long supply lines which result from this lead to an increase in the dead volume.

The transfer of the tiles produces different loads in the two directions of motion.

In order to achieve an optimum motion sequence, we shall investigate the control behaviour of the linear axes

- with various weight loads and
- with various dead volumes.

- The following experiments will be carried out in order to determine the effects of the mass load and various tubing lengths:
1. Assembly of the pneumatic and electrical circuits
 2. Determination of the settling time T_a without a load
 3. Determination of the settling time T_a with a load
 4. Determination of the settling time T_a with various lengths of tubing

Exercise

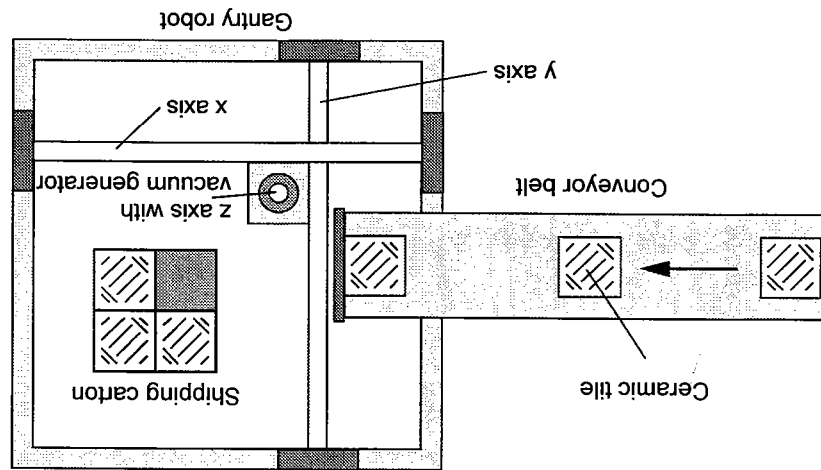


Fig. A21.2:
Positional sketch

Execution

21.1 Assembly of the pneumatic and electrical circuits

- Assemble the components in accordance with the circuit diagrams provided.
- Check the control direction.

21.2 Determining the settling time T_a without a mass load

- Use the voltage generator to input a square-wave reference variable signal (offset: 5 V, amplitude: 2 V, frequency: 0.5 Hz).
- Set the correcting variable offset relative to the reference variable in such a way that the slide moves in the middle of its stroke range.
- Optimise the status controller using the empirical method and note the coefficients. In order to obtain comparable results, select a position coefficient $K_x = 1.5$ and an overall gain $P = 11$.
- Measure the settling time T_a and enter this into the table.

21.3 Determining the settling time T_a with a mass load

- Fit a mass of 5 kg to the slide.

When doing this, observe the safety and fitting instructions given on the data sheet.



- Optimise the controller for a loaded slide and note the coefficient settings (for $K_x = 0.7$ and $P = 11$).
- Measure and note the settling time T_a .
- Compare the results with those obtained in step 2.



Further values can be measured by fitting additional mass loads.

21.4 Determining the settling time T_a with various lengths of tubing

- Fit various lengths of tubing between the proportional valve and the linear axis. Always use identical lengths of tubing for the two valve-to-axis lines.
- Optimise the controller for the various tubing lengths and note the coefficient settings (for $K_x = 1.5$ and $P = 11$).
- Measure and note the settling time T_a .
- Evaluate the results by answering the questions below.

21.1 Assembly of the pneumatic and electrical circuits

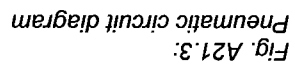


Fig. A21.3:

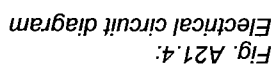


Fig. A21.4:

WORKSHEET

21.4 Determining the settling time T_a with various lengths of tubing

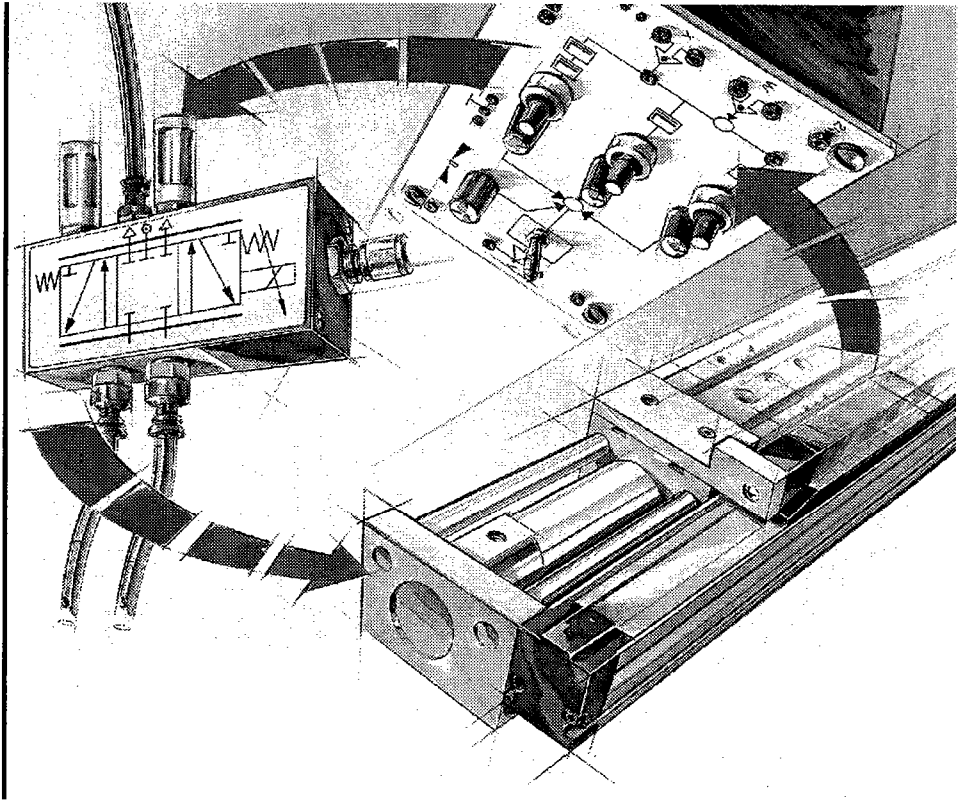
Tubing length [mm]	K_x	K_x	K_x	P	T_a [ms]
250	1.5			11	
2000	1.5			11	

Table A21.3:
Settling time

What do you observe with regard to the settling time?

Closed-Loop Pneumatics

TP111



FESTO

Section B – Fundamentals

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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 Signal

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.

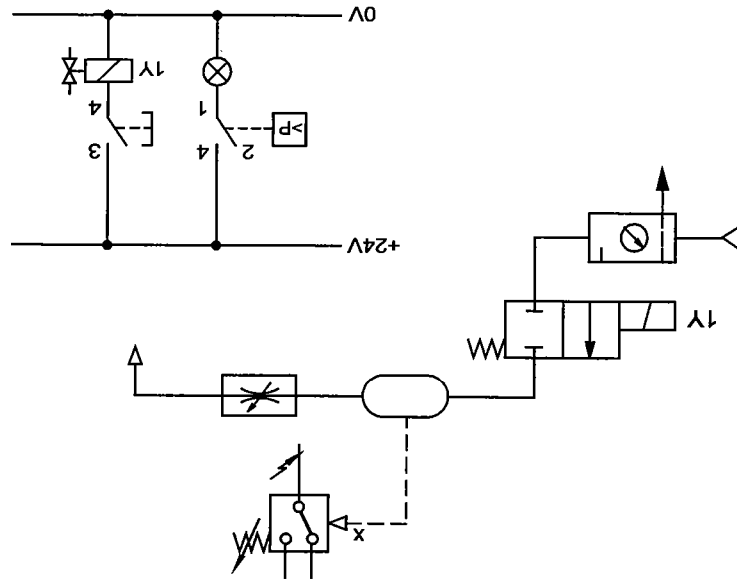


Fig. B1.1:
Reservoir with
pressure monitoring

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.

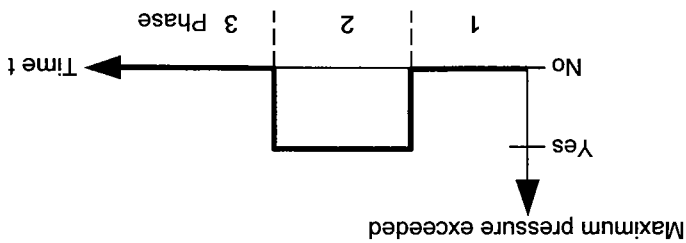


Fig. B1.2:
Binary signal as a
function of time

Analogue signal

In the case of the pneumatic 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.

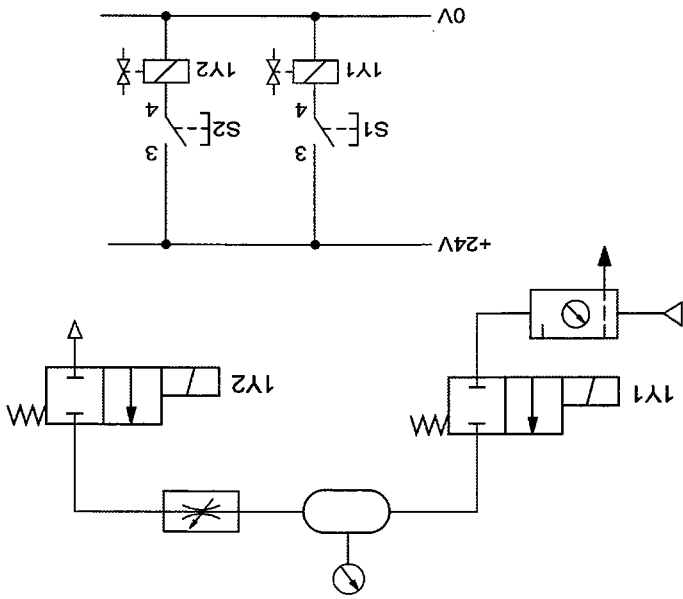


Fig. B1.3:
Reservoir with
pressure gauge

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.

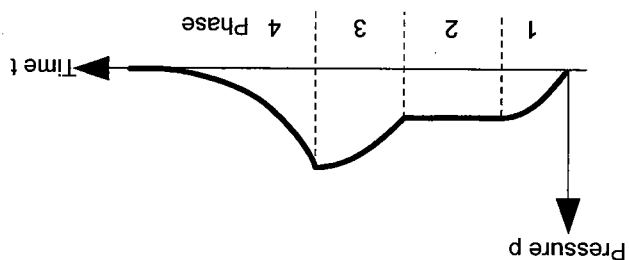


Fig. B1.4:
Analogue signal as a
function of time

Signals for valve actuation

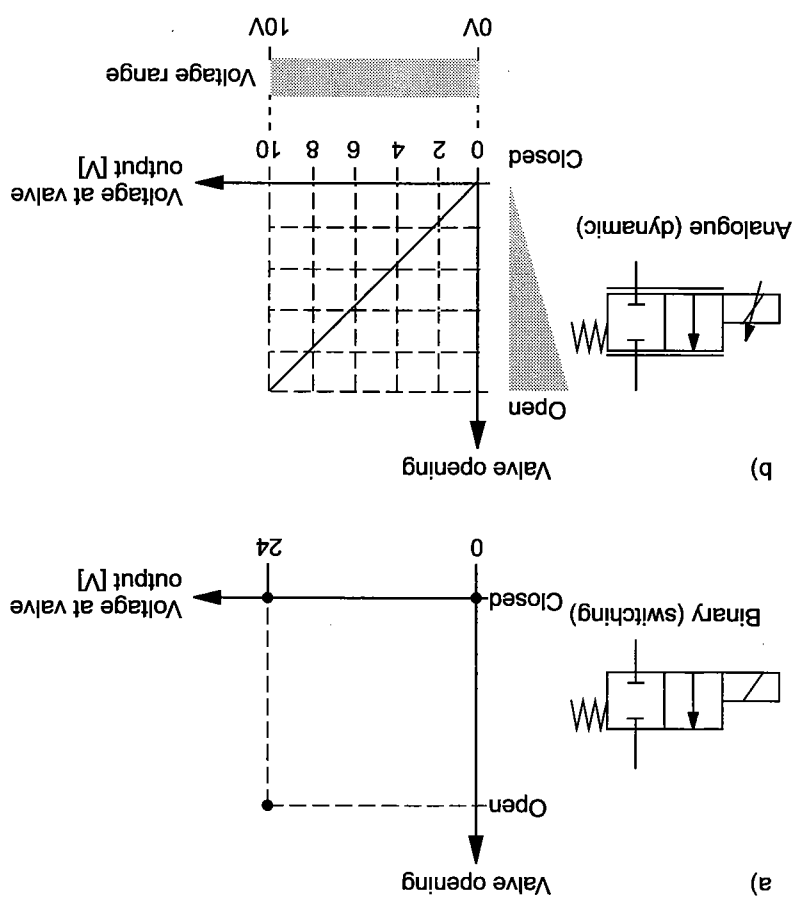
A binary signal is used to actuate a switching valve (Fig. B1.5a). The signal and thus the opening of the valve can assume only two values:

- Signal 0 V, valve closed
- Signal 24 V, 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 0 V means: Valve closed.
- signal of 5 V means: Valve half open.
- With a signal of 10 V the maximum valve opening is achieved.

Fig. B1.5:
Action of a
switching valve and
adynamic 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 pneumatic 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 U 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 pneumatic 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.

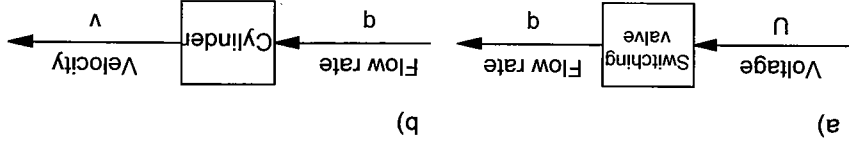


Fig. B1.6a + b:
Block diagrams for a
switching valve and a
pneumatic cylinder

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. B1.7d shows the step response of a valve.

Phase 1: The input signal is zero. The valve is closed.

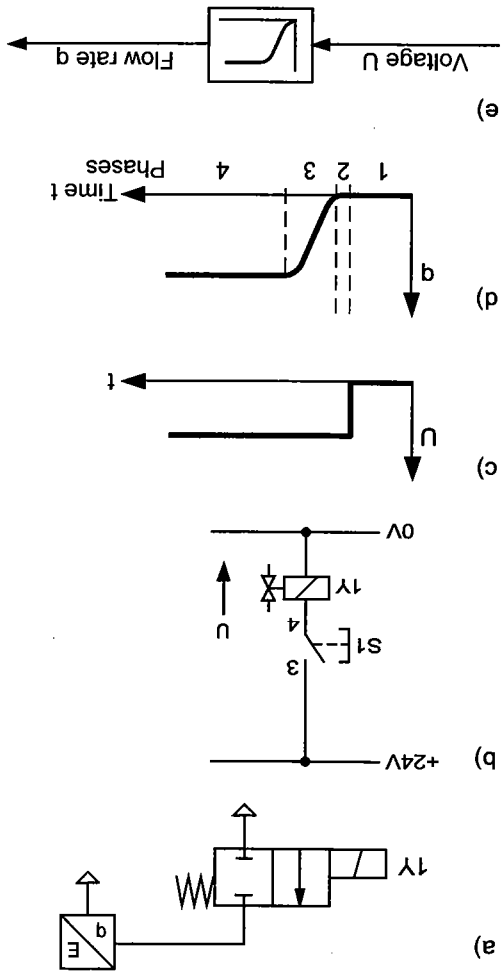
Phase 2: The input signal has changed. The spool does not as yet move. The flow rate remains at zero for the time being.

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 valve



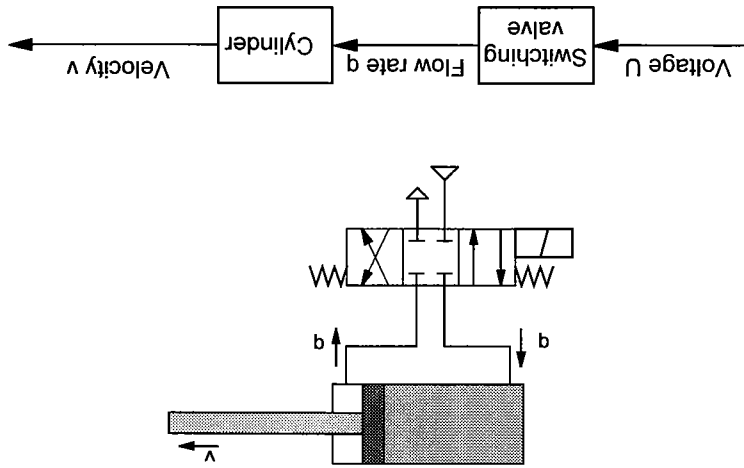
1.3 Signal flow diagram

In the signal flow diagram, the individual transmission blocks of a circuit are linked together.

Series circuit

Fig. B1.8 shows a pneumatic circuit consisting of a switching valve and pneumatic cylinder. The output signal of the switching valve forms the input signal for the pneumatic 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.

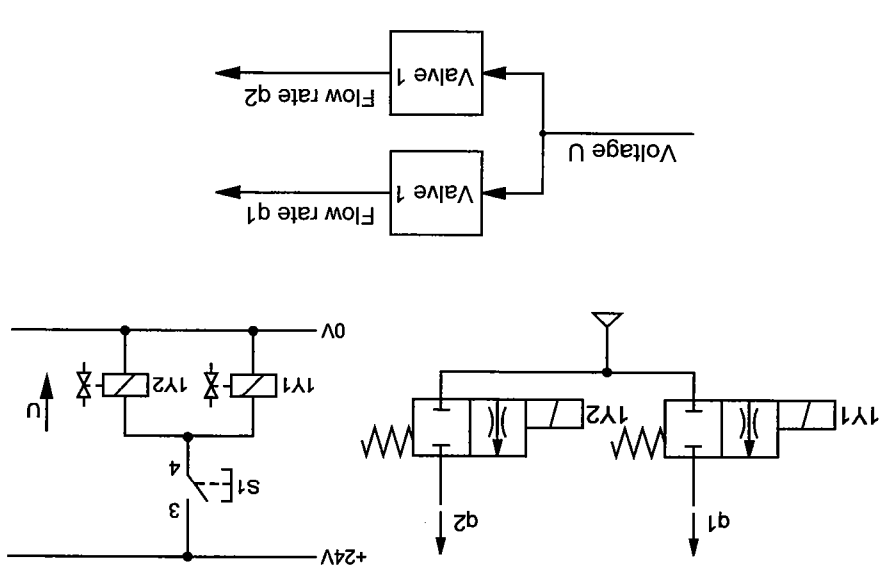


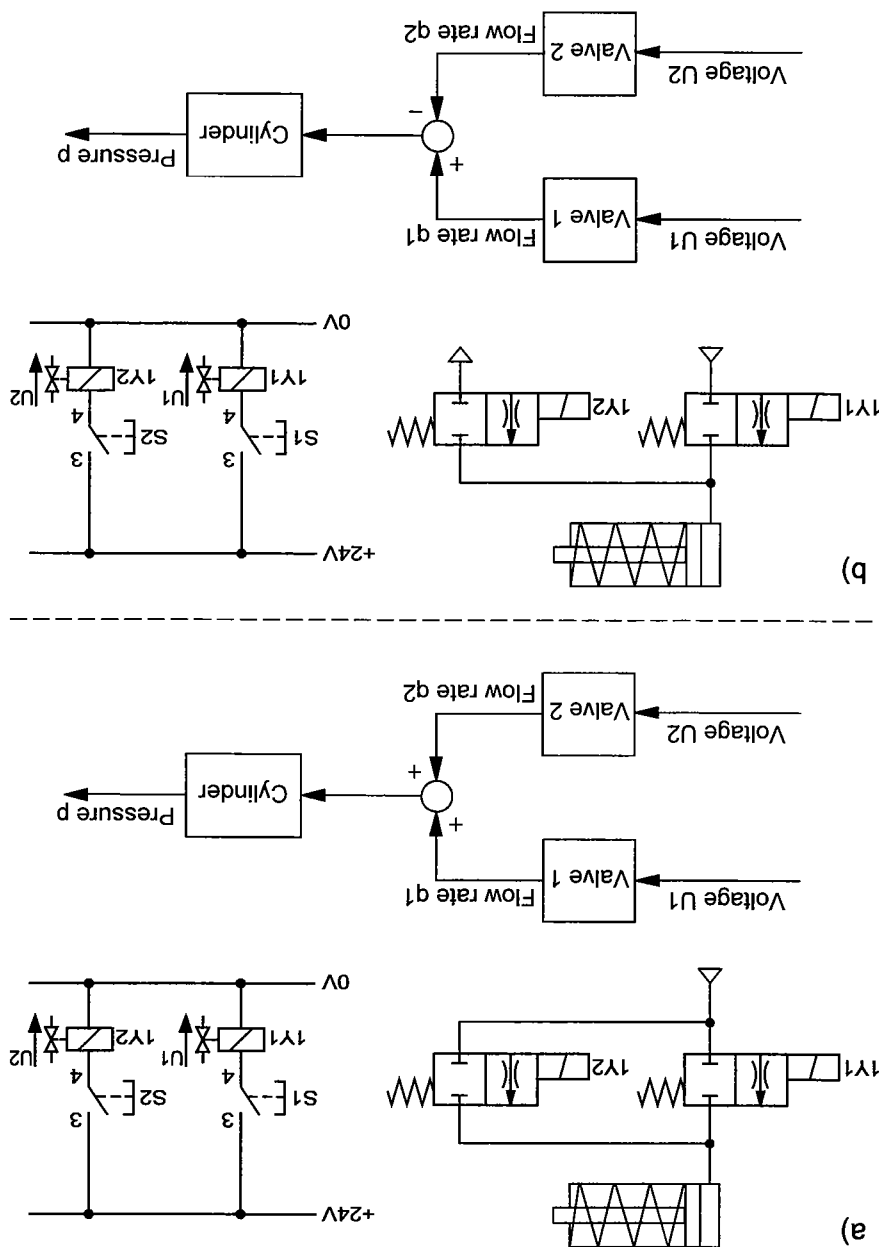
Fig. B1.9:
Signal flow diagram:
Branch

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. B1.10a). 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 (Fig. B1.10b).

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.

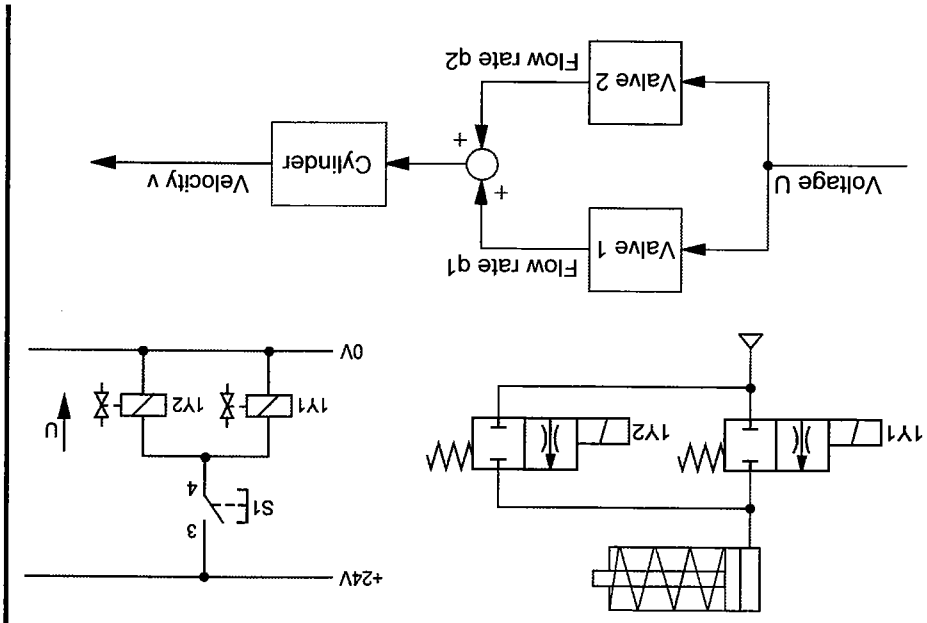


Fig. B1.11:
Signal flow diagram:
Parallel circuit

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. B1.12c shows the transition function of a pneumatic valve.

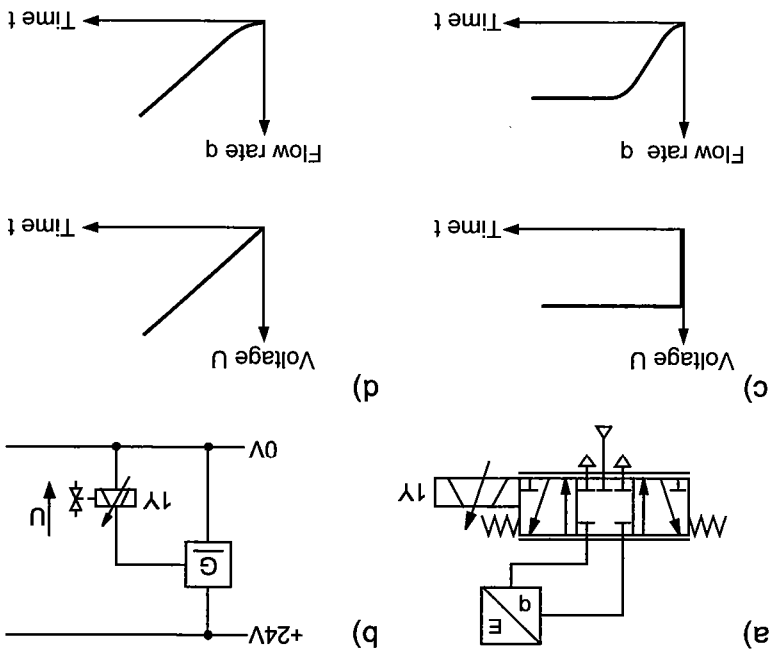
- The voltage U forms the input signal. This is subjected to a step-change.
- The flow rate q forms the output signal. This changes continuously. The change in the flow rate occurs with a delay relative to the change in the voltage.

Ramp function

Fig. B1.12d shows a ramp function of a pneumatic valve.

- The voltage U 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



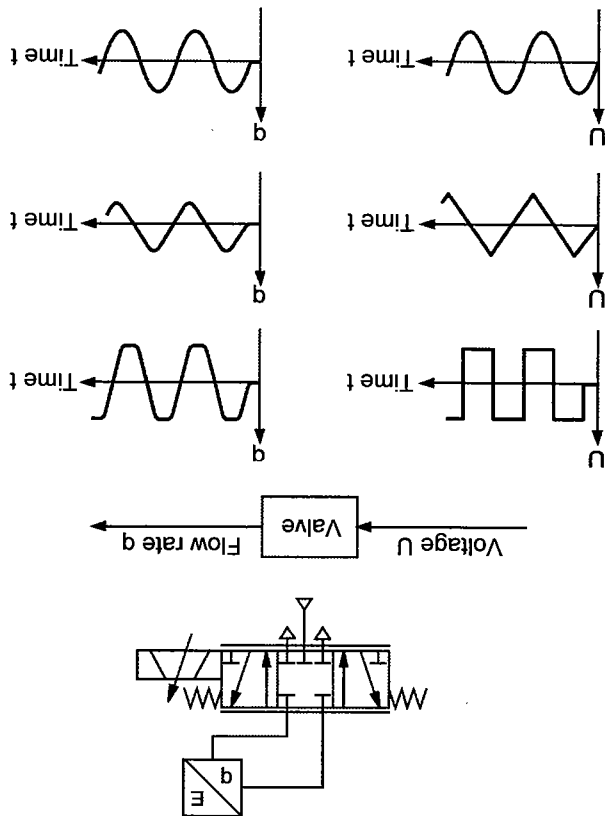
In practice, test signals are produced with an electrical function generator. The three most common types of test signals are:

- 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 pneumatic 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 pneumatic circuit for the open-loop control of velocity. The velocity of the piston rod is measured with a speed sensor. The piston of the pneumatic 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 4 V.

Fig B1.14b shows the associated signal flow diagram:

- The required voltage, i.e. 4 V, 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.

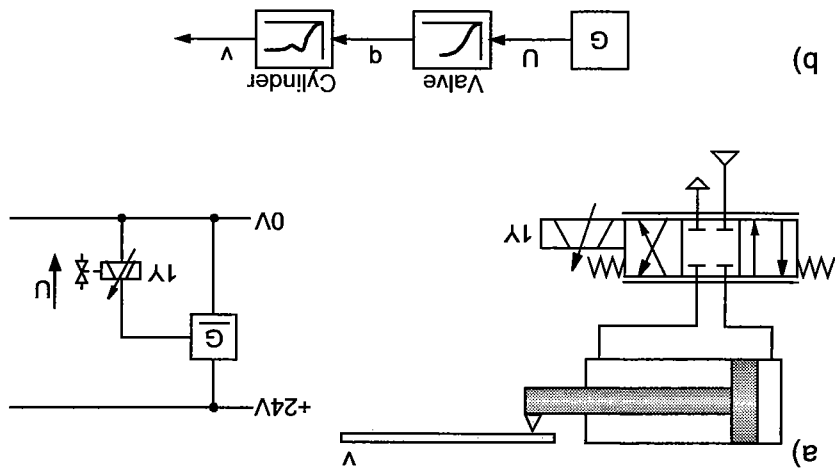


Fig. B1.14:
Open control loop

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 pneumatic 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.

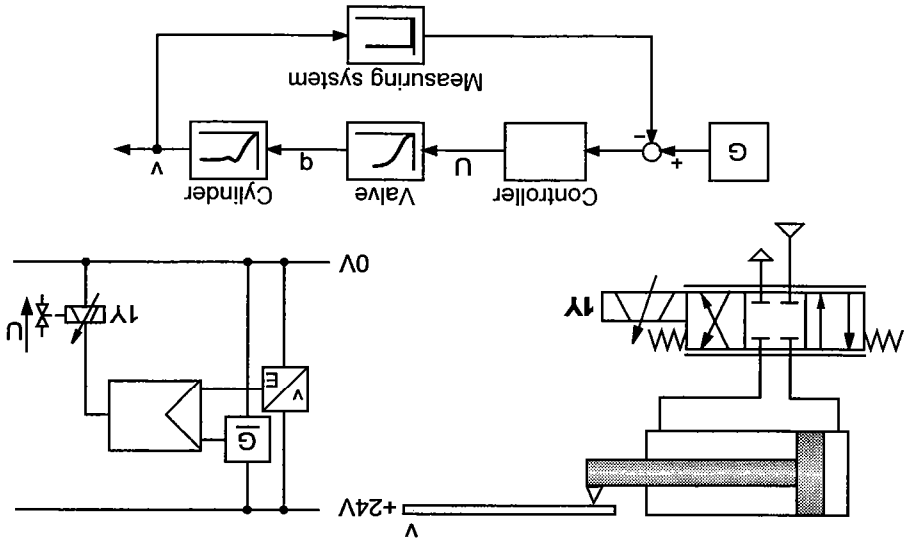


Fig. B1.15:
Closed control loop for
speed control

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.

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

Table B1.1:
Signal flow diagrams for
open-loop and
closed-loop controls

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".

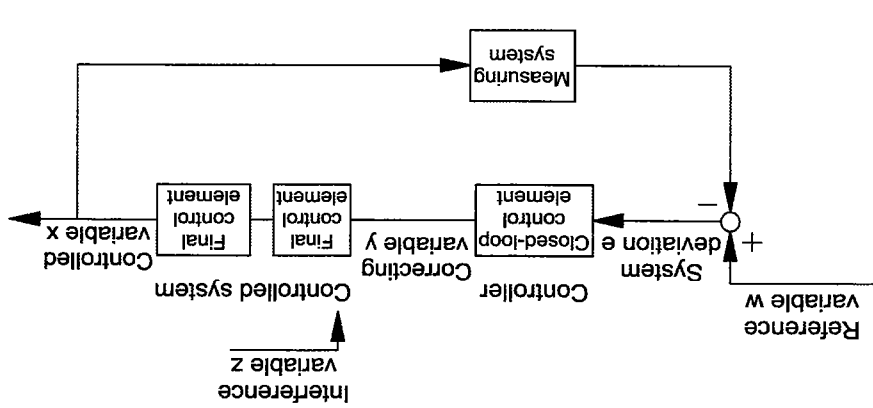


Fig. B1.16:
Closed control loop:
Terminology

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 pneumatic 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.

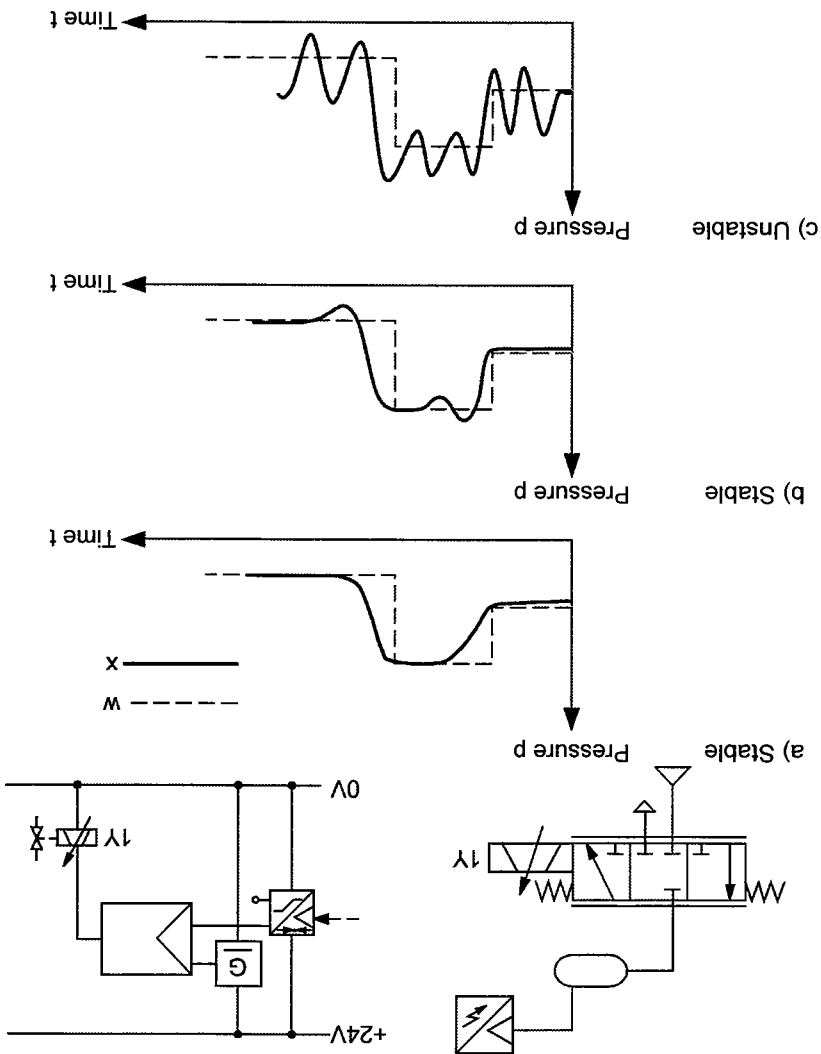
1.7 Stability and instability

Fig. B1.17 shows a closed-loop pneumatic 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 B1.17b). 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 fulfills 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 be 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.

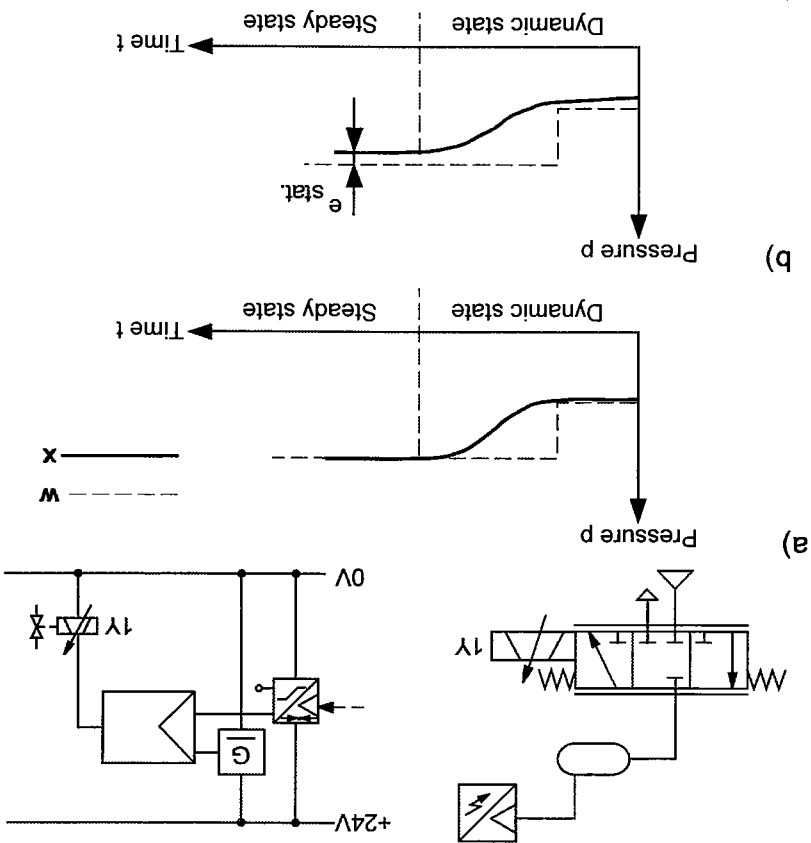
Steady-state system deviation

The steady-state system deviation is calculated as follows:

$$e_{\text{stat}} = w - x \quad \text{where} \quad w: \text{Constant} \quad x: \text{Constant}$$

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 fulfill 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.

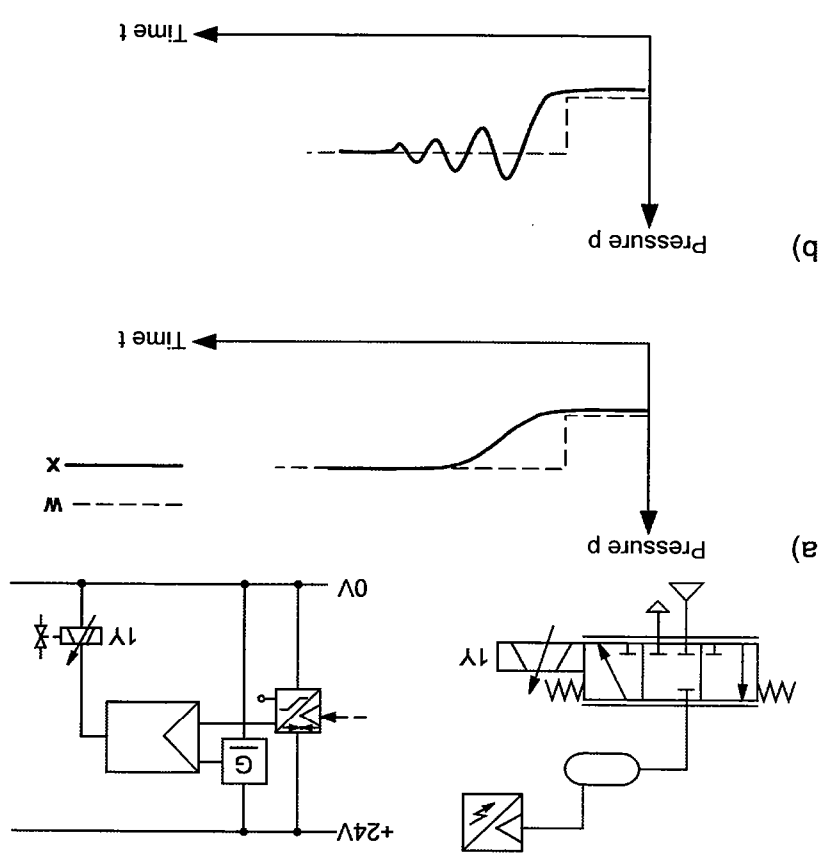


Fig. B1.19:
Dynamic behaviour of two
closed-loop pressure
control circuits

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 t_0 , 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.

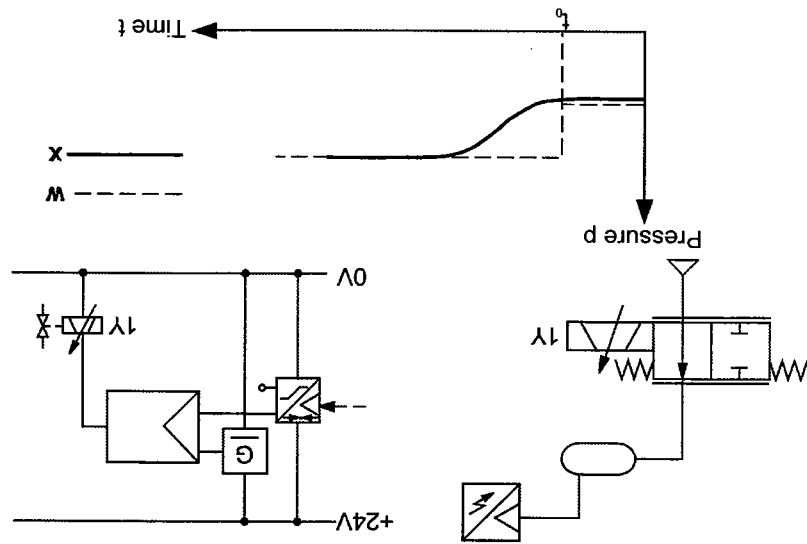


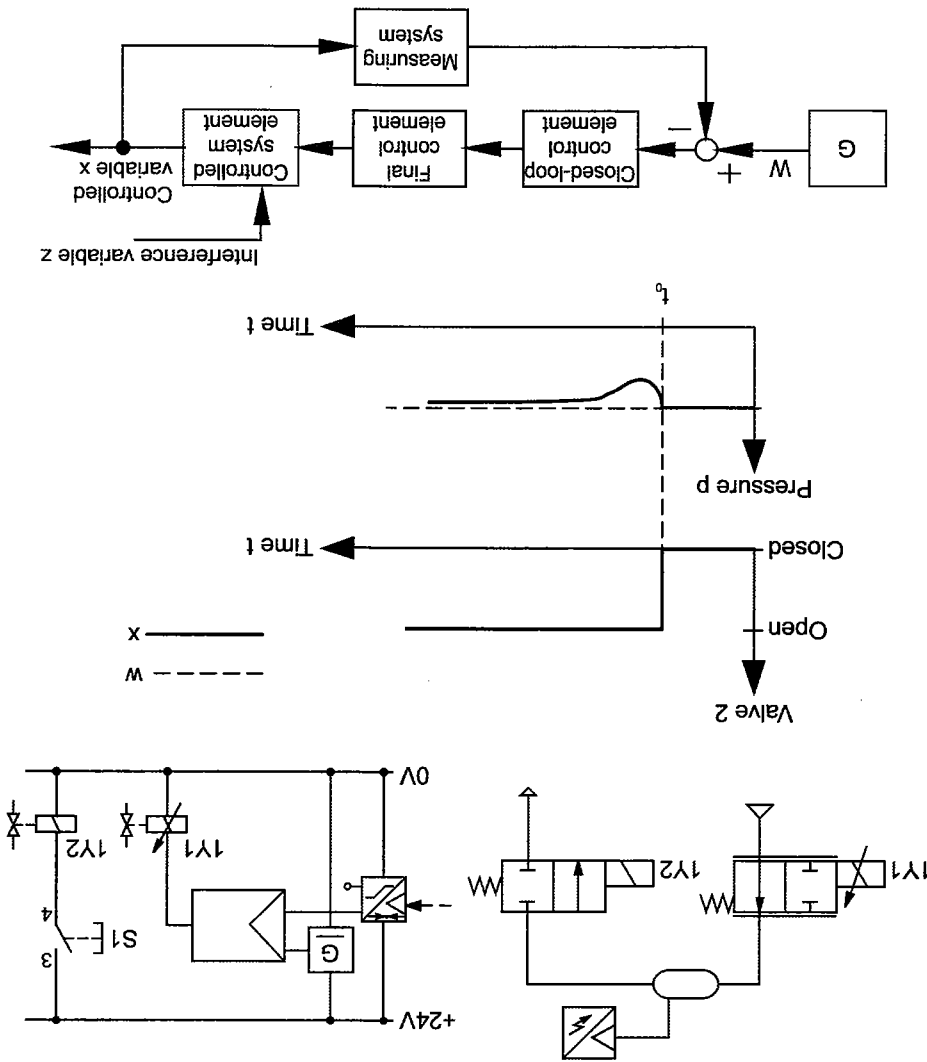
Fig. B1.20:
Pneumatic pressure control:
Response to setpoint
changes

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:
Pneumatic pressure control:
Response to interference



1.10 Fixed-value, follow-up and timing control systems

Fixed-value control system

Fig. B1.22 shows a pneumatic circuit for pressure control. The pressure regulator is used to achieve a constant supply pressure of 6 bar. 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.

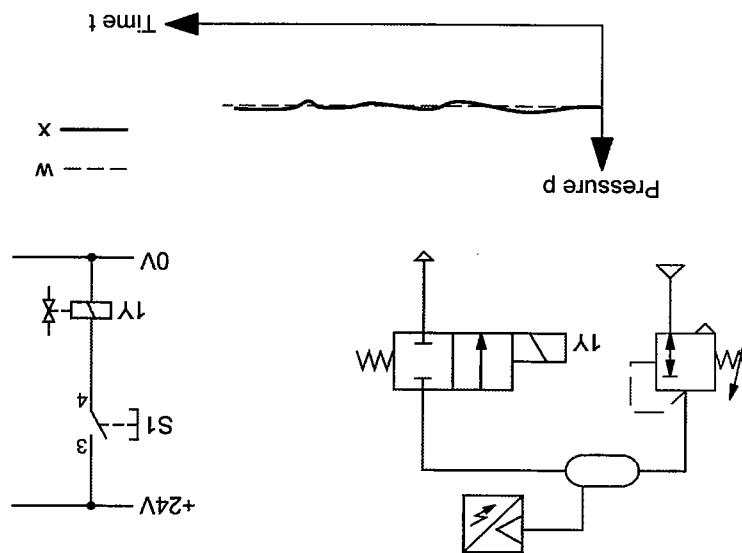


Fig. B1.22
Fixed-value
control system

Follow-up control system

Fig. B1.23 shows a pneumatic 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.

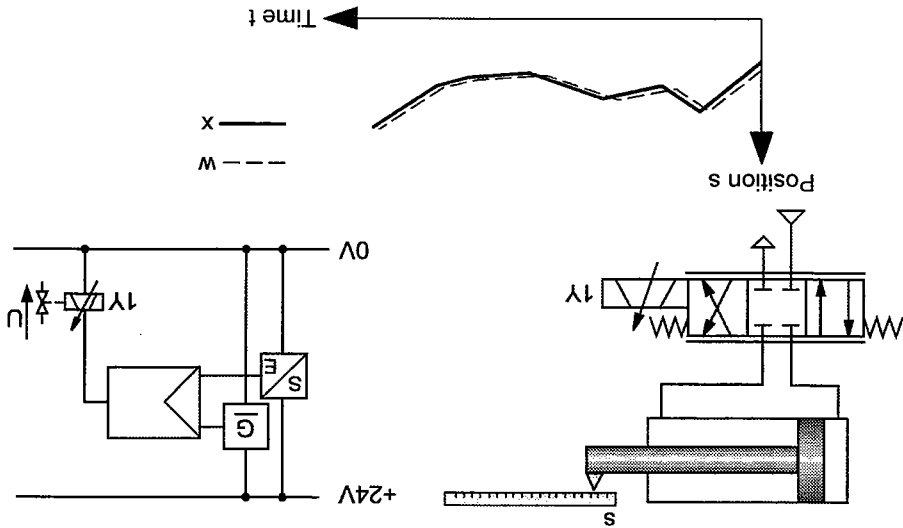


Fig. B1.23:
Fixed-value control system

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.

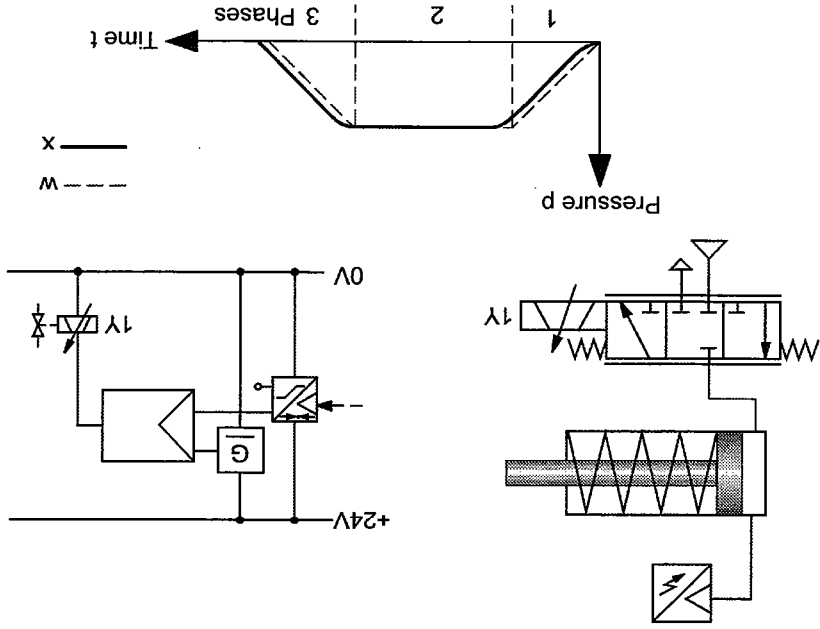


Fig. B1.24:
Follower control system

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 pneumatic 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.

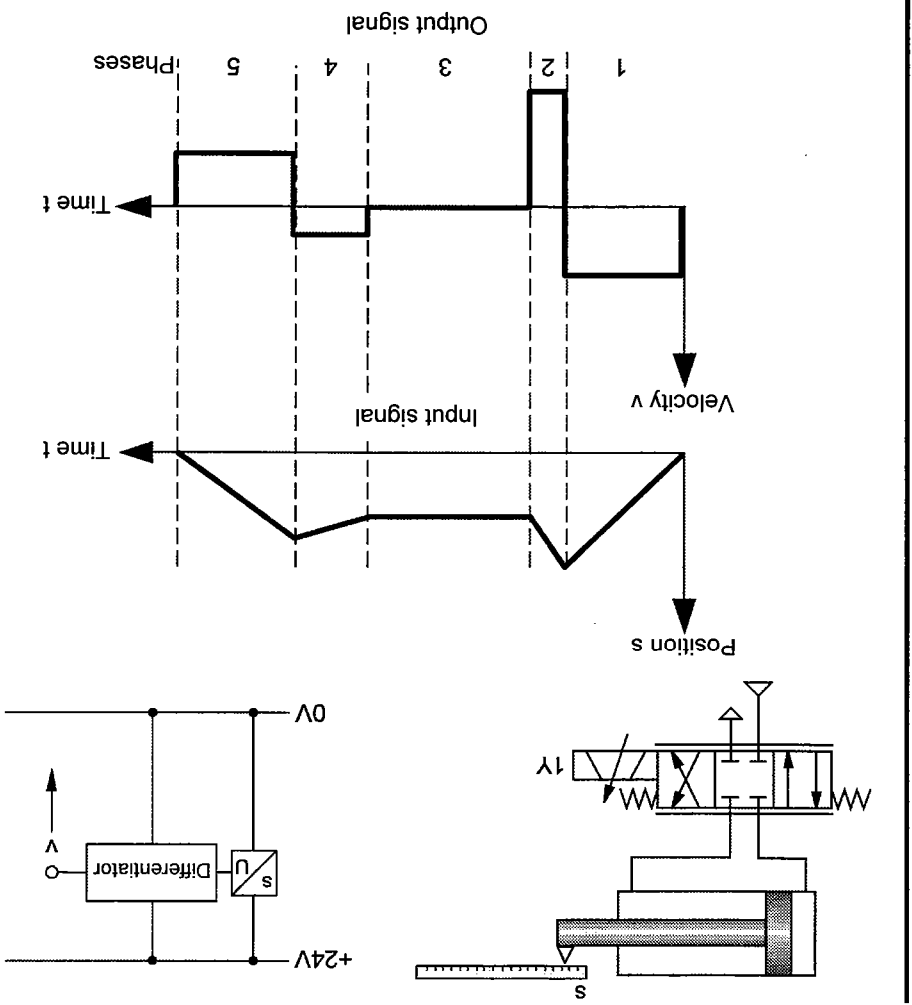
- In phase 2, the piston moves in the negative direction. The input signal of the differentiator falls. The output signal has a negative value.

- In phase 3, the piston of the pneumatic 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.

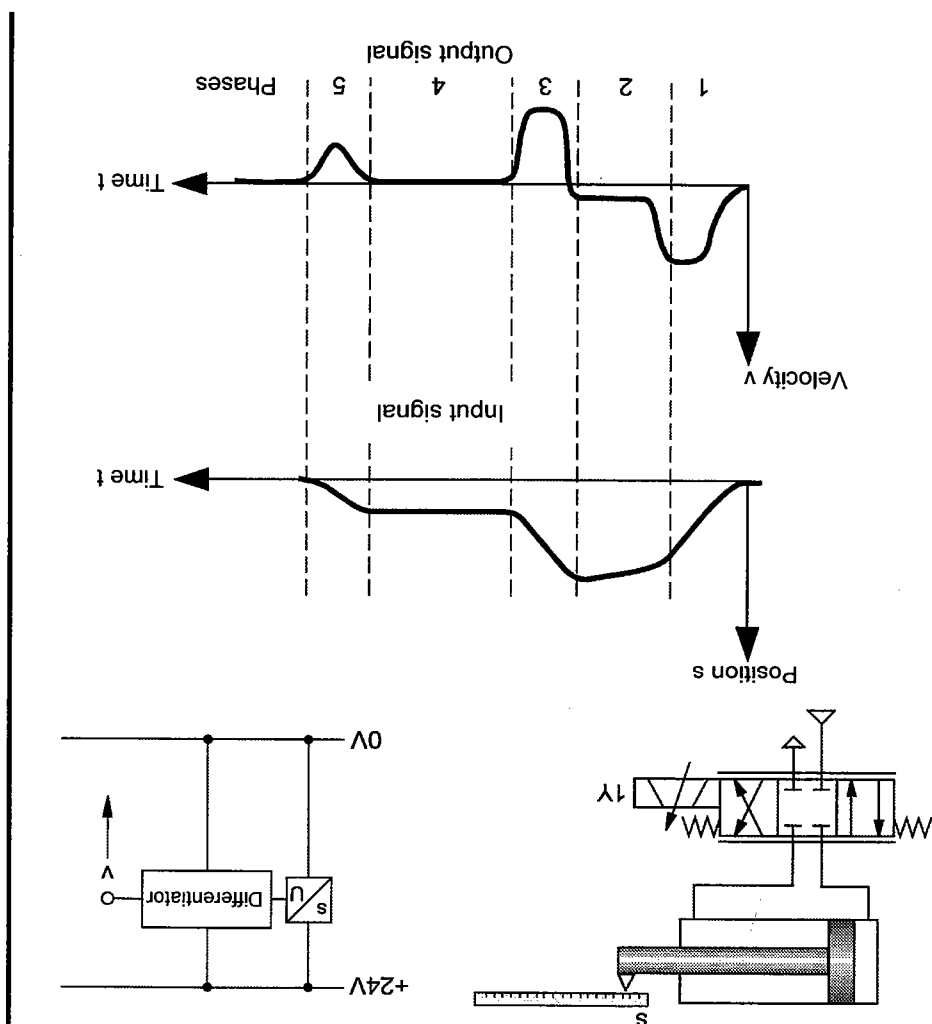
Fig. B1.25:
Timing control system



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

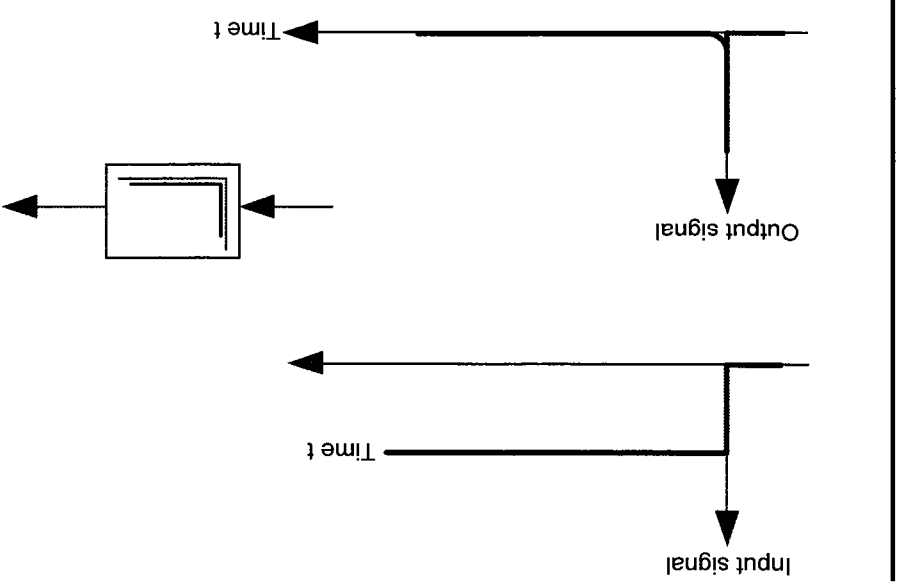


Block diagram and transition function of a differentiator

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.

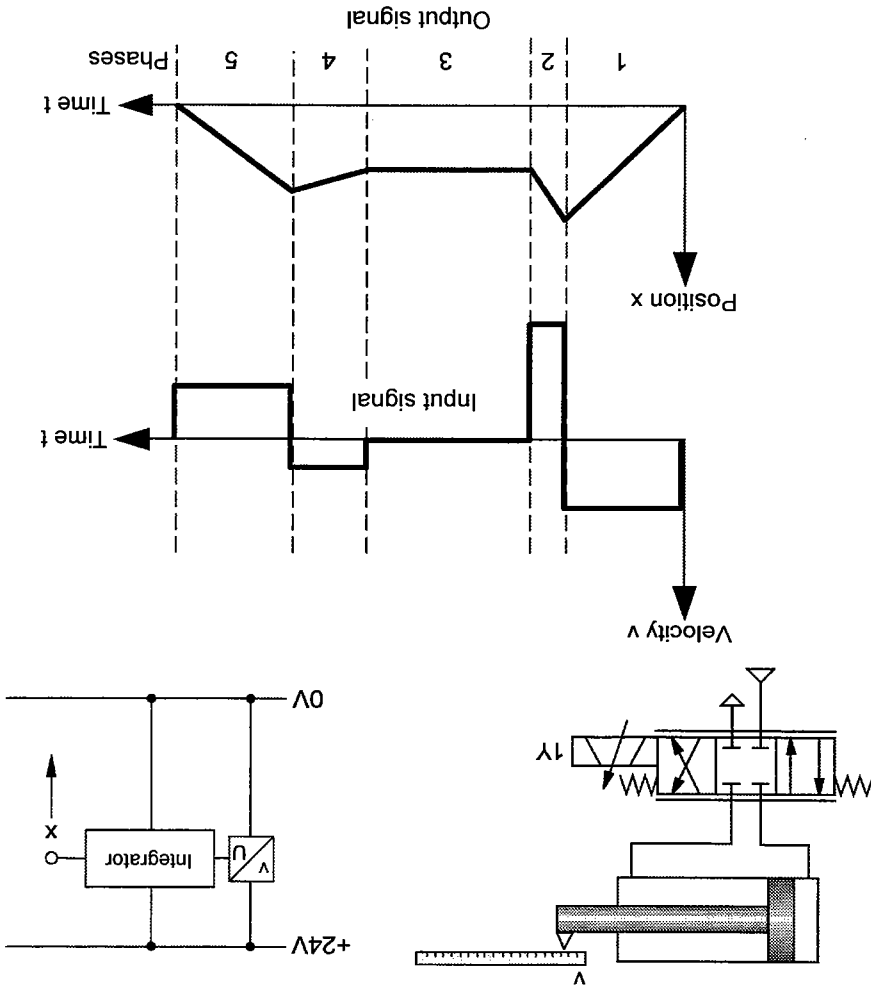
- In phase 2, the velocity is less than zero. The piston rod moves in the negative direction. The output signal of the integrator falls.

- 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:
Block diagram of a
differentiator



In Fig. B1.28, the value of the input signal exhibits step changes. The gradient of the output signal thus 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).

- 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.

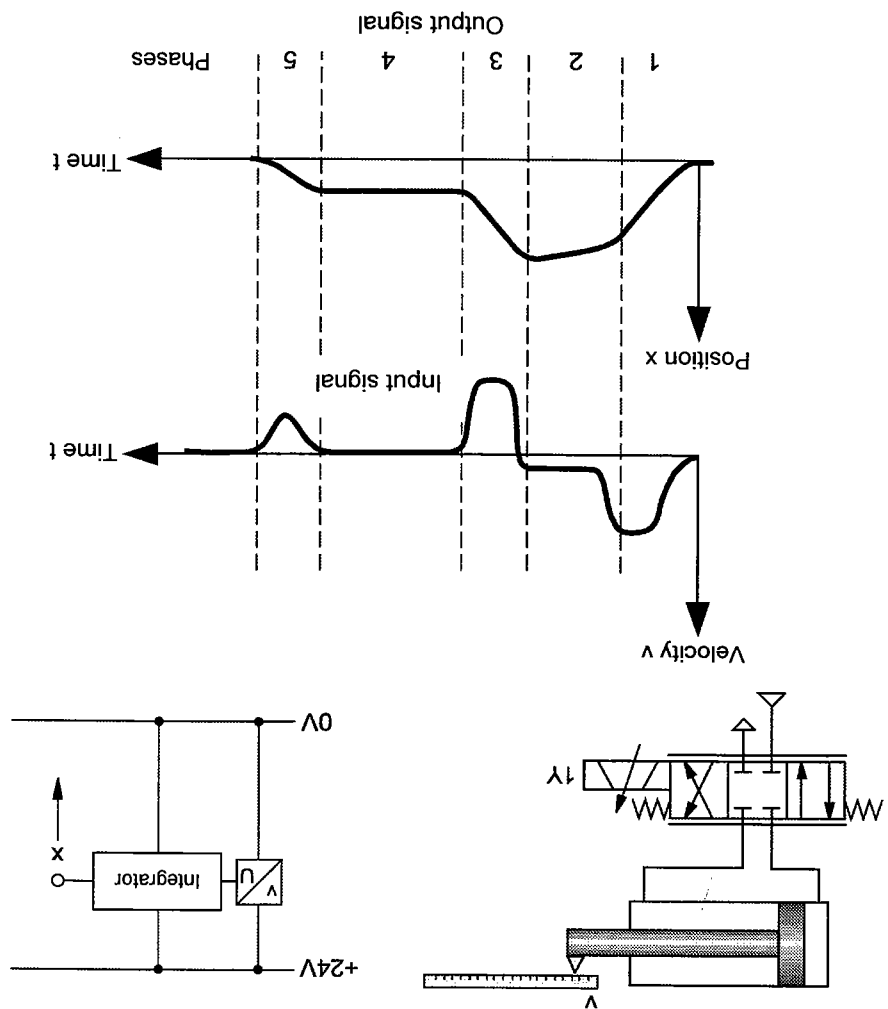
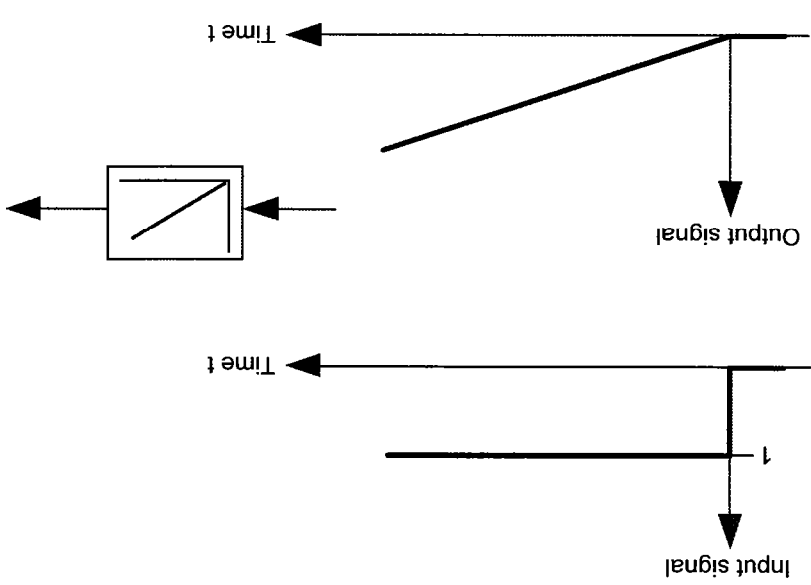


Fig. B1.29:
Integration of a signal

Bild 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:

$$a(t) = \int e(t) dt$$

Pneumatic closed-loop controlled systems

A controlled system consists of a final control element and a controlled-system element (Fig. B1.16). In pneumatic 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 pneumatic components but also variables such as load forces, frictional forces and masses. For example, a pneumatic cylinder actuator which has to move 50 kg backwards and forwards will react more slowly than a similar actuator which has to move only 5 kg.

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).

Pneumatic controlled systems can generally be described by one of the models in Table B2.1. Suitable models are specified below for various pneumatic controlled systems.

<i>Controlled systems with compensation</i>	
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 systems without compensation	Controlled system with dead time

Table B2.1:
Examples of models
of pneumatic
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 pneumatic 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.

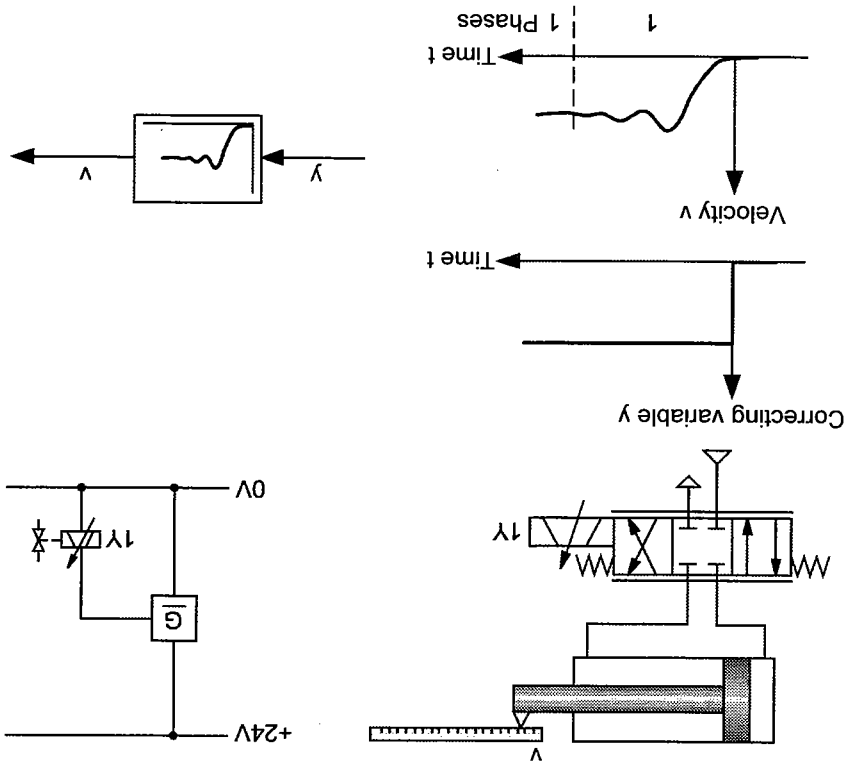
In order to determine the transition function, the valve is energised with a correcting signal which exhibits a step change at the point in time $t = 0$. We can distinguish between two phases:

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 pneumatic 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.

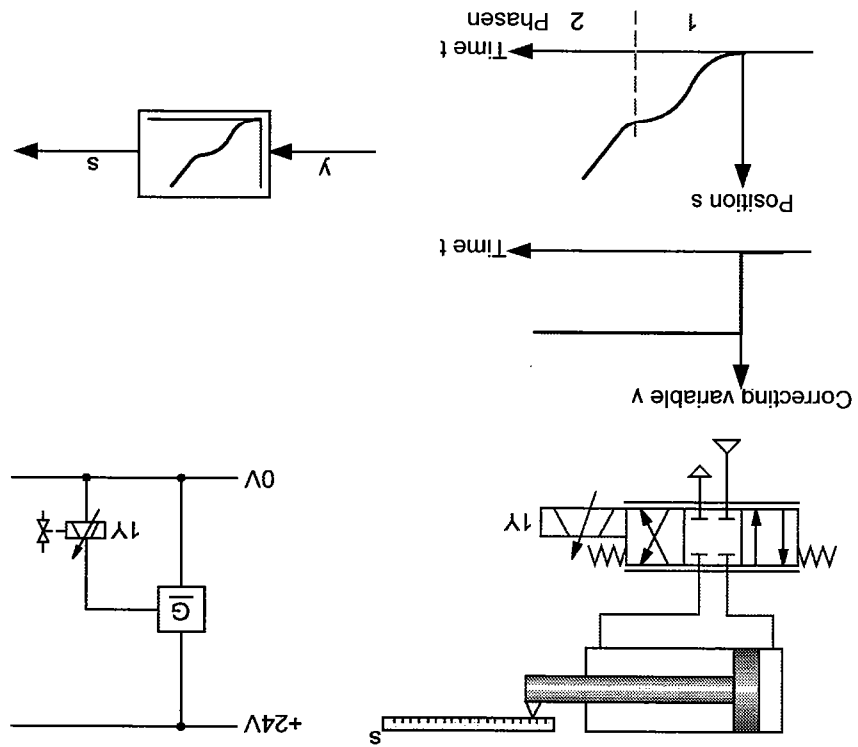
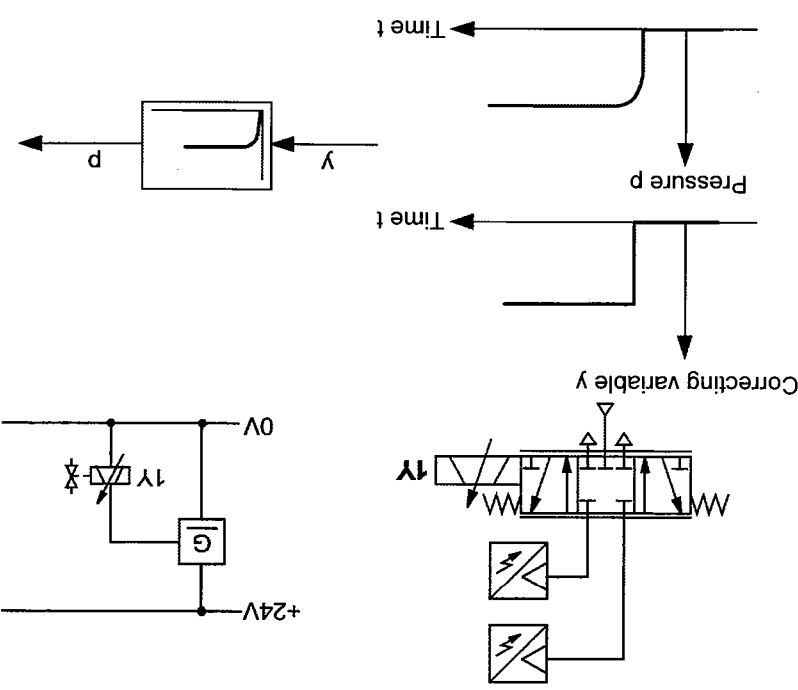


Fig. B2.2:
Block diagram and
transmission characteristics
for
a controlled system
without compensation

2.2 Short-delay pneumatic control 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.

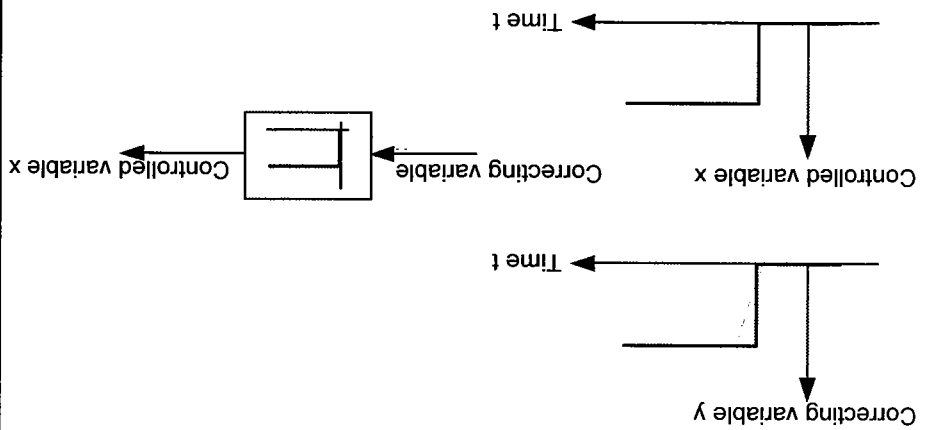
Fig. B2.3:
Short-delay
pressure control system



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

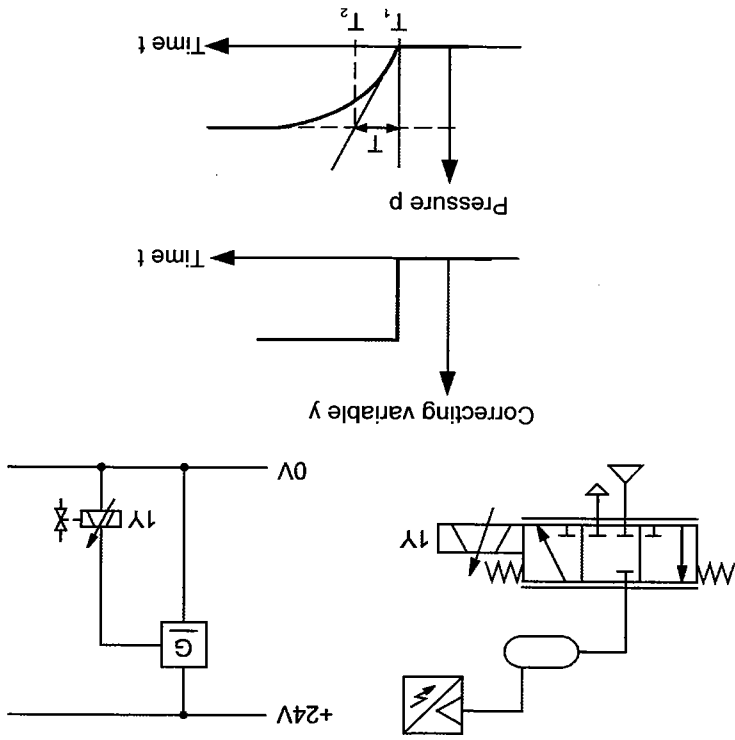


2.3 First-order pneumatic controlled system

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 pneumatic controlled systems

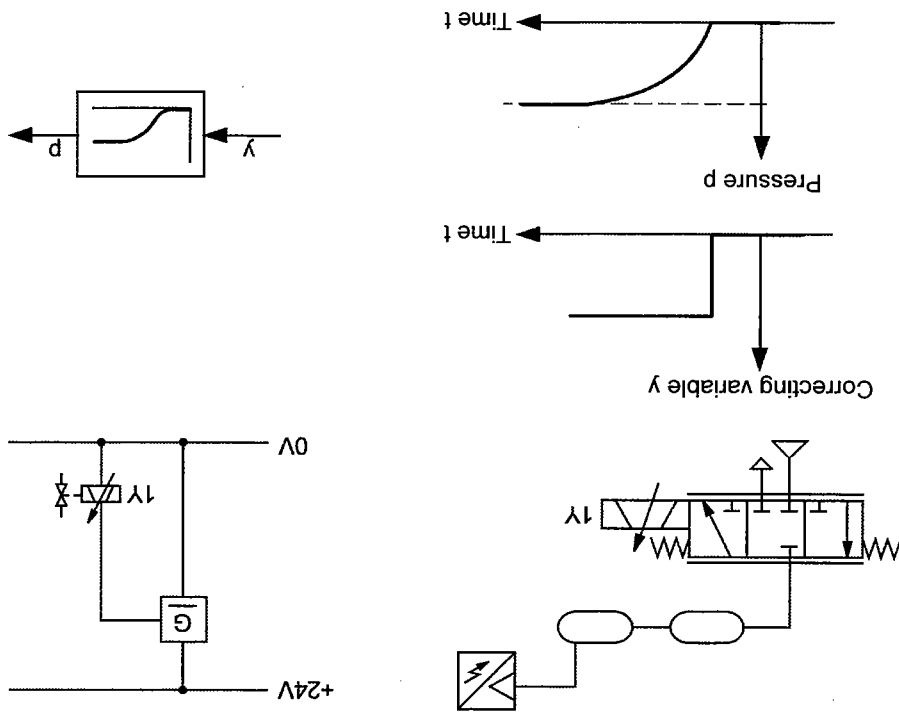
Similar energy storage devices

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 pneumatic 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 pneumatic cylinder can be regarded as air springs. The piston of the pneumatic cylinder is clamped between these springs. The spring/mass system is capable of oscillation. For this reason, oscillations may result from a step response.

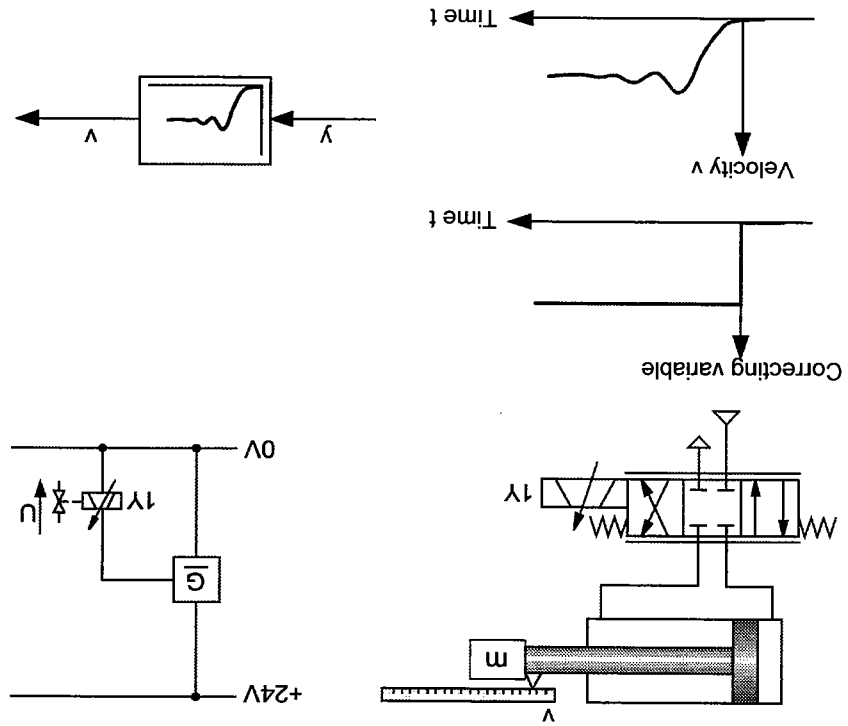


Bild B2.7:
Pneumatic
cylinder actuator with
velocity sensor

Comparison of second-order controlled systems

Table B2.2 shows a comparison of two second-order pneumatic controlled systems.

Table B2.2:
2nd order
controlled systems

Energy storage devices	Two identical energy storage devices	Two non-identical energy storage devices
Step response	No oscillations	With oscillations
Example	Two pneumatic reservoirs	Pneumatic cylinders

2.5 Third-order pneumatic 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 U 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.

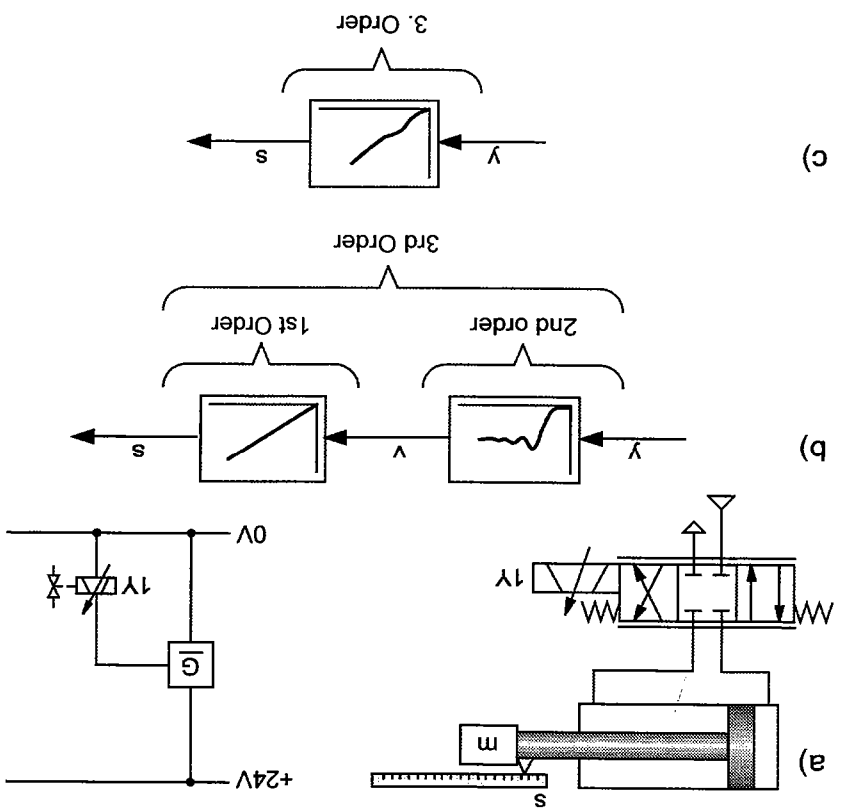
The output signal of the integrator corresponds to the output signal of the controlled system.

The order of the overall controlled system is determined by adding together the orders of the two sub-systems (Fig. B2.8b):

$$\begin{aligned} \text{Order of a controlled system} &= \text{Order of 1st sub-system} + \text{Order of 2nd sub-system} \\ &= 2 + 1 \\ &= 3 \end{aligned}$$

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:
Pneumatic 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 pneumatic actuator with speed sensor (second-order controlled system, Fig. B2.7) and the pneumatic actuator with position sensor (third-order controlled system, Fig. B2.8) have the same pneumatic components. The order of the two controlled systems is different because their output signals are different.

2.6 Controlled systems with dead time

Fig. B2.9 shows a pilot-actuated switching valve with a pressure sensor connected in the port to the consuming device. The voltage for the actuation of the valve forms the input signal of the circuit. The pressure sensor supplies the output signal.

When the input signal changes, the pilot stage is first actuated. Only when a sufficiently high pressure has built up in the pilot stage does the valve spool actuate the main stage. The output signal edge is thus delayed relative to the input signal edge by the period T_t . The period T_t is known as the dead time. In the case of a valve of large nominal size (e.g. G1/2), the dead time can be more than 50 ms.

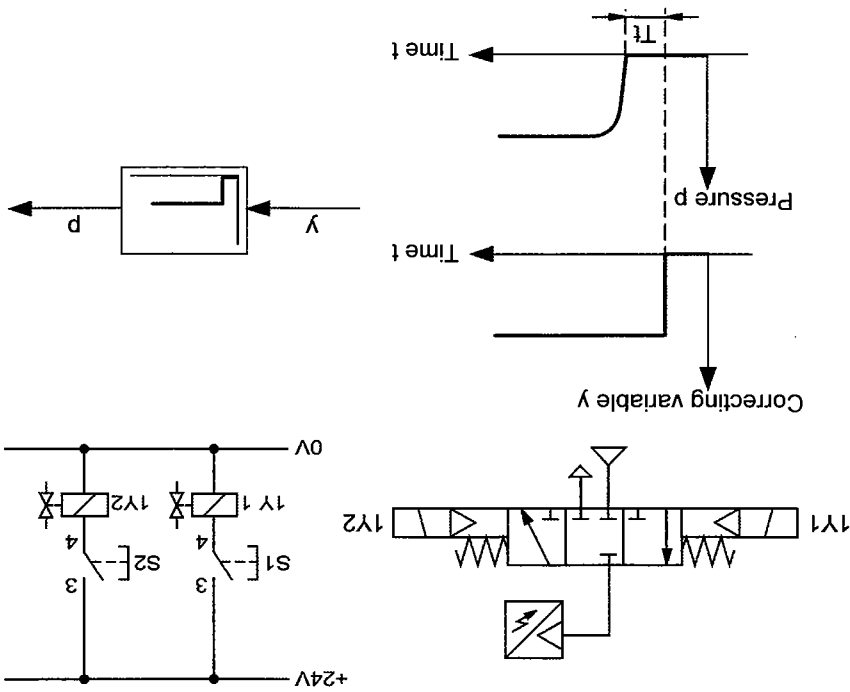


Fig. B2.9:
Pilot-actuated
pneumatic switching valve

2.7 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.

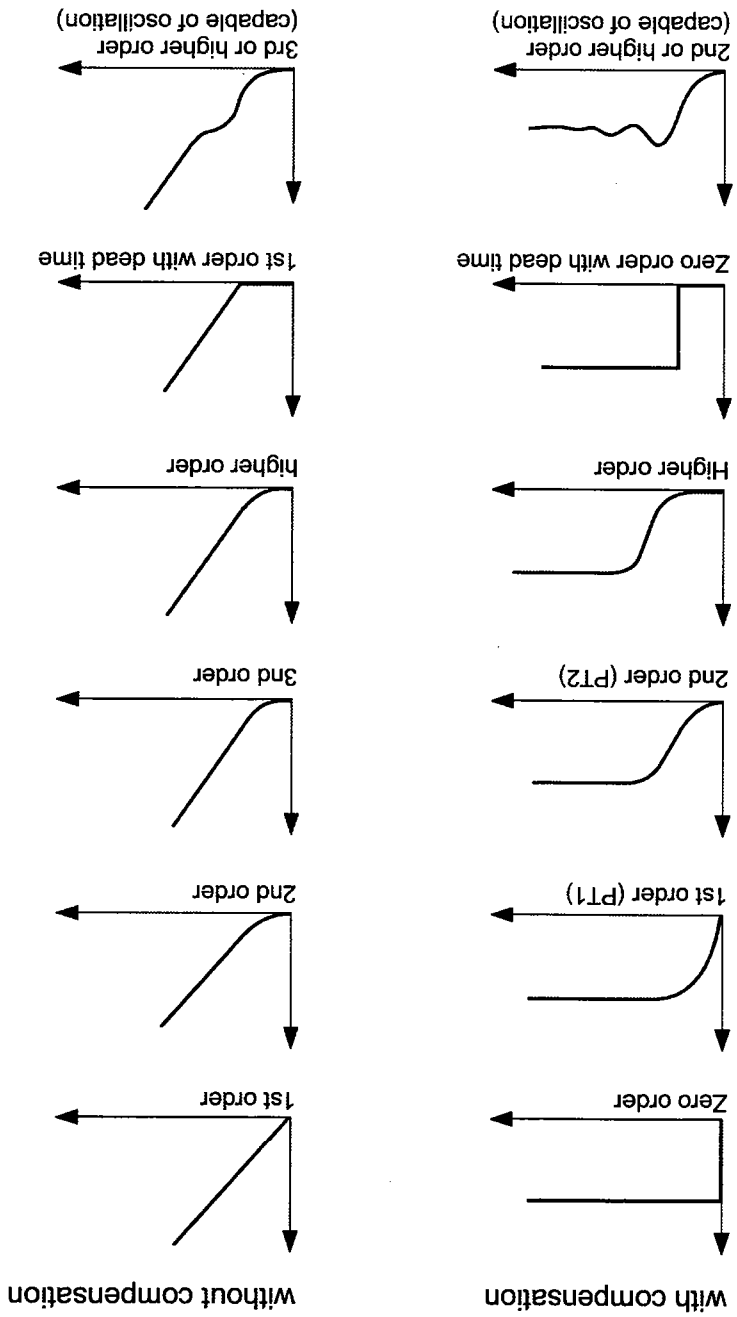
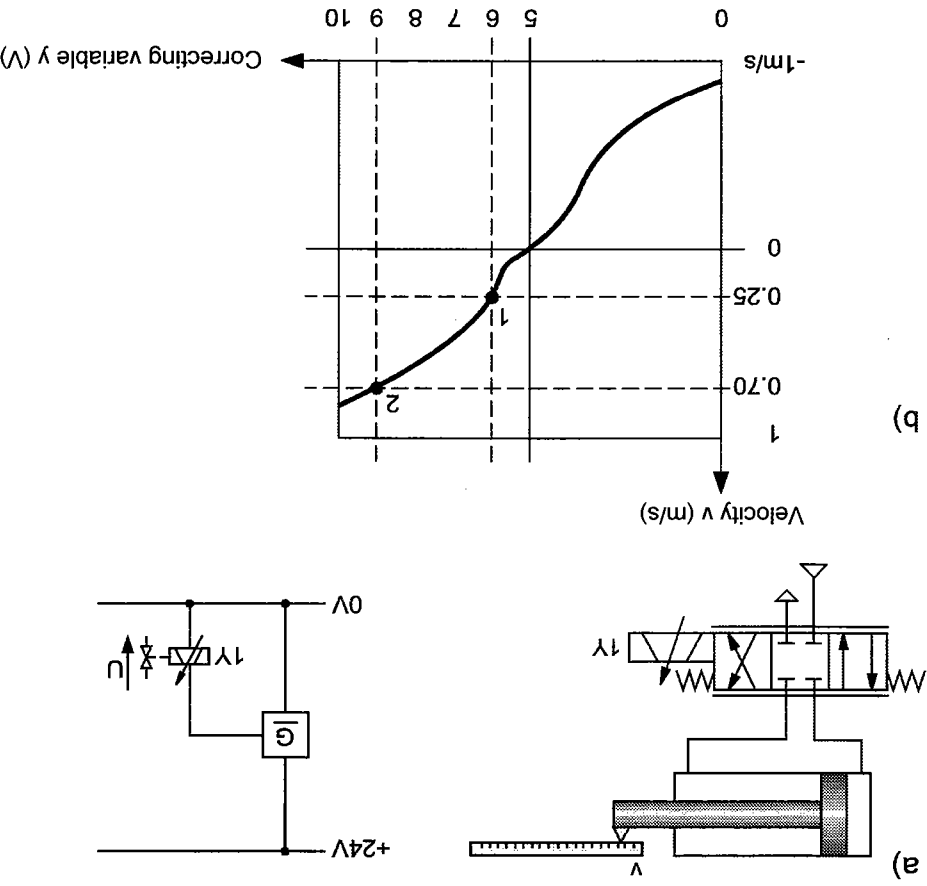


Fig. B2.10:
Step response behaviour of
controlled systems

2.8 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. B2.11:
Steady state characteristic
for a pneumatic 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. B2.11b).

Operating point

Each velocity is assigned a valve operating point. For a velocity of 0.25 m/s, the operating point is at 6 V, while for a velocity of 0.7 m/s it is at 9 V.

Controlled-system gain KS

The gain factor KS of a controlled system with compensation is defined as follows:

$$K_S = \frac{\text{Change in output signal}}{\text{Change in controlled variable}} = \frac{\text{Change in input signal}}{\text{Change in correcting variable}} = \frac{\Delta y}{\Delta x}$$

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. B2.11b. 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
pneumatic actuator

pneumatic actuator	Operating point 1	Operating point 2
Correcting variable 1	6 V	9 V
Correcting variable 2	6.2 V	9.2 V
Change in correcting variable	0.2 V	0.2 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	$\frac{0.04 \frac{m}{s}}{0.2 V} = \frac{0.2 m}{s} \text{ (sv)}$	$\frac{0.02 \frac{m}{s}}{0.2 V} = \frac{0.1 m}{s} \text{ (sv)}$

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. B2.11b, 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 .

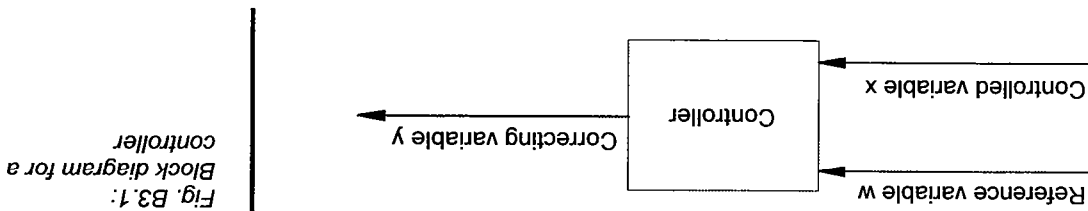


Fig. B3.1:
Block diagram for a
controller

Dynamic and non-dynamic controllers

Controllers are divided into two different classes:

- Non-dynamic controllers (alternative title: switching controllers)
- Dynamic controllers

The properties 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
Pneumatic valve type	Switching valve	Dynamic valve
Advantage	Less expensive	Better control quality

Tabelle B3.1:
Stetige und
unstetige Regler

Table B3.2:
Pneumatic controller
structures

Non-dynamic controllers		Dynamic controllers	
Two-step-action controllers	P controllers	Standard controllers	Status controllers
Three-step-action controllers	I controllers		
Multi-step-action controllers	PD controllers		
	PID controllers		

Both dynamic and non-dynamic controllers have a variety of controller structures. The most important controller structures used in pneumatics are summarised in the table below.

3.1 Two-step-action controller

The correcting variable of a two-step-action controller can assume two different values.

Example of application

- A compressed-air reservoir is filled via a switching valve:
 - If the pressure in the reservoir lies below the pressure setpoint value, the switching valve is opened.
 - When the pressure in the reservoir has reached the pressure setpoint value, the switching valve is closed.

Two-step-action controller with switching difference

In order to prevent the two-step-action controller from switching backwards and forwards too often, a controller is used which has different switch-on and switch-off values. The difference between these two values is known as the switching difference. The switching difference influences the control behaviour:

- If we wish the controller to switch as little as possible, a large switching difference should be selected (Fig. B3.2a).

- If, on the other hand, it is important to keep the deviation between the setpoint and actual value as small as possible, there must be only a small difference between the switch-on and switch-off values (Fig. B3.2b).

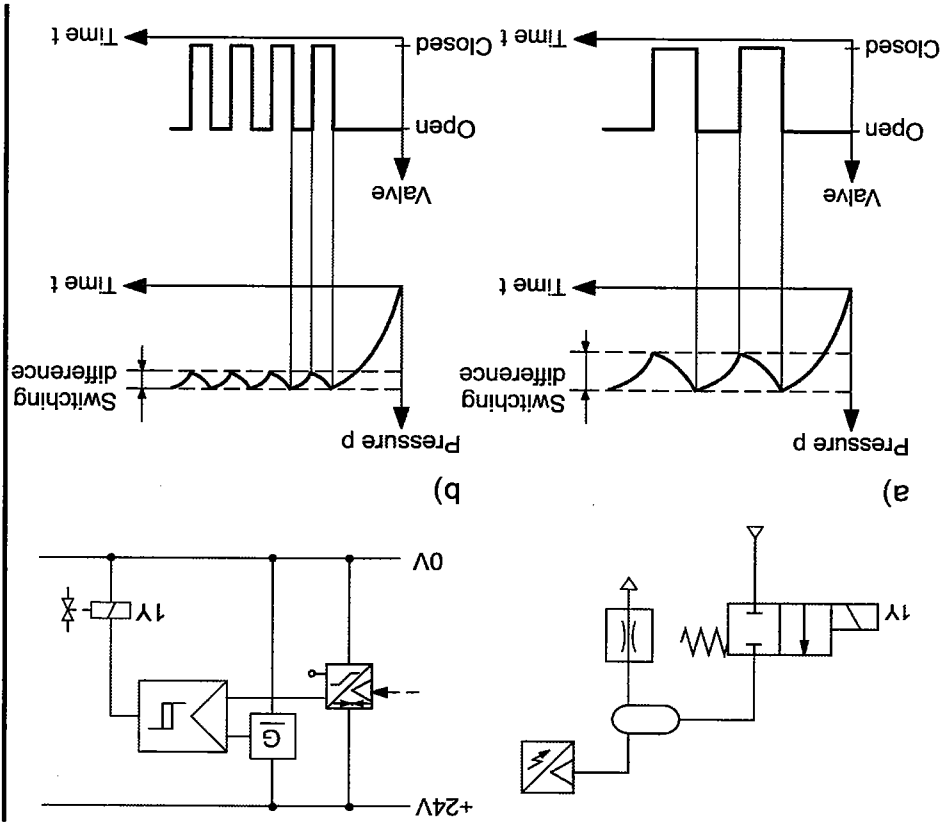


Fig. B3.2:
Pressure control
two-step-action controller

3.2 Three-step-action controller

The correcting variable of a three-step-action controller can assume three different values.

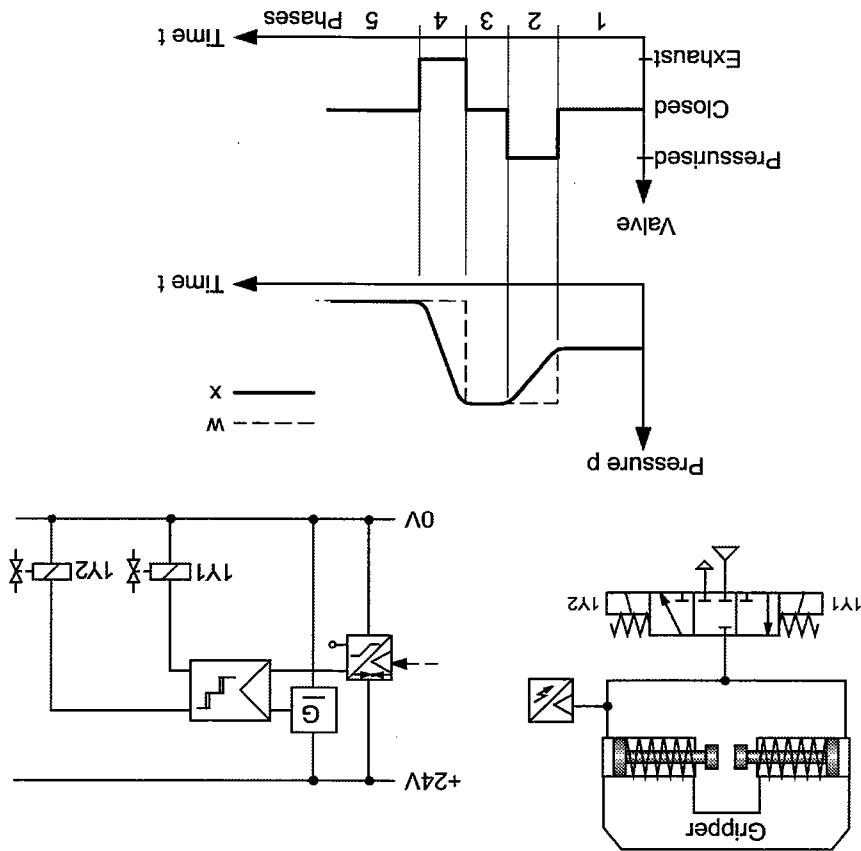
Example of application

Fig. B3.3 shows a pneumatic gripper with a closed-loop control system. The gripping force is varied by increasing or decreasing the pressure in the actuating cylinders. Three switching positions are required to achieve pressure control. Fig. B3.3 shows a control operation.

- If the reference variable and controlled variable are the same, the valve is closed (phases 1, 3 and 5).
- If the reference variable is higher than the controlled variable, the gripper is fed with compressed air via a 3/3-way valve (phase 2).
- If the controlled variable is higher than the reference variable, the gripper is exhausted via the 3/3-way valve (phase 4).

A type of controller suitable for this application is known as a three-step-action controller, due to the fact that it has three different correcting variable values. The frequency with which a three-step-action controller switches can be reduced by using a controller with a switching difference.

Fig. B3.3:
Pressure control with
three-step-action controller



3.3 Multi-step-action controller

In the case of a multi-step-action controller, the correcting variable can assume more than three different values. The number of different correcting variable values determines the exact name used (e.g. four-step-action controller, five-step-action controller).

The greater the number of switching positions a controller has, the higher the control quality which can be achieved.

This means: It is possible to achieve either a smaller steady-state system deviation or a higher reaction speed for the closed-loop control circuit.

Example of application

Fig. B3.4 shows a closed-loop pressure control circuit for a gripper. The controller is able to set five correcting variable values. The gripper is pressurised and exhausted via two 5/3-way switching valves. There is the following relationship between the system deviation and the correcting variable:

Phase 1: The value of the reference variable is considerably higher than the value of the controlled variable. This means a large positive system deviation. The gripper is pressurised via both switching valves.

Phase 2: The system deviation has become smaller but is still positive. The gripper is pressurised via one switching valve.

Phase 3: The system is very small. Both switching valves are closed.

Phase 4: The system deviation is negative. The value of the system deviation is large. The gripper is exhausted via both switching valves.

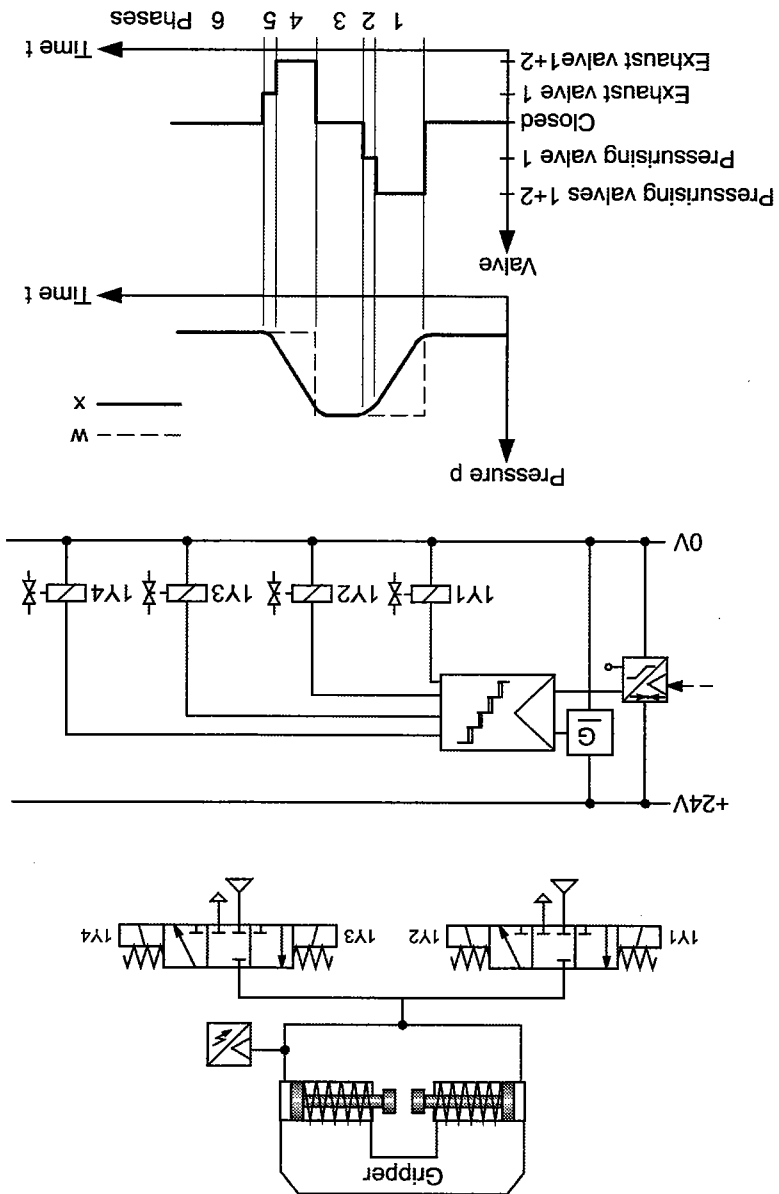
Phase 5: The system deviation is still negative. The value of the system deviation has become smaller. The gripper is exhausted via one switching valve.

Phase 6: The system deviation is very small. Both switching valves are closed.

In comparison with a three-step-action controller (Fig. B3.3), a five-step-action controller offers the following advantage for this application:

The energisation of the second switching valve allows fast compensation for a large system deviation.

Fig. B3.4:
Pressure control with
a five-step-action controller
and two 5/3-way valves



3.4 Block diagrams for non-dynamic controllers

Two-step-action, three-step-action and multi-step-action 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 variable 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.

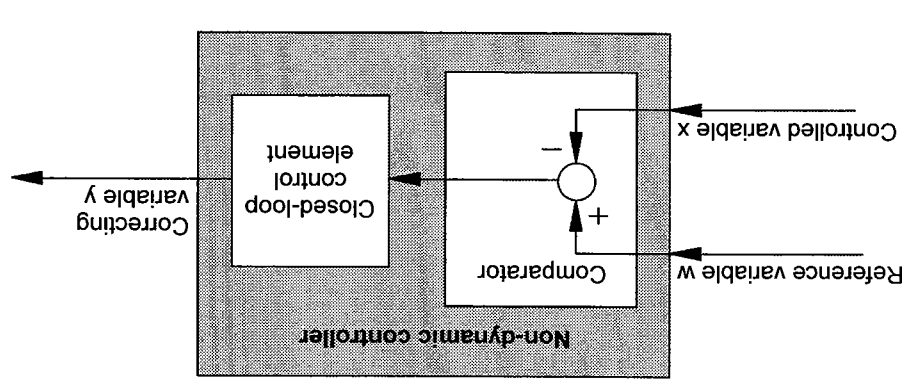


Fig. B3.5:
Signal flow diagram for a
non-dynamic controller

Block diagram of a closed-loop control element

- Fig. B3.6 shows the relationship between signal curves, the characteristic for the closed-loop control element and the block diagram. A two-step-action controller with switching difference is taken as an example.
- Fig. B3.6a shows the curve for the reference variable and the controlled variable as a function of time.
 - Fig. B3.6b shows the system deviation, i.e. the difference between the reference variable and the controlled variable. This forms the input signal for the closed-loop control element.
 - Fig. B3.6c shows the correcting variable. This forms the output signal of the closed-loop control element.

In order to construct the characteristic for the closed-loop control element (Fig. B3.5d), the following variables are used:

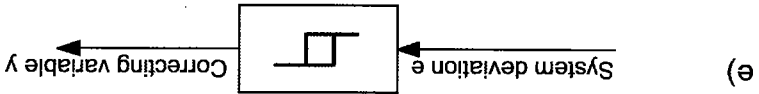
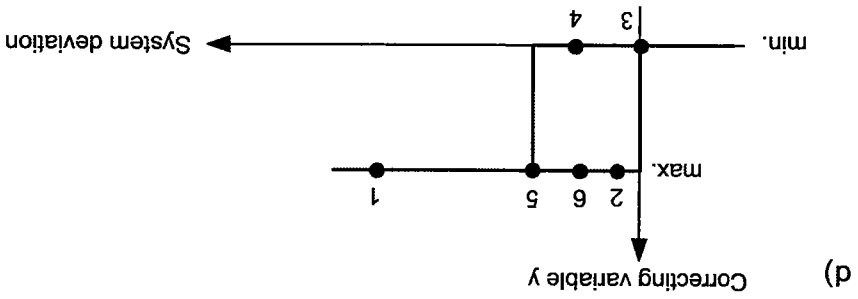
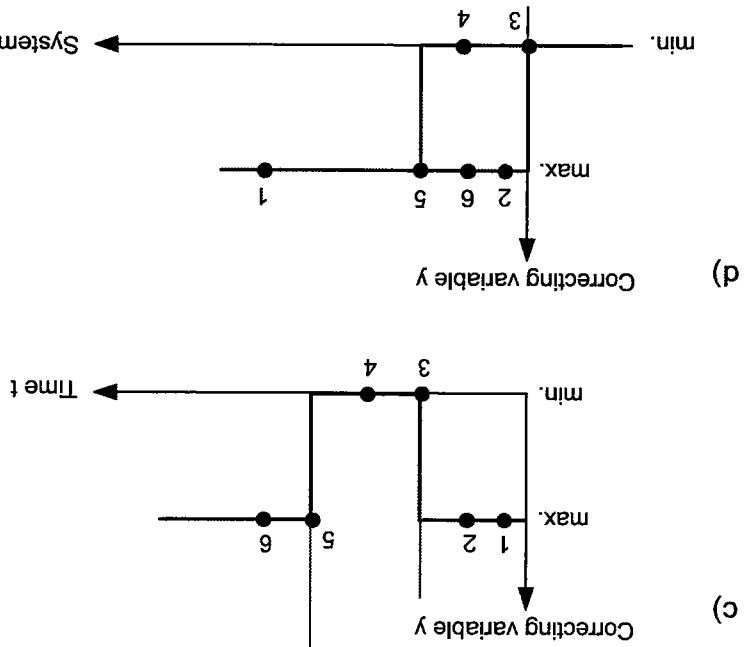
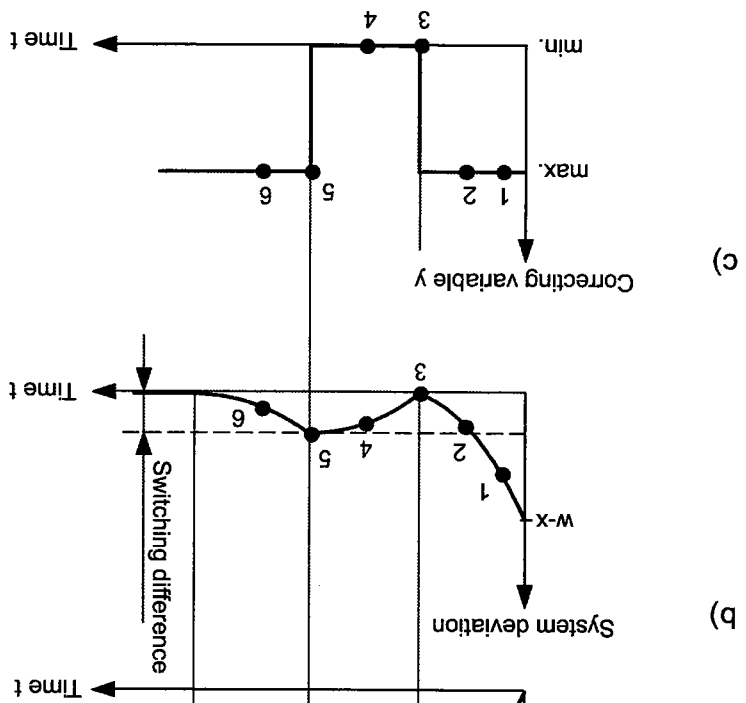
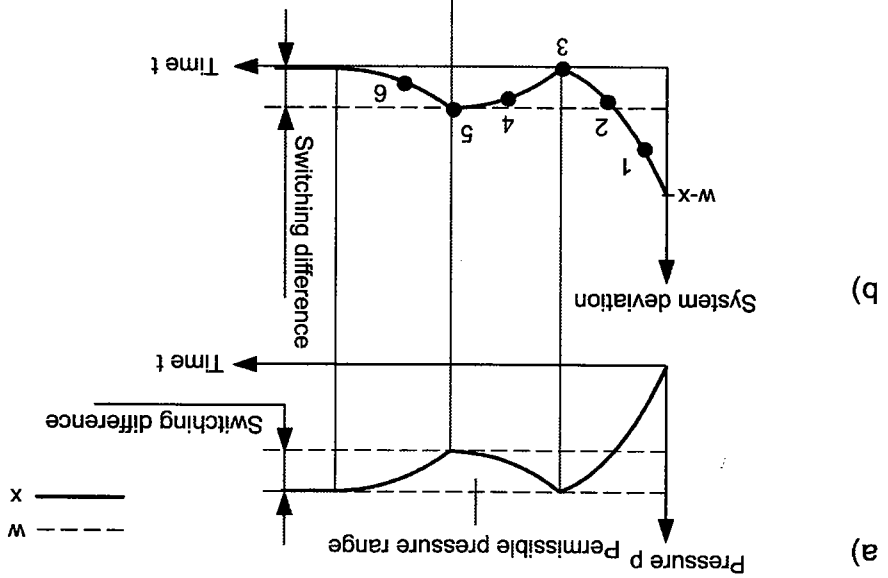
- The system deviation, i.e. the input signal of the closed-loop control element, in the horizontal direction
- The correcting variable, i.e. the output signal of the closed-loop control element, in the vertical direction

Following this, the measured values from Figs. B3.6b and B3.6c are plotted in Fig. B3.6d point by point:

- At time interval 1, the system deviation is positive. The valve is open.
- At time interval 2, the system deviation is still positive and the valve remains open.
- At time interval 3, the system deviation is zero and the valve closes.
- At time interval 4, the switching threshold has not yet been reached. The valve remains closed.
- At time interval 5, the system deviation is greater than the specified switching threshold. The valve opens again.
- At time interval 6, the system deviation is positive and the valve opens.

The resulting characteristic is plotted in the block diagram for the two-step-action closed-loop control element (Fig. B3.6e).

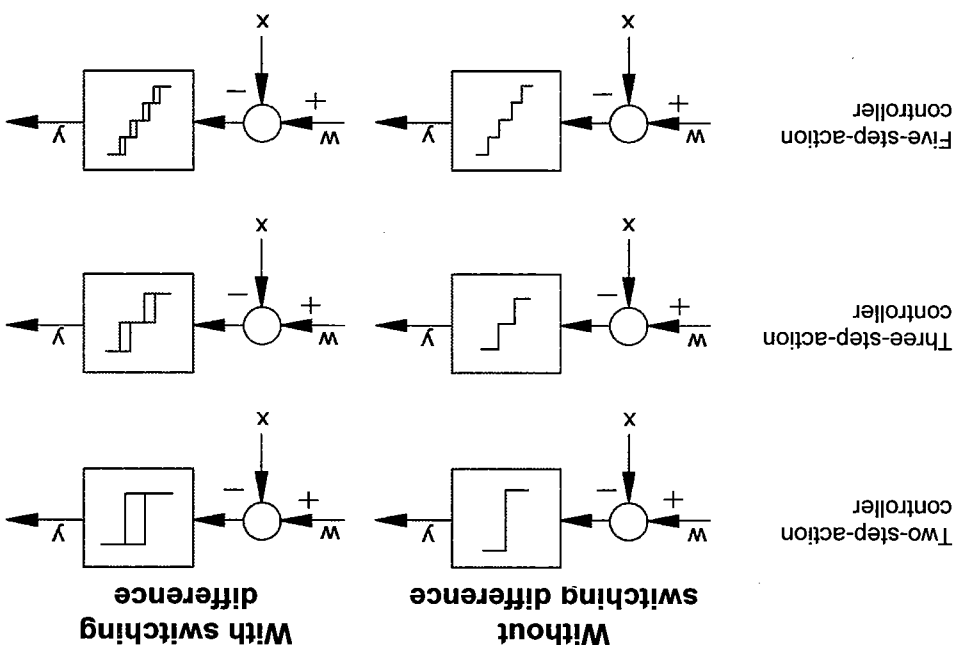
Fig. B3.6:
Signal curve, characteristic
and block diagram for a
two-step-action controller
with switching difference



Block diagrams for non-dynamic controllers

Fig. B3.7 shows block diagrams for various non-dynamic controllers. In the case of a controller with switching difference, two different characteristic branches are described for a rising and falling system deviation respectively.

Fig. B3.7:
Block diagrams for
non-dynamic controllers



3.5 P controller

Proportional-action 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 shows a closed-loop speed control circuit with a proportional-action controller (P controller). When the reference variable executes a step change, the closed-loop control circuit reacts as follows:

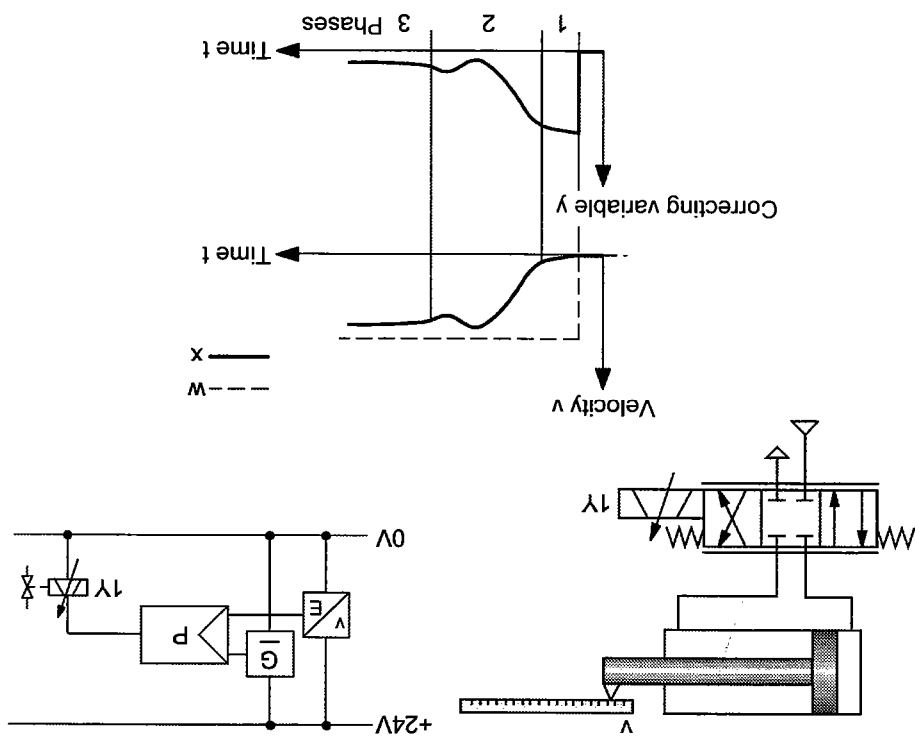
Phase 1: The system deviation is very large. The valve is wide open.

Phase 2: The system deviation becomes smaller. The correcting variable and the valve opening accordingly also become smaller.

Phase 3: The system deviation, the correcting variable and thus also the valve opening are constant.

As this example shows, a steady-state system deviation results with a combination of a controlled system with compensation and a P controller.

Fig. B3.8:
Speed control with a proportional-action controller



Transition function of P closed-loop control element

If the system deviation executes a step change with a proportional-action controller, the controller reacts with a step change in the correcting variable. Figs. B3.9b and B3.9c show two transition functions for proportional-action controllers with different proportional-action coefficients

Equation for P closed-loop control element

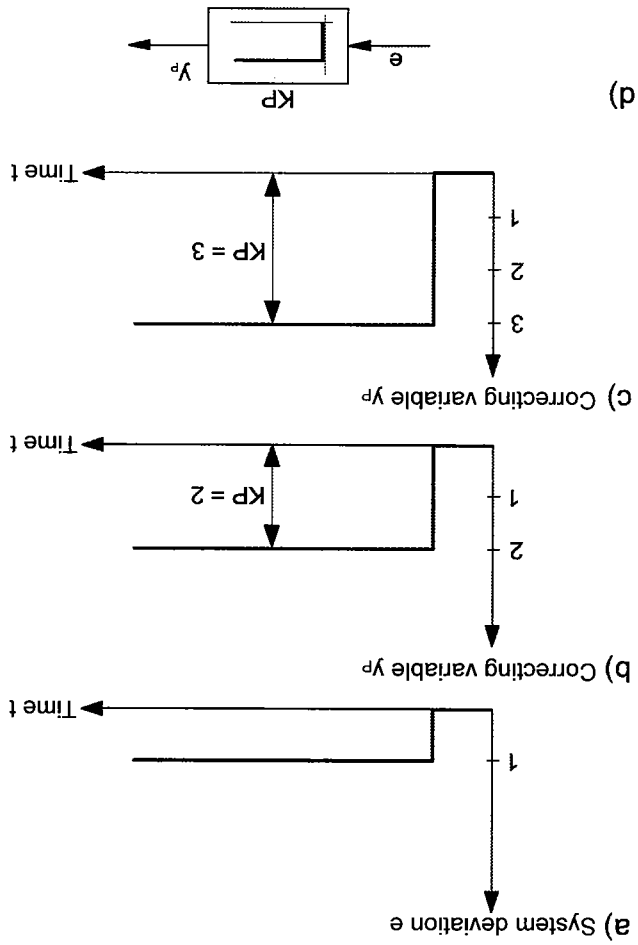
The correcting variable y with a proportional-action controller is calculated in accordance with the following equation:

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

K_P is known as the proportional-action coefficient or the proportional gain. The correcting variable of a P controller becomes greater

- the higher the proportional gain K_P and
- the larger the system deviation e

Fig. B3.9:
Transition functions for
two P controllers with differ-
ent controller coefficients



3.6 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. B3.10 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. B3.8), no steady-state system deviation occurs in a closed-loop control circuit with an integral-action controller.

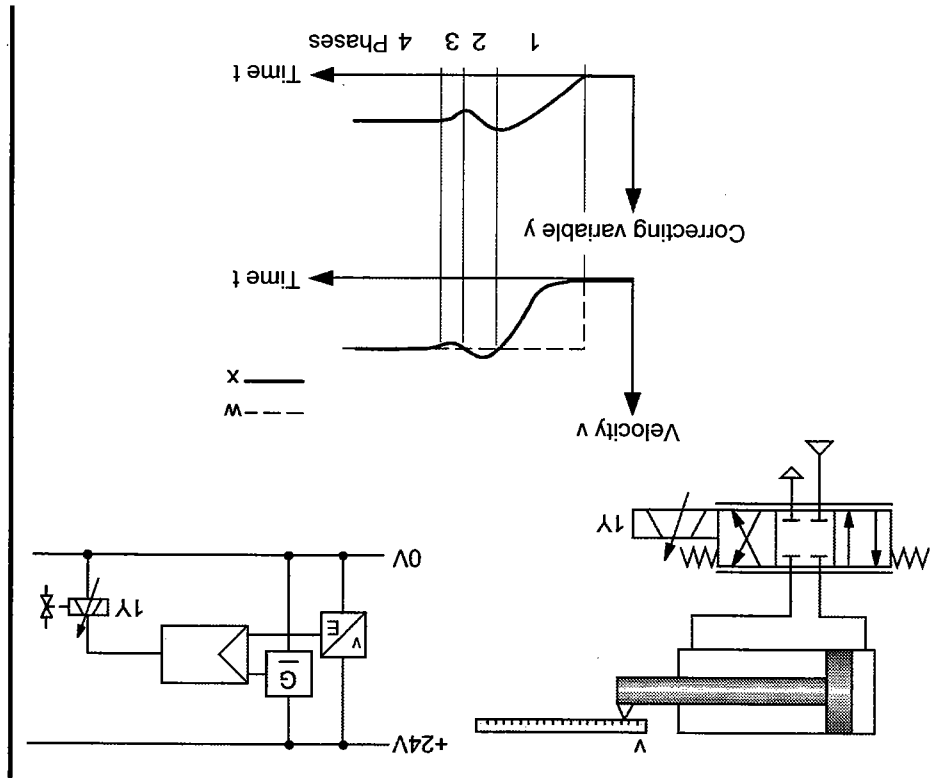


Fig. B3.10:
Speed control with integral-
action controller

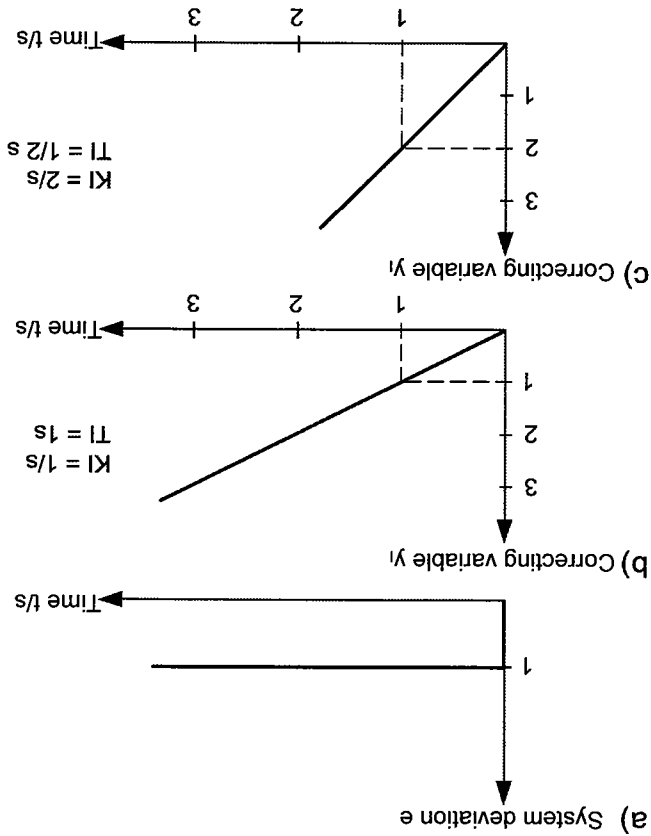
Transition function of I closed-loop control element

When the system deviation executes a step change, the correcting signal exhibits a ramp change. The gradient is higher

- the greater the system deviation
- the higher the controller gain K_I or
- the smaller the time constant T_I

Figs. B3.11b and B3.11c show the transition functions for two integral-action closed-loop control elements with different controller gain values or time constants.

Fig. B3.11:
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 coefficient of the integral-action controller.

3.7 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.

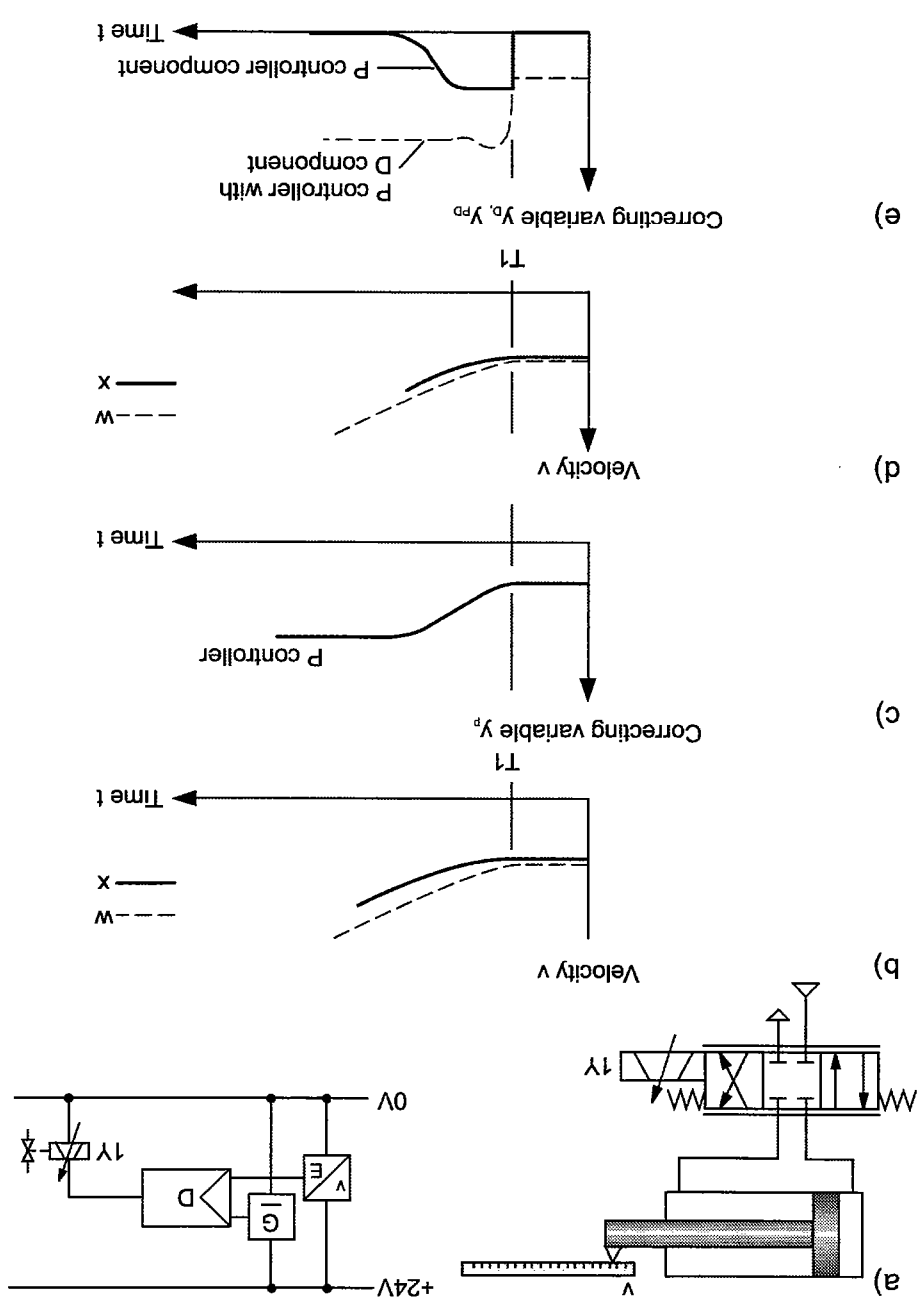
Example of application

Fig. B3.12 shows a closed-loop speed control circuit for a pneumatic 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. B3.12b shows the behaviour of the closed-loop control circuit with a P controller. Fig. B3.12c 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. B3.12d 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 (Fig. B3.12e) 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. B3.12d).

Fig. B3.12:
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 K_D
- the steeper the gradient of the increase in the system deviation

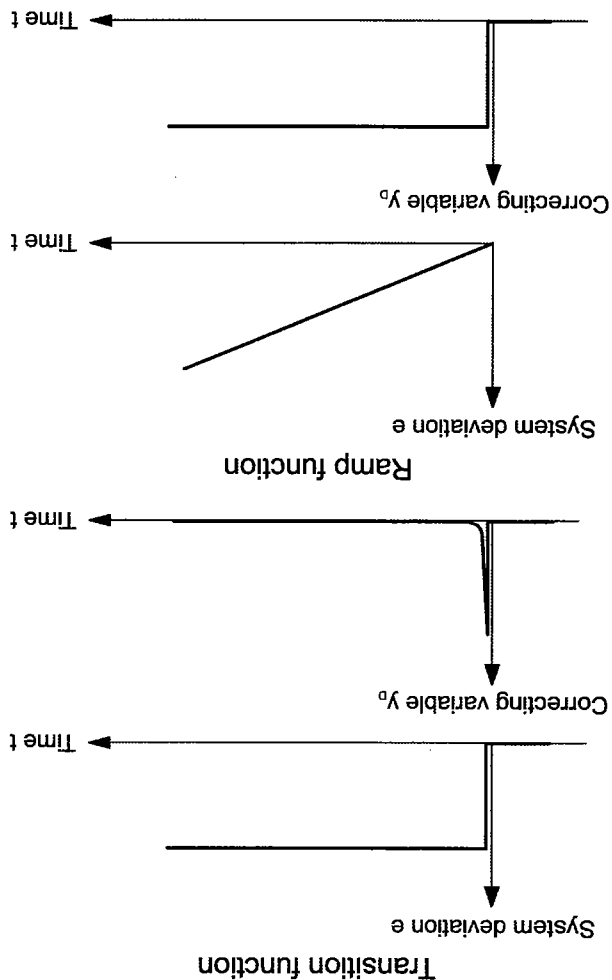


Fig. B3.13:
Transition and ramp
functions of D controller
component

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.

3.8 PI, PD and PID controllers

Table 3.2 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 con- trol 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.

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

Table B3.4:
Properties of PI, PD and PID controllers

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 K_P and the integral-action coefficient K_I
- or by the proportional-action coefficient K_P and the integral-action time T_n

Integral-action time

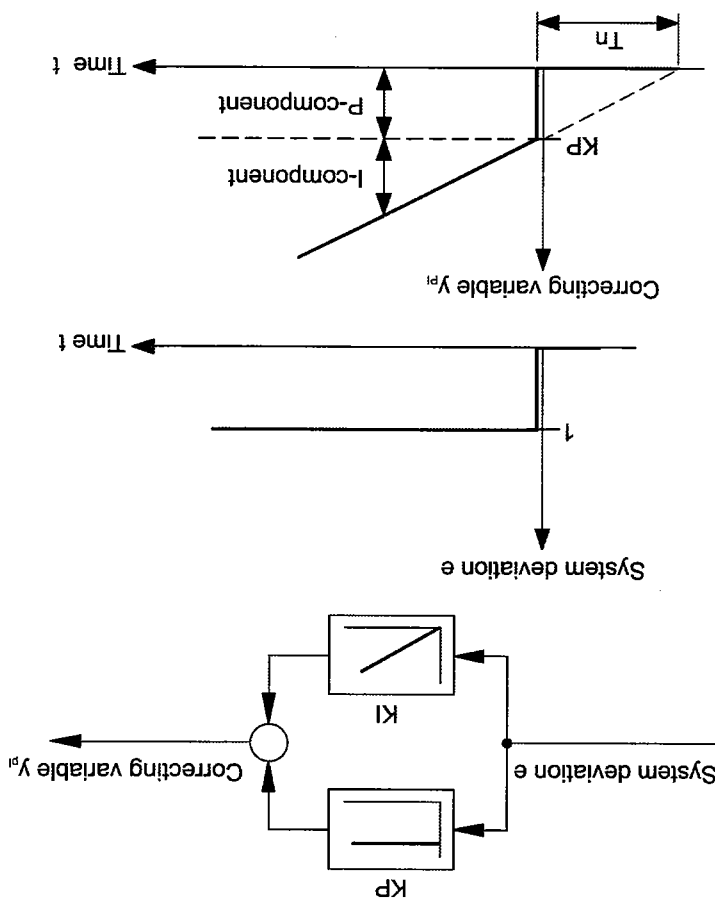
The integral-action time T_n can be calculated from the proportional-action coefficient K_P and the integral-action coefficient K_I , using the following formula:

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

Transition function of PI closed-loop control element

The transition function of a PI controller is shown in Fig. B3.14. 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 K_P and integral-action time T_n can be read from the transition function.

Fig. B3.14:
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:

$$y = K_P (w - x) + K_I \cdot \int (w - x) \, dt = K_P \cdot e + K_I \cdot \int e \, dt$$

$$y = K_P (w - x) + \frac{1}{T_N} \cdot \int (w - x) \, dt = K_P (e + \frac{1}{T_N} \int e \, dt)$$

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. B3.15).

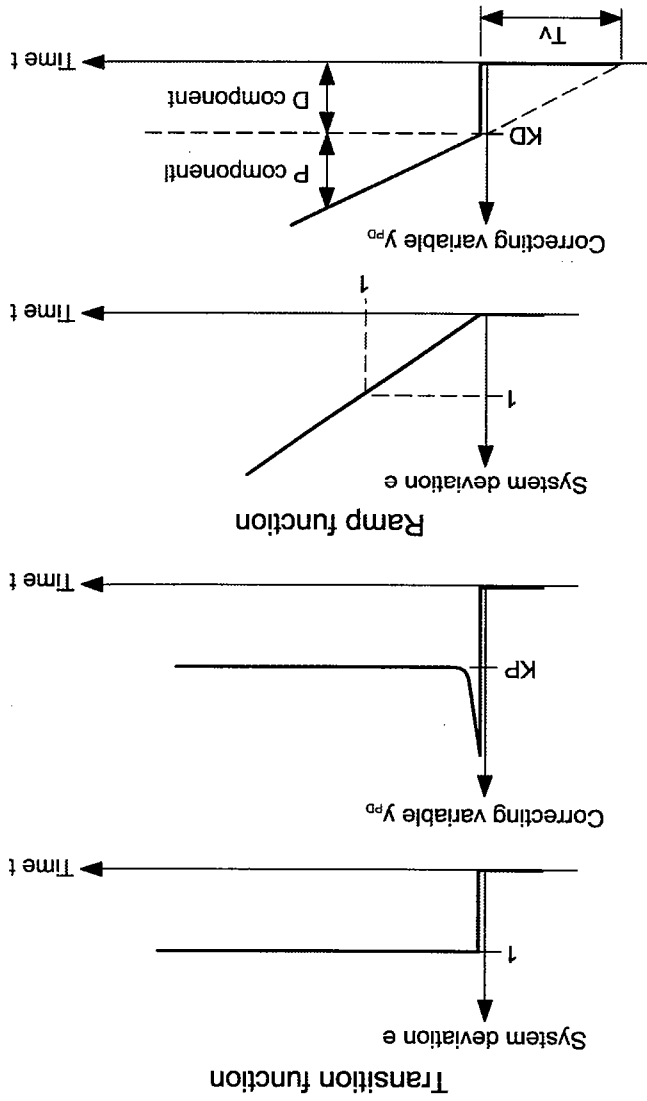
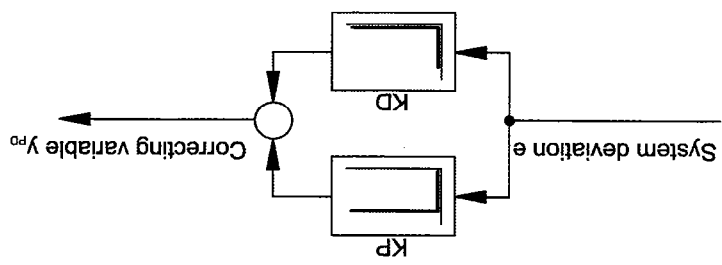


Fig. B3.15:
Signal flow diagram,
transition and ramp
functions for PD controller

The behaviour of a PD controller is determined by two characteristic variables:

- Either by the proportional-action coefficient K_P and the derivative-action coefficient K_D
- or by the proportional-action coefficient K_P and the derivative-action time T_v

Derivative-action time T_v

There is the following relationship between the derivative-action time T_v , the proportional-action coefficient K_P and the derivative-action coefficient K_D :

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

Transition and ramp functions of PD controller

The transition and ramp functions of a PD controller are shown in Fig. B3.15:

- The proportional-action coefficient K_P can be read from the transition function.

- The derivative-action coefficient K_D and the derivative-action time T_v 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:

$$y = K_P (w - x) + K_D \cdot \frac{d}{dt} (w - x) = K_P \cdot e + K_D \cdot \frac{d}{dt} e$$

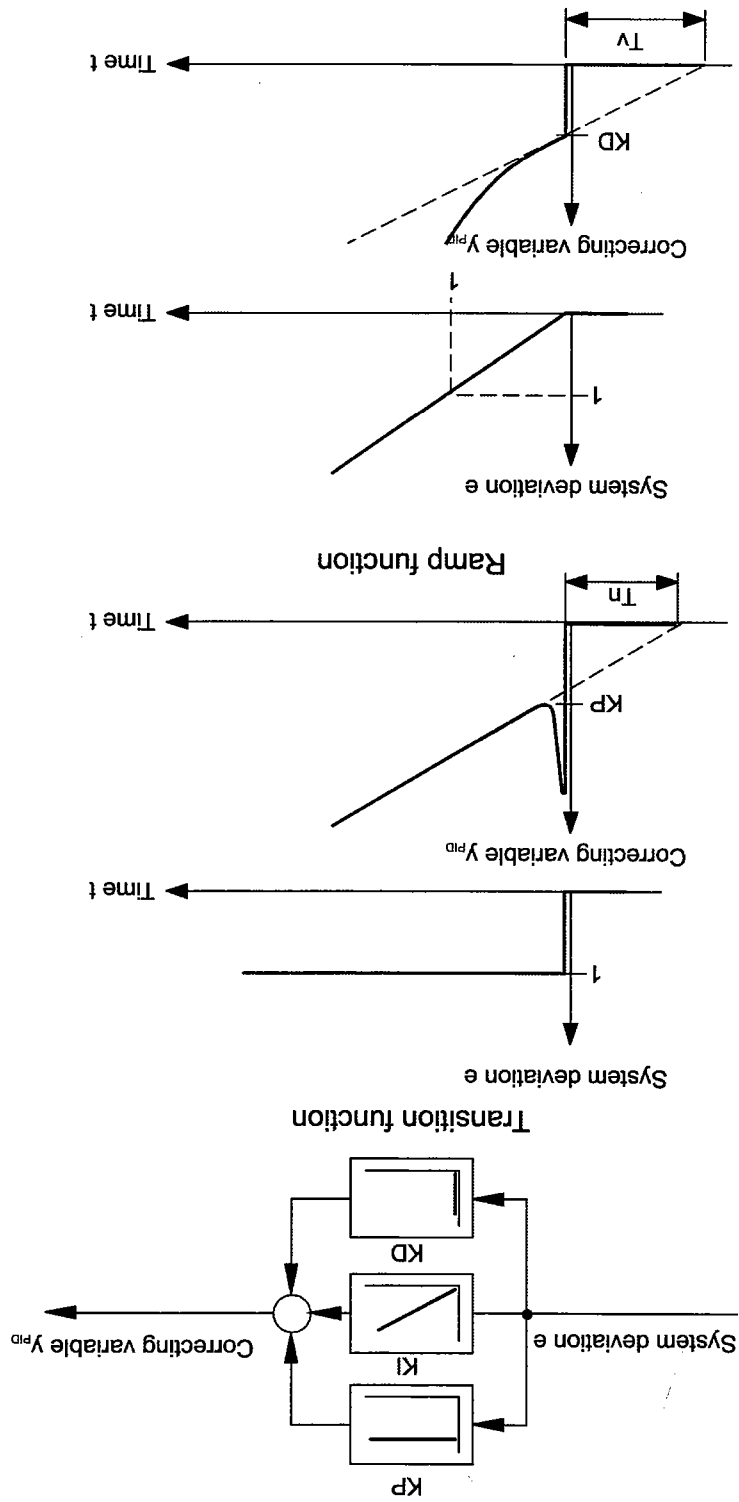
$$y = K_P (w - x + T_v \cdot \frac{d}{dt} (w - x)) = K_P (e + T_v \cdot \frac{d}{dt} e)$$

PID controller

A PID controller combines the advantages of P, I and D controllers. Fig. B3.16 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 (K_P , K_I and K_D)
- or by the proportional gain, the derivative-action time and the integral-action time (K_P , T_v and T_n).

Fig. B3.16:
Signal flow diagram,
transition and ramp
functions for PID controller



Derivative-action time T_v and integral-action time T_n

The derivative-action time and integral-action time are governed by the same formulae as for the PI and PD controllers:

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

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

Transition and ramp functions of PID closed-loop control element

- Fig. B3.16 shows the transition and ramp functions of the PID controller:

- The proportional-action coefficient K_P and the integral-action time T_n can be read from the transition function.

- The derivative-action coefficient K_D and the derivative-action time T_v can be read from the ramp function.

Equations for PID closed-loop control element

The following equations are used to calculate the correcting variable:

$$y = K_P (w - x) + K_I \cdot \int (w - x) dt + K_D \cdot \frac{d}{dt} (w - x)$$

$$= K_P \cdot e + K_I \cdot \int e dt + K_D \frac{d}{dt} e$$

or

$$y = K_P (w - x) + \frac{T_n}{\int (w - x) dt} + T_v \cdot \frac{d}{dt} (w - x) = K_P (e) + \frac{T_n}{\int e dt} + T_v \frac{d}{dt} (e)$$

3.9 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)

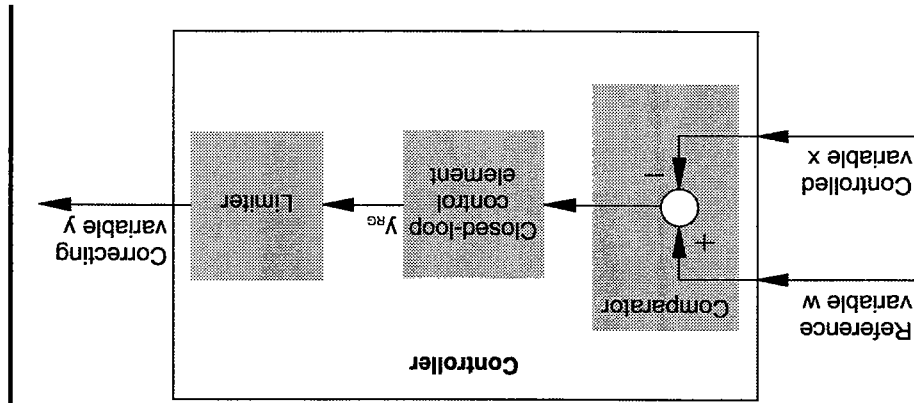


Fig. B3.17:
Signal flow diagram for a
standard dynamic controller

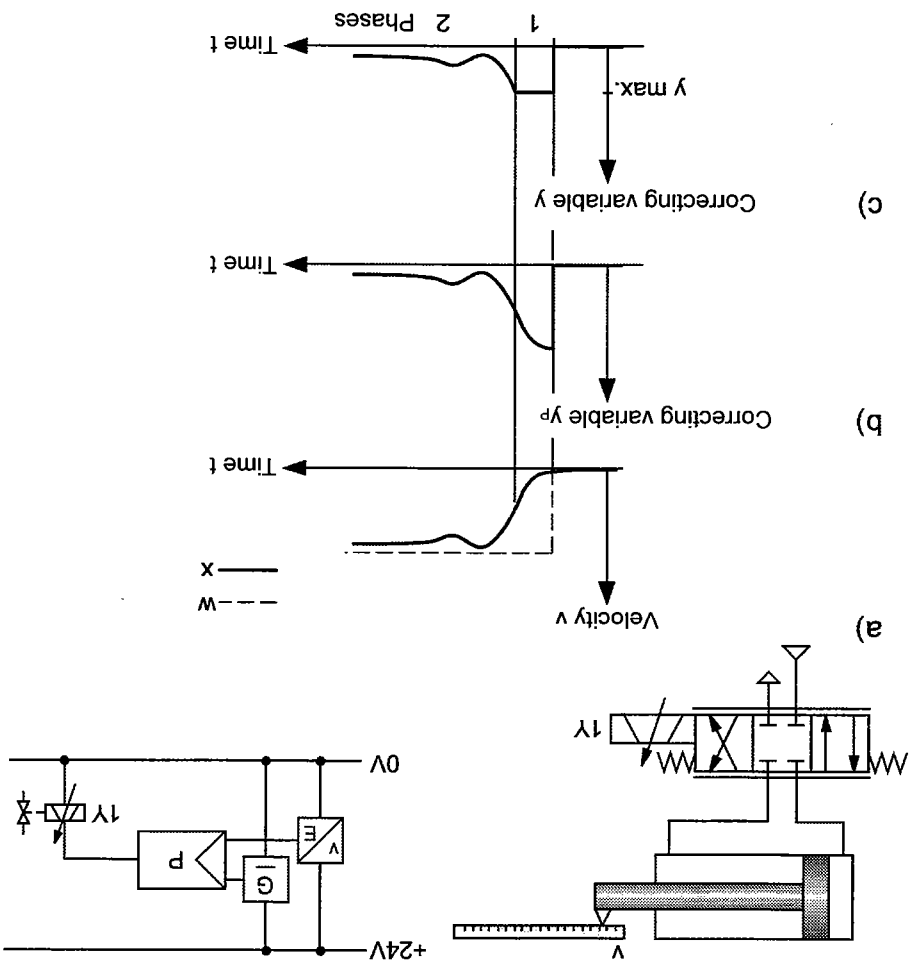
Example of application of correcting-signal limiter

Fig. B3.18 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 y_P generated by the closed-loop control element rises to a high value (Fig. B3.18b). The variable y_P 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. B3.18c).

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. B3.18b and B3.18c are the same.

Fig. B3.18:
Speed control with
correcting signal limitation

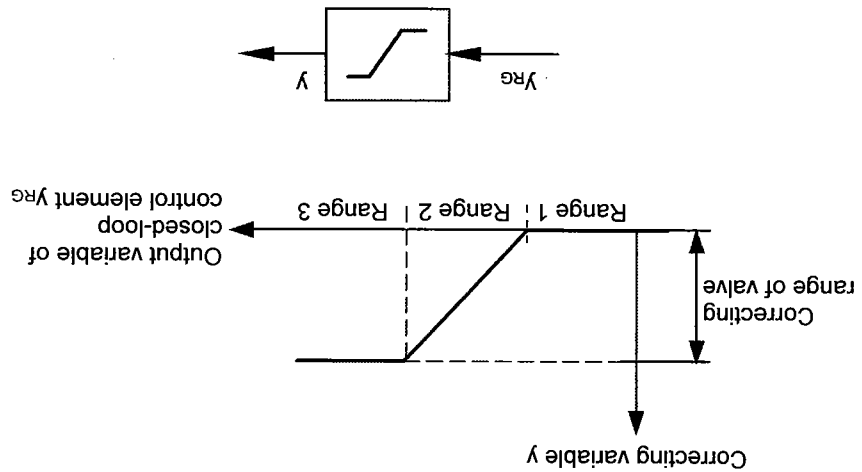


Characteristic for a limiter

The characteristic of a limiter is shown in Fig. B3.19. 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.

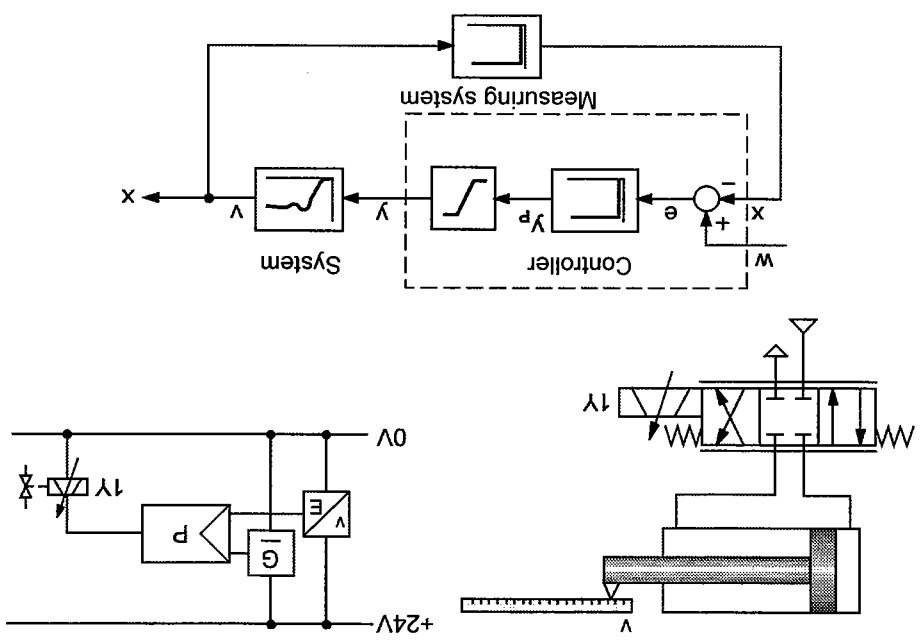
Fig. B3.19:
Characteristics and
block diagram for a
limiter



- Fig. B3.20 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. B3.20:
Closed-loop control circuit
with P controller



Block diagrams for dynamic controllers

Fig. B3.21 shows block diagrams for P, I, PI, PD and PID controllers.

Fig. B3.21:
Block diagrams for P, I, PI,
PD and PID controllers

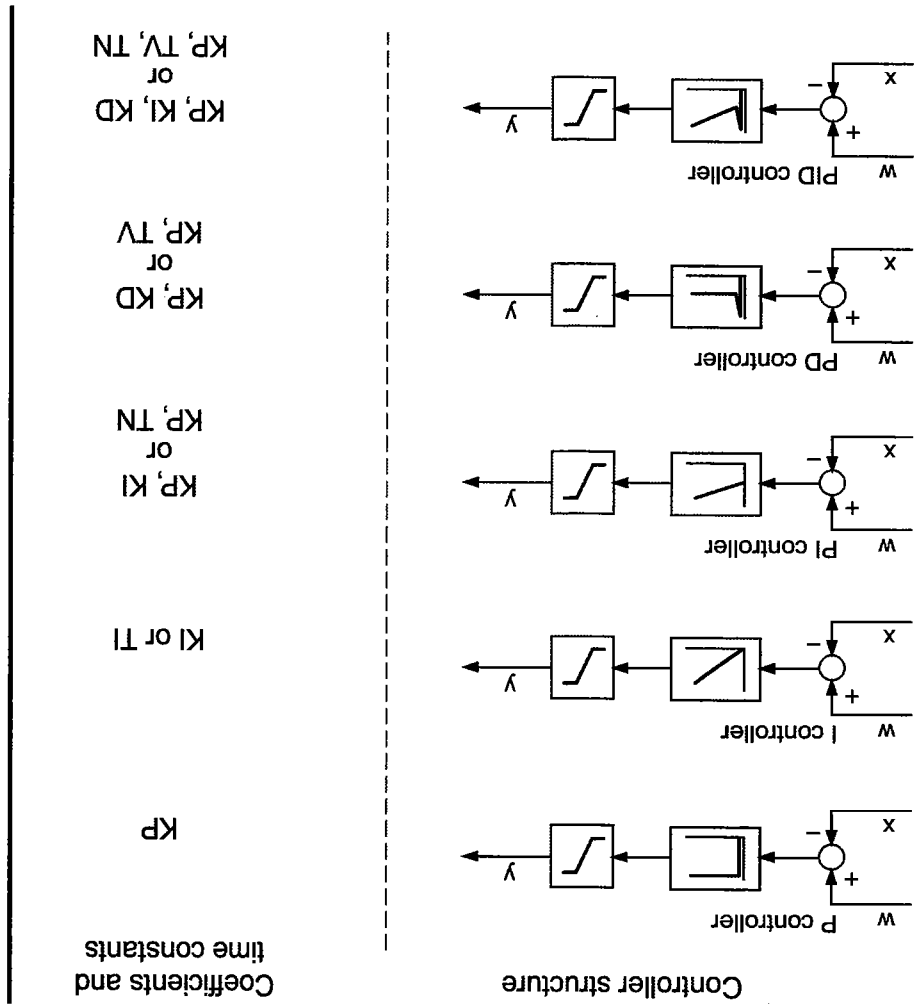


Table B3.4:
Controller coefficients and
time constants

Conversion of K_P , T_v , T_n to K_I , K_D	$K_I = \frac{T_n}{K_P}$	$K_D = K_P \cdot T_v$
Conversion of K_P , K_I , K_D to T_n , T_v	$T_n = \frac{K_I}{K_P}$	$T_v = \frac{K_D}{K_P}$

Conversion of controller parameters and controller time constants

PID controllers are usually distinguished by their proportional-action coefficient K_P and time constants T_v and T_n . 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.

3.10 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 pneumatic positioning actuator is one of the types of controlled systems which cannot be controlled adequately with a standard controller. A pneumatic positioning actuator is a controlled system without compensation which is capable of oscillation.

A third-order model will generally be selected for a pneumatic positioning actuator. It will then be necessary to loop back three variables in the status controller. The following three variables are generally selected:

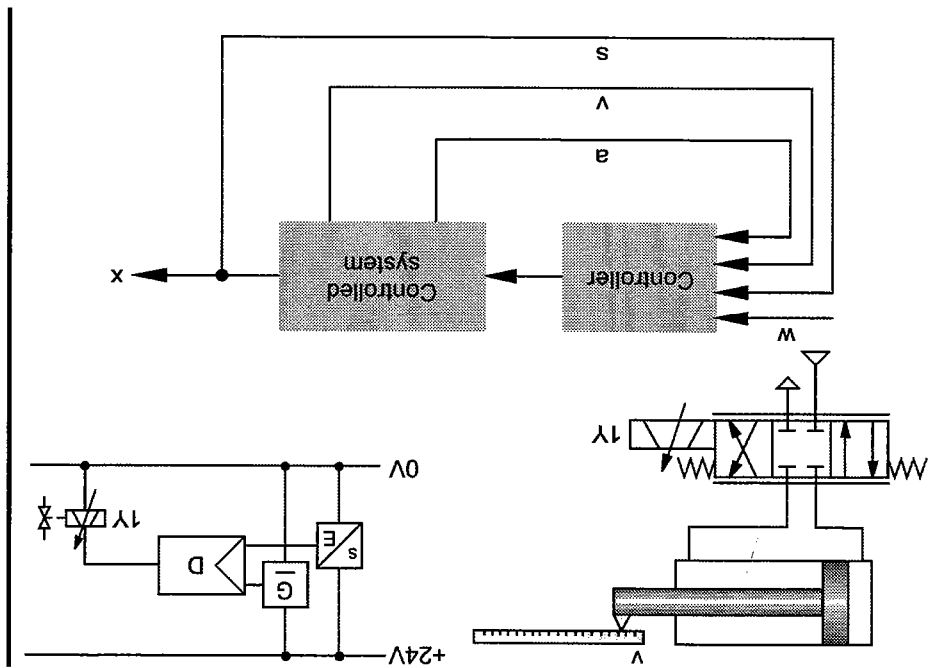
The position s of the piston

The velocity v of the piston

The acceleration a of the piston

The controller is accordingly known as a triple-loop controller.

Fig. 3.22:
Closed-loop control circuit
for a
pneumatic
positioning actuator



Differentiation

Pneumatic positioning actuators are equipped with a positional trans-

ducer. In order to reduce costs, the velocity and acceleration are not measured with sensors. These must be calculated from the position by differentia-

Controller equation

The following overall equation results for the calculation of the correcting variable:

$$y = KX (w - x) - K\dot{X} \cdot \frac{d}{dt} \frac{d}{dt} \frac{d^2x}{dt^2}$$

Fig. B3.23:
Signal flow diagram for
triple-loop
status controller

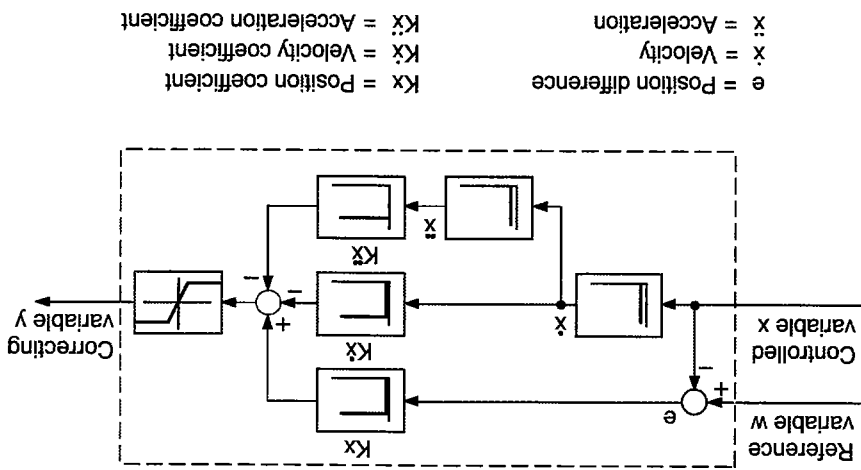


Fig. B3.23 shows the associated signal flow diagram.

3.11 Selection of controller structure

- The choice of controller structure depends on the type of controlled system concerned.
- Fig. B3.24 shows suitable controller structures for the various types of controlled systems with compensation.
- Fig. B3.25 provides a summary of suitable controllers for the various types of controlled systems without compensation.

Fig. B3.24:
Controller structures for
controlled systems
with compensation

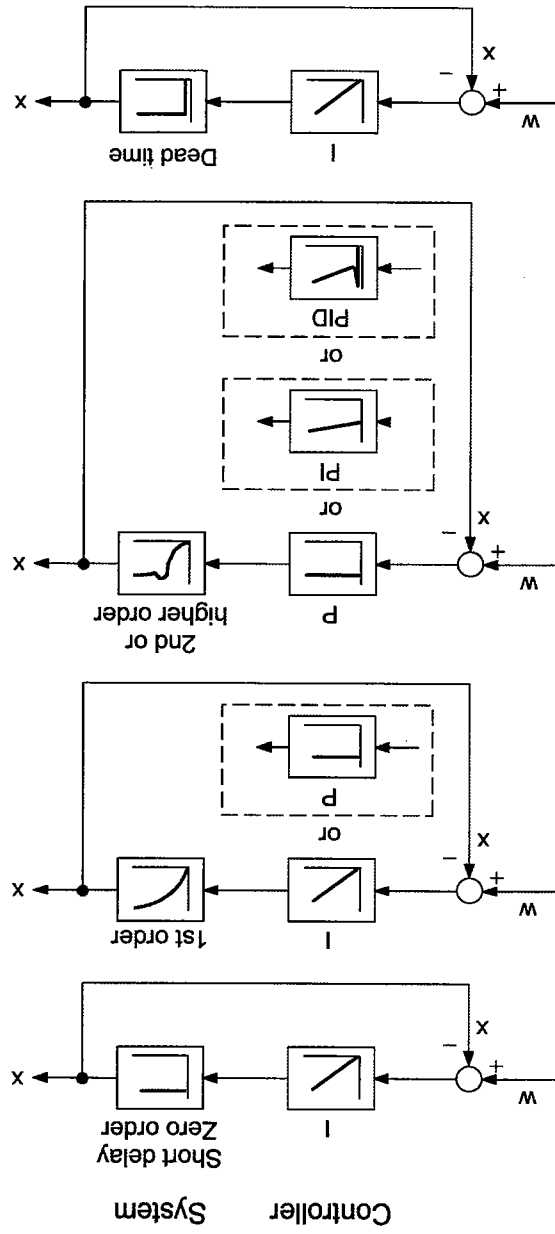
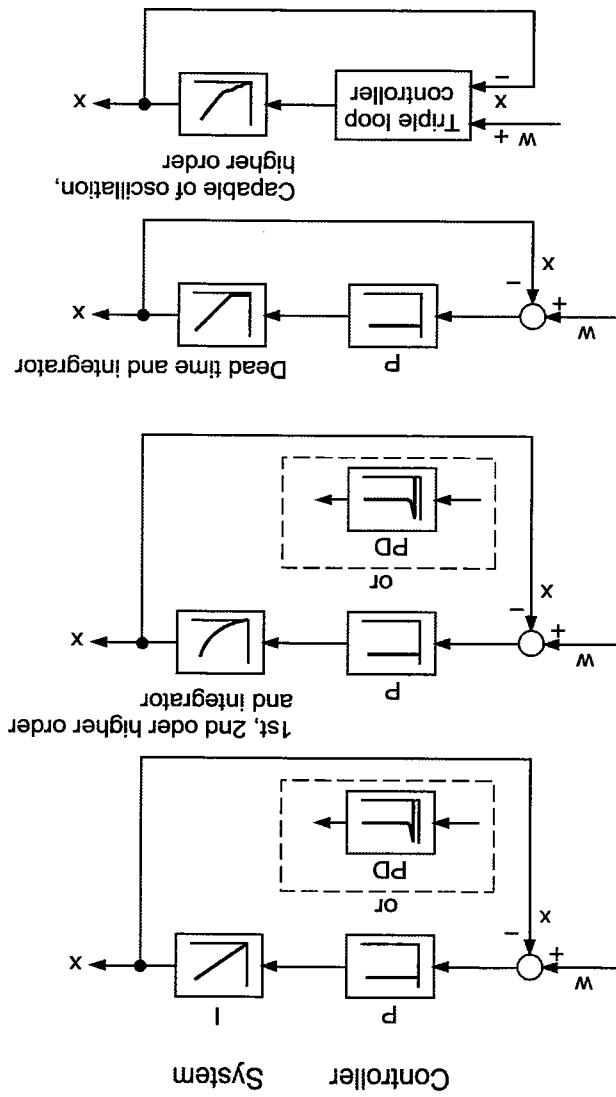


Fig. B3.25:
Controller structures for
controlled systems
without compensation



3.12 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.

Control factor =

Steady-state change in output variable (controlled variable) in closed control loop
 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. B3.26a shows a pneumatic open-loop control circuit. A constant velocity is produced with a constant correcting variable. This is a controlled system with compensation. In Fig. B3.26b, 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. B3.26:
Response to interference
of an open control loop

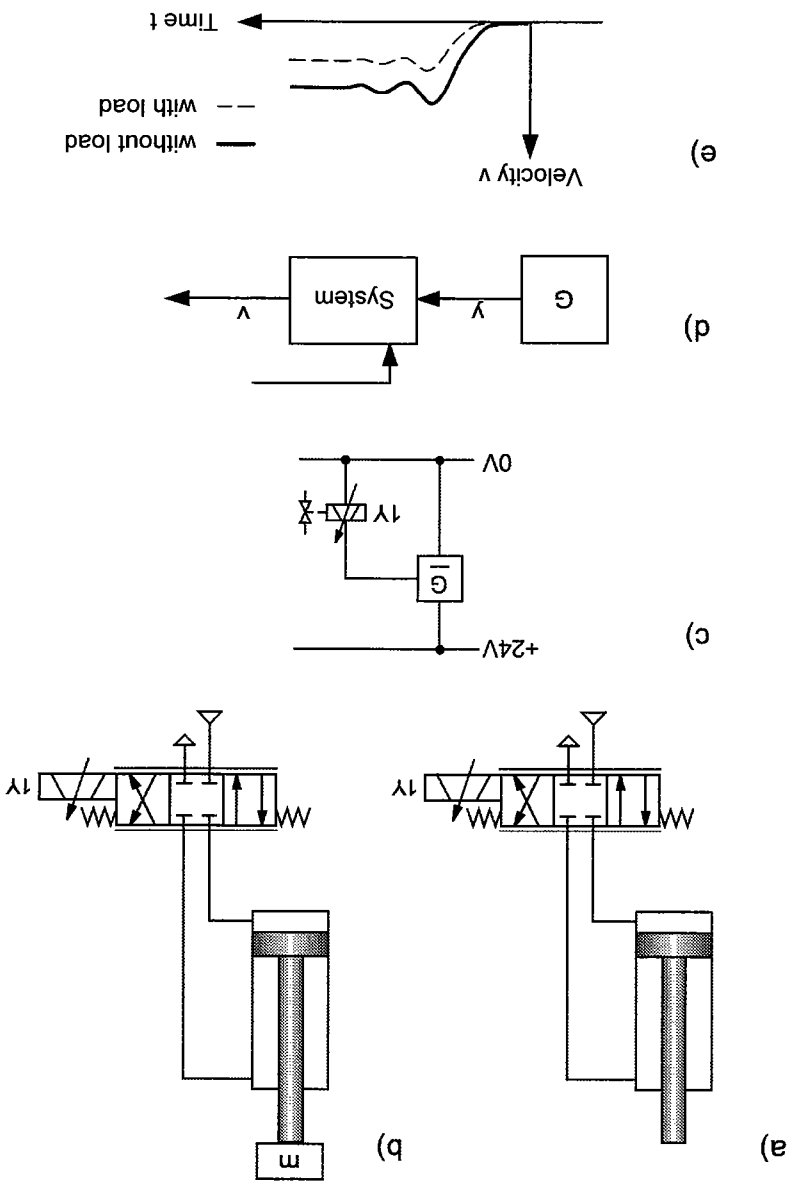
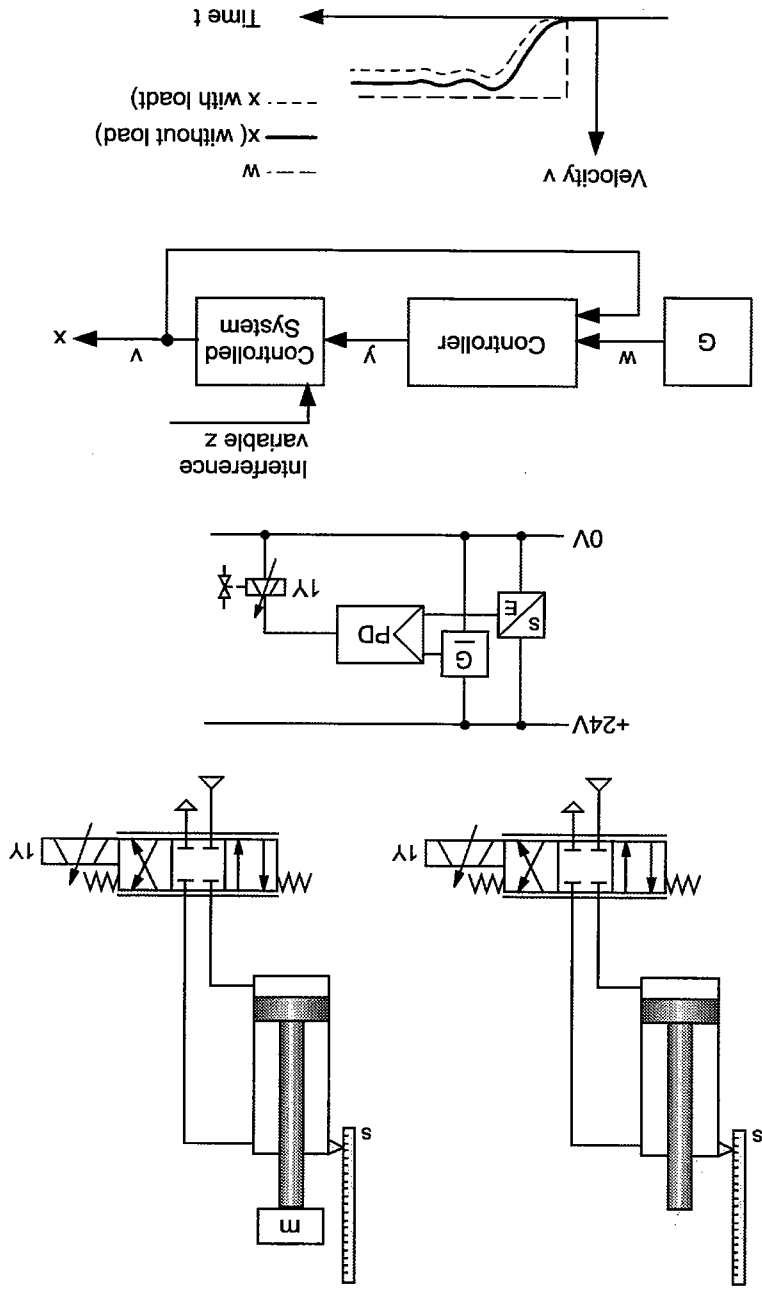


Fig. B3.27 shows a pneumatic actuator with closed-loop speed control. In the case of this actuator, too, the velocity is lower when the piston rod is subjected to a load. The reduction in velocity in the closed-loop control circuit is much smaller than the reduction in velocity in the open-loop control circuit. The response to interference of the closed-loop control circuit is significantly better.

Fig. B3.27:
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 K_P
- In the controlled system by the factor K_S
- In the measuring system by the factor K_{meas}

The formula for closed-loop gain is thus as follows:

$$V_0 = K_P \cdot K_S \cdot K_{meas}$$

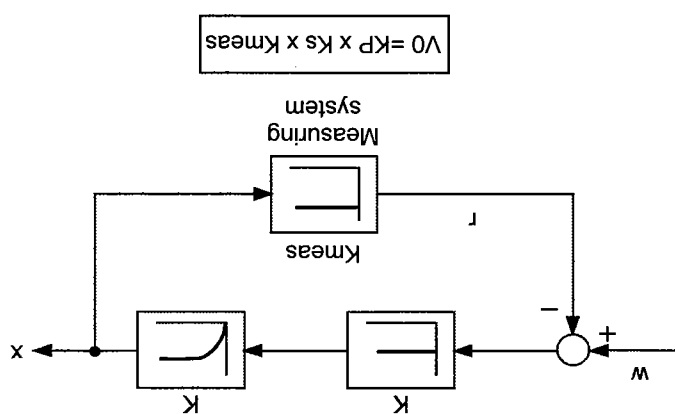


Fig. B3.28:
Calculation of
closed-loop gain

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 pneumatic actuator:

$$K_P = 1.5$$

$$K_S = \frac{0.2 \frac{m}{s}}{V}$$

$$K_{meas} = \frac{10 V}{\frac{m}{s}}$$

The closed-loop gain is thus:

$$V_0 = K_P \cdot K_S \cdot K_{meas} = 3$$

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 pneumatic 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

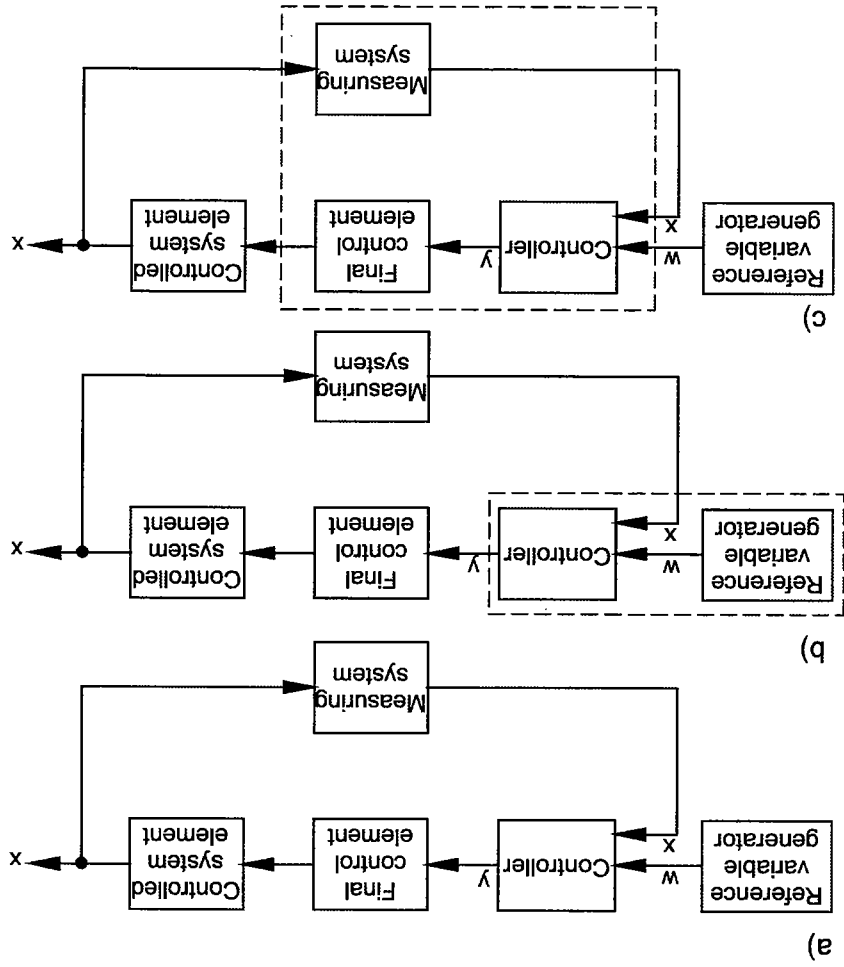


Fig. B4.1:
Closed-loop control circuit

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

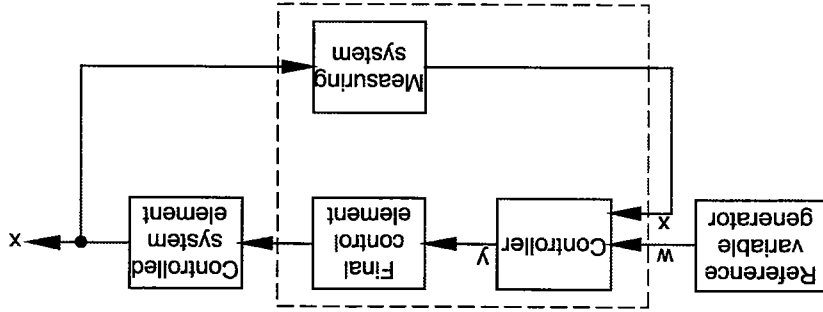
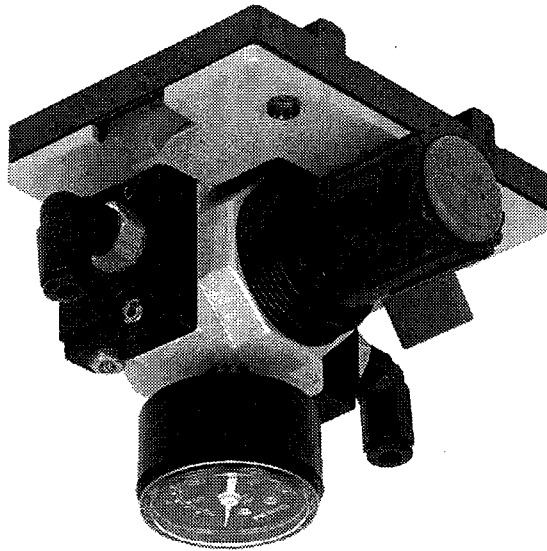
Advantages		Disadvantages
Closed-loop control circuit consists of small number of devices	Individual devices more expensive to replace	
Lower cable and tubing costs	Device suitable only for certain types of closed-loop control circuits	
Less expensive	easier servicing	

Manually-operated pressure regulator

Fig. B4.2 shows a pneumatic pressure regulator. This valve has the following functions in the closed-loop control circuit:

- Controller
- Final control element
- Measuring system

Fig. B4.2:
Pneumatic pressure
regulator with
manual operation



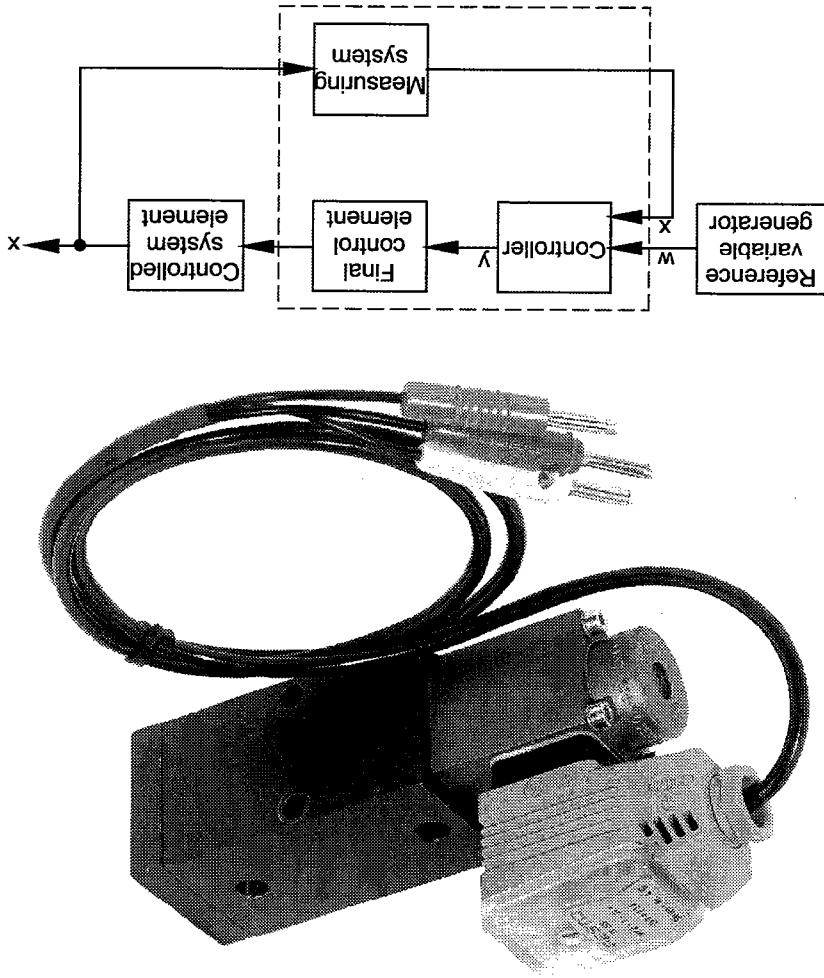
Apart from the closed-loop control element, all the boxes of the signal flow diagram are combined in a single unit.

Electrically-actuated pressure regulator

Fig. B4.3 shows an electrically-actuated pressure regulator. This valve fulfils the following functions in the closed-loop control circuit:

- Controller
- Final control element
- Measuring system

Fig. B4.3:
Pneumatic pressure
regulator with electrical
actuation



Double-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. B4.4, for example, has the following tasks:

- Generation of the reference variable for a pneumatic positioning actuator
- Closed-loop control of the pneumatic positioning actuator
- Monitoring of the pneumatic positioning actuator
- Processing of binary signals (PLC functions)

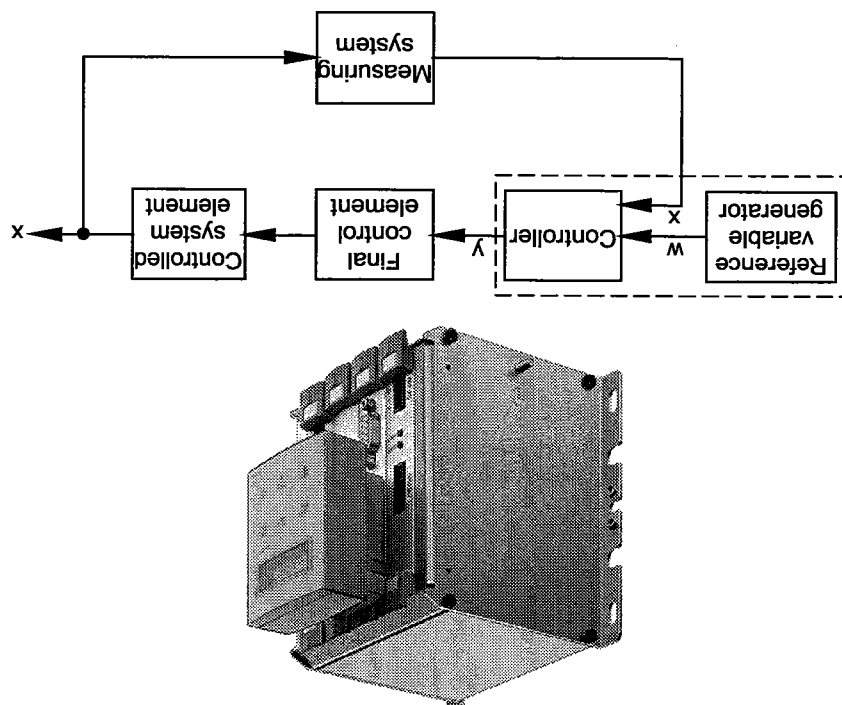


Fig. B4.4:
Double-axis control system

Numerical control

The control system shown in Fig. B4.4 is a 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.

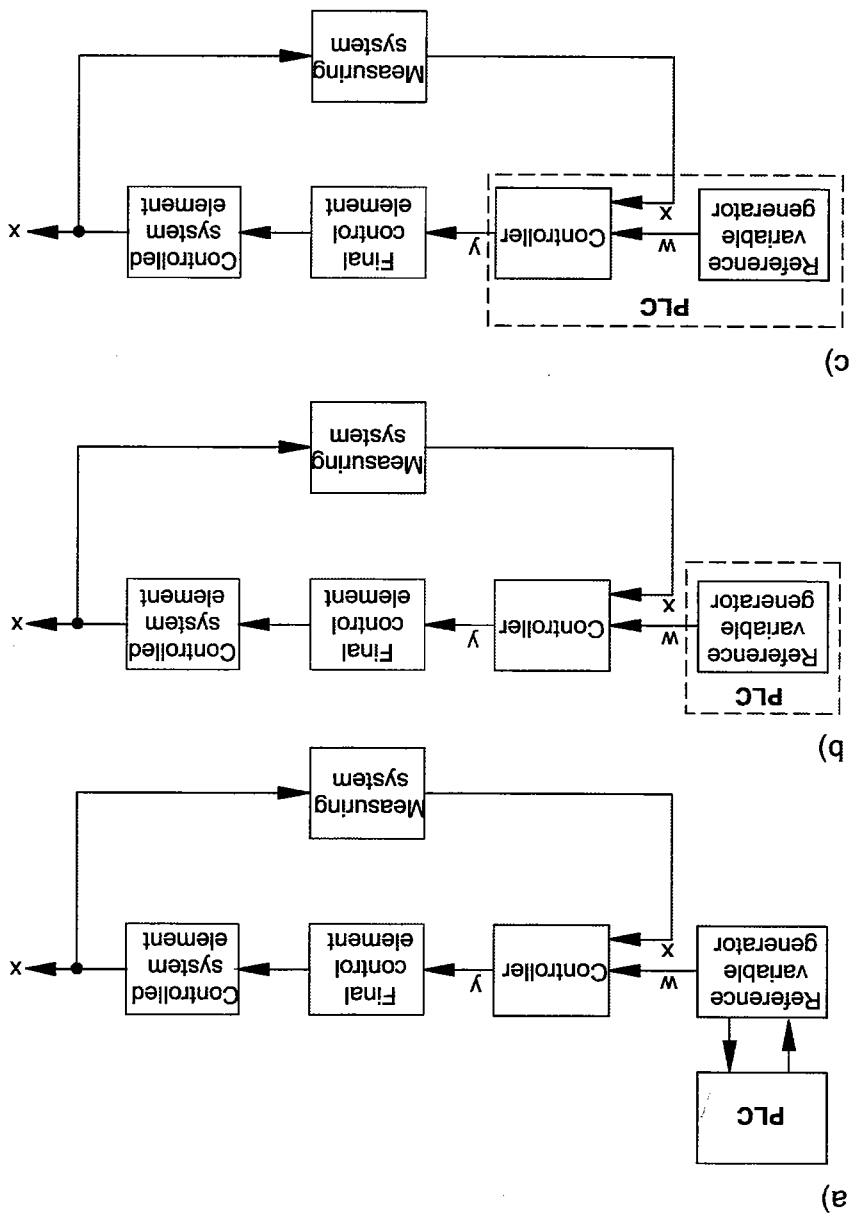
Programmable logic controller

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. B4.5a).

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. B4.5b).

Certain programmable logic controllers provide both a reference-variable generation function and a controller function in a single unit (Fig. B4.5c).

Fig. B4.5:
Implementation of
closed-loop control circuits
with
programmable logic
controllers



4.2 Pneumatic and electrical controllers

Controller without auxiliary power supply

Fig. B4.2 shows a pneumatic pressure controller which operates without an auxiliary power supply. The energy required to adjust the opening cross-sections is obtained from the compressed air itself.

Cross-bellows controller

A further example of a controller without an auxiliary power supply is a cross-bellows controller (Fig. B4.6). This is mainly used in process technology. A ring is attached to four bellows. The setpoint pressure acts on bellows 1, while the pressure to be controlled acts on bellows 2. The compressed air flows via a control nozzle. The movable ring acts as a baffle.

■ When the pressure in bellows 2 is lower than in bellows 1, the ring moves to the right (Fig. B4.6b). This increases the distance between the nozzle and baffle and the pressure in the control nozzle falls. The valve, acting as a final control element, is opened wider, with the result that the actual pressure value moves to equal the setpoint pressure.

■ If the pressure in bellows 2 is too high, the ring moves to the left (Fig. B4.6c). The pressure at the control nozzle rises, the flow cross-section in the valve is reduced, and the pressure in bellows 2 falls.

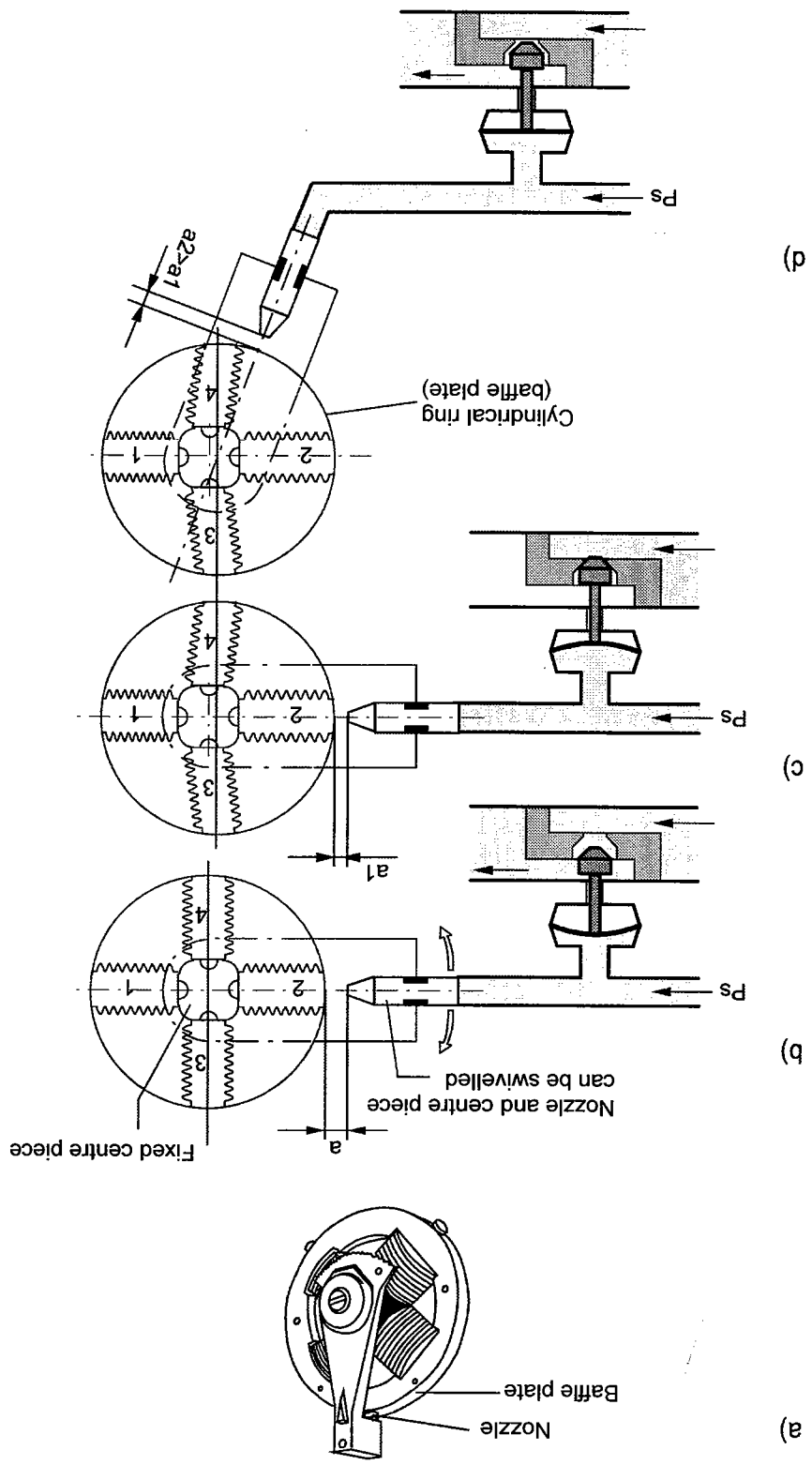
Bellows 3 and 4 generate a feedback signal for the ring.

The controller gain of the cross-bellows controller is adjusted by swivelling the nozzle.

■ In Figs. B4.6b and B4.6c, the nozzle is directly in the line of action of the two bellows 1 and 2. The change in the length of the two bellows chambers acts directly on the distance between the nozzle and baffle. The controller gain is at its maximum.

■ In Fig. B4.6d, the nozzle lies outside the line of action. A change in the length of the bellows chambers results in only a small change in the distance between the nozzle and baffle. The controller gain is reduced.

Fig. B4.6:
Cross-bellows controller



Controller with auxiliary power supply

Fig. B4.7 shows a closed-loop pneumatic pressure control circuit in which an auxiliary power supply is required. The controller is supplied with electrical energy and the valve is actuated electrically.

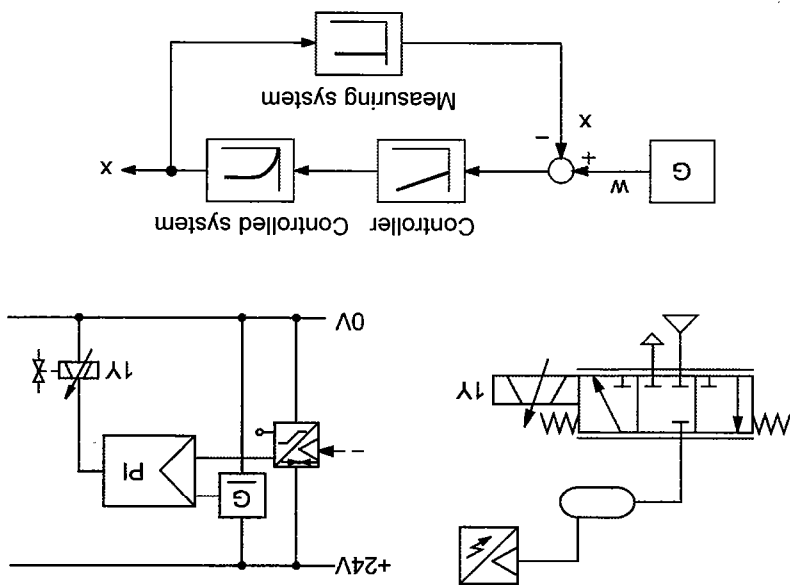


Fig. B4.7:
Pressure control system
with auxiliary power supply

Vergleich elektrischer und pneumatischer Regler

The advantages of electrical and pneumatic controllers for applications are shown in Table B4.2.

Advantages of electrical controllers		Advantages of pneumatic controllers	
Easier connection to electrical control systems	Simpler design	Fewer devices generally required (no need for separate measuring system)	Robust (unaffected by dust and humidity)
Inexpensive way to produce complex closed-loop control systems (e.g. with several feedback signals and limiters)			
Better response to errors (output of error messages)			
Higher control accuracy			

Table B4.2:

Comparison of electrical and pneumatic controllers

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 pneumatic 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.

Energy form	Analogue controllers		Example
	Digital controllers	Electrical controllers	Cross-bellows controller
	Electrical controllers	Electr. PID controller	Controller for one axis of a CNC machine tool

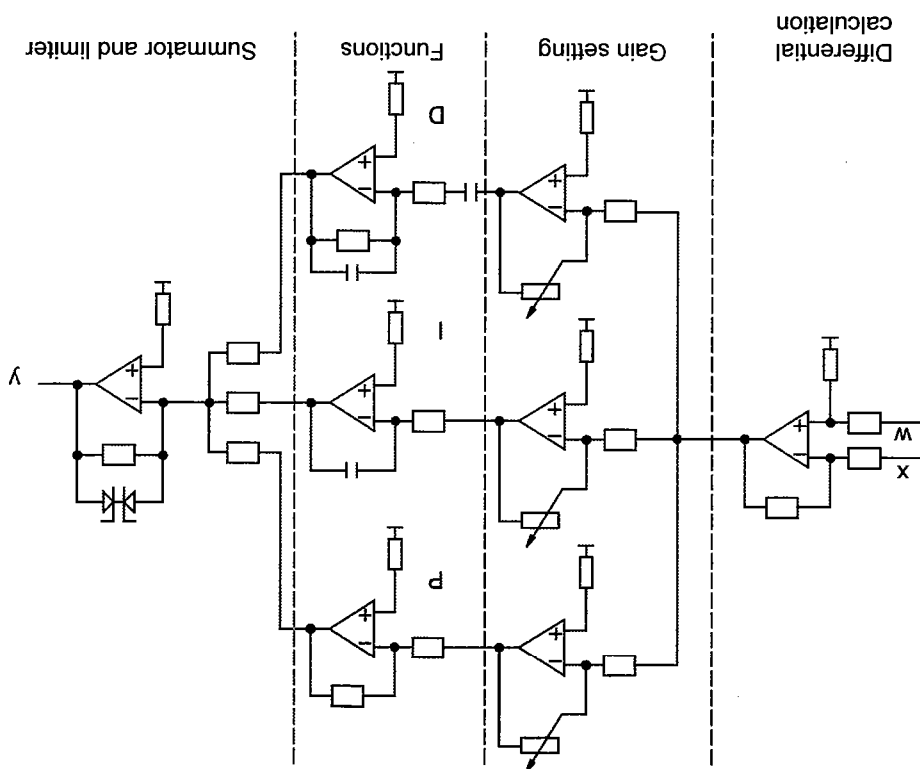
Table B4.3:

Analogue and digital controllers

Analogue electrical controller

Fig. B4.8 shows a circuit for an analogue electrical PID controller. The circuit consists of several operational amplifiers, equipped with capacitors and resistors.

Fig. B4.8:
Circuit for an analogue PID
controller (simplified)



Digital controller

Fig. B4.9 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.

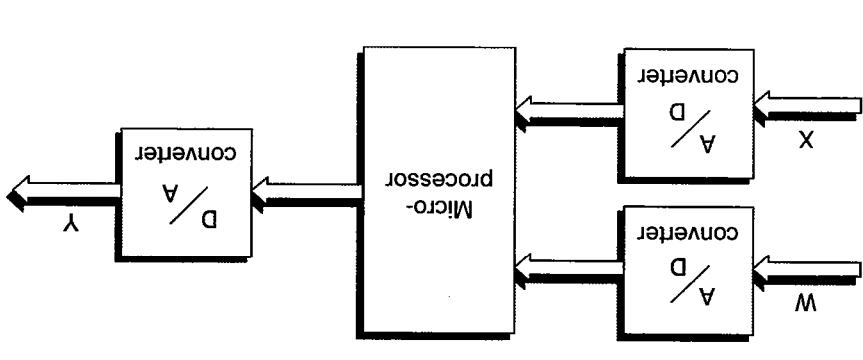


Fig. B4.9:
Signal flow in a
digital controller

The advantages of analogue and digital controllers are compared in Table B4.4.

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 systems
	Less affected by electrical interference

Table B4.4:
Advantages of analogue
and digital controllers

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	Monitoring functions	Controlled variable input of controller	Correcting variable	Controller parametrisation	Operating conditions	Safety requirements	Ambient temperature	Dust	Humidity	Electrical interference fields	Output of error messages	Power supply
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Directional control valves

5.1 Purpose of a directional control valve

A directional control valve links various valve ports together as a function of a correcting signal.

Purpose of a directional control valve in a closed-loop pneumatic control circuit

A directional control valve acts as a final control element in a closed-loop pneumatic control circuit. Directional control valves are used in various closed-loop control circuits:

- In position control circuits (e.g. pneumatic positioning actuator)
- In linear speed control circuits (for example, a pneumatic actuator which is required to operate at different speeds)
- In rotary speed control circuits (e.g. a rotary cylinder or pneumatic motor)
- In control circuits for angle of rotation (e.g. a rotary cylinder or pneumatic motor)
- In control circuits for flow rate (e.g. in process installations)

Either pressure regulators or directional control valves can be used in the following closed-loop control circuits:

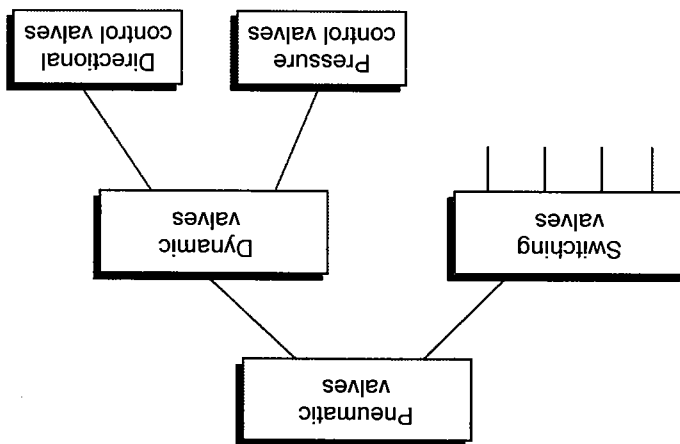
- In a pressure control circuit (e.g. to maintain the pressure in a compressed-air reservoir at a constant value)
- In a force control circuit (e.g. for a pneumatic press)
- In a torque control circuit (e.g. for a pneumatic wrench)

5.2 Types of valves

A distinction is made in pneumatics between switching valves and dynamic valves. Both types of valves are used in closed-loop control circuits:

- Switching valves in combination with non-dynamic controllers
- Dynamic valves in combination with dynamic controllers

Fig. B5.1:
Types of
pneumatic valves



The mode of operation of pneumatic switching valves is explained in Festo Didactic's textbooks 101 and 201. The following remarks refer to dynamic valves.

Pressure and directional control valves

Valves are classified into different groups according to their functions, e.g. pressure control valves, flow control valves and directional control valves. In the case of dynamic pneumatic valves, we make a distinction between the following (Fig. B5.1):

- Directional control valves, with which the correcting variable determines the position of the valve spool
- Pressure control valves, with which the pressure at the port to the consuming device is controlled as a function of the correcting variable

Components of a directional control valve

Directional control valves assume the function of a final control element in closed-loop control circuits. Since the directional control valves we are

- considering here are energised electrically, the final control element comprises three function boxes:
- An electrical amplifier which supplies the electrical energy
- An electromechanical converter to position the valve slide
- The mechanical components of the valve to control the flow of air

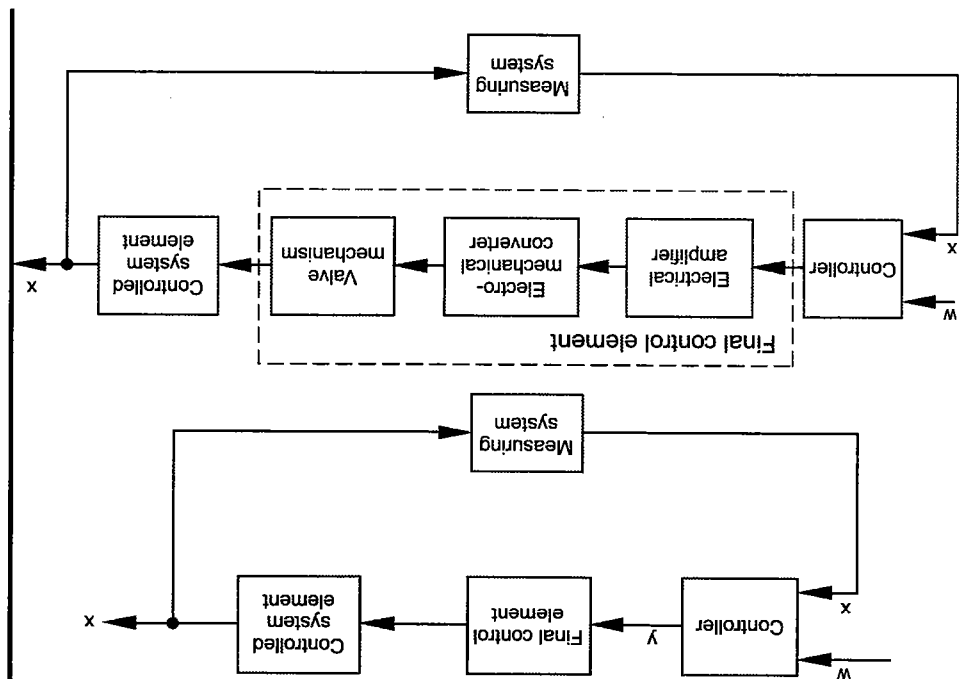


Fig. 5.2:
Dynamic directional control
valve as final control
element in a closed-loop
control circuit

- The electromechanical converter and the mechanical components form part of an electropneumatic directional control valve. There are various possibilities for the location 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. B4.3)

Fig. B5.3:
Directional control valve
with
separate plug-in card
(Kolvenbach)

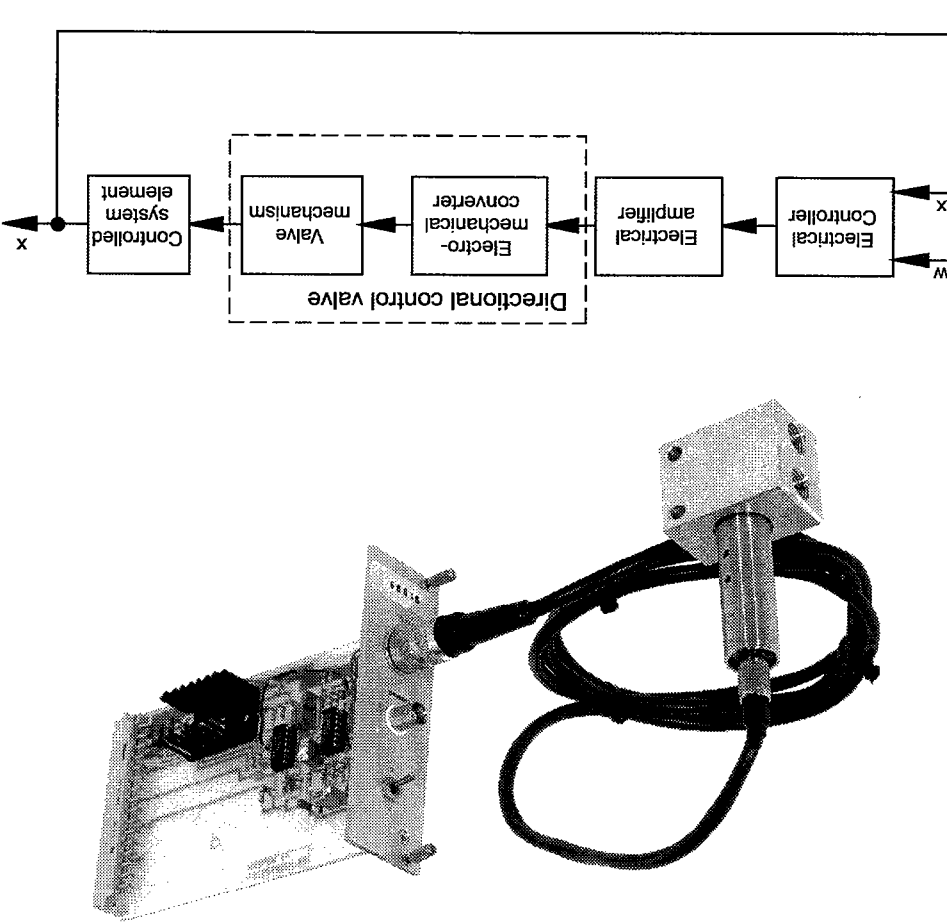
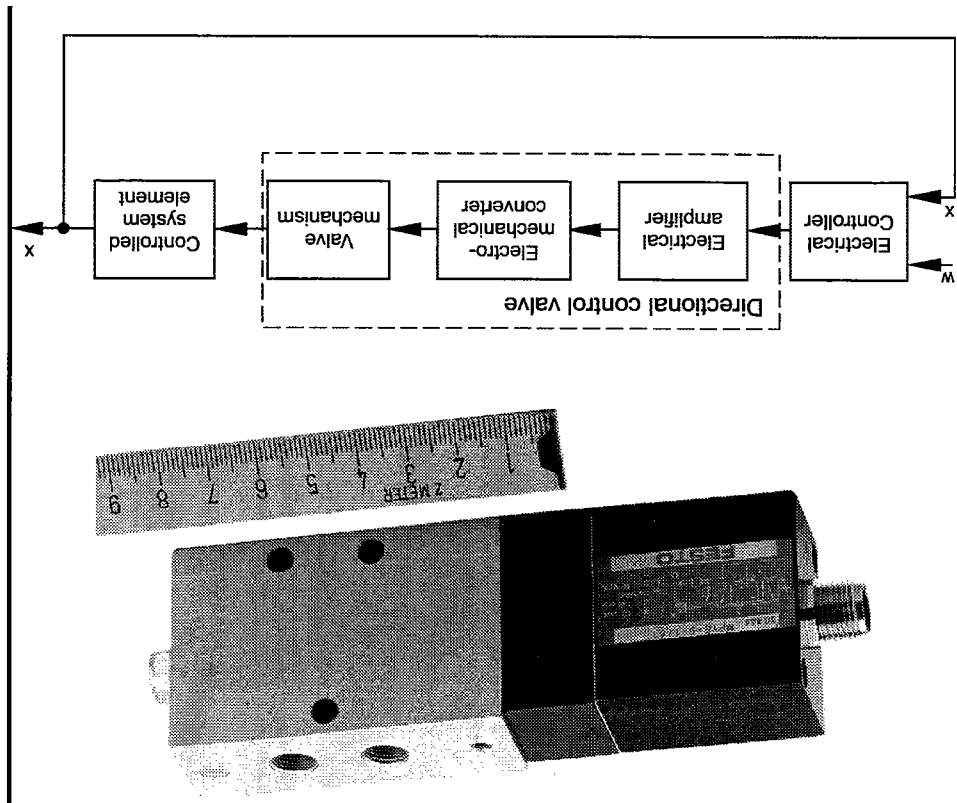


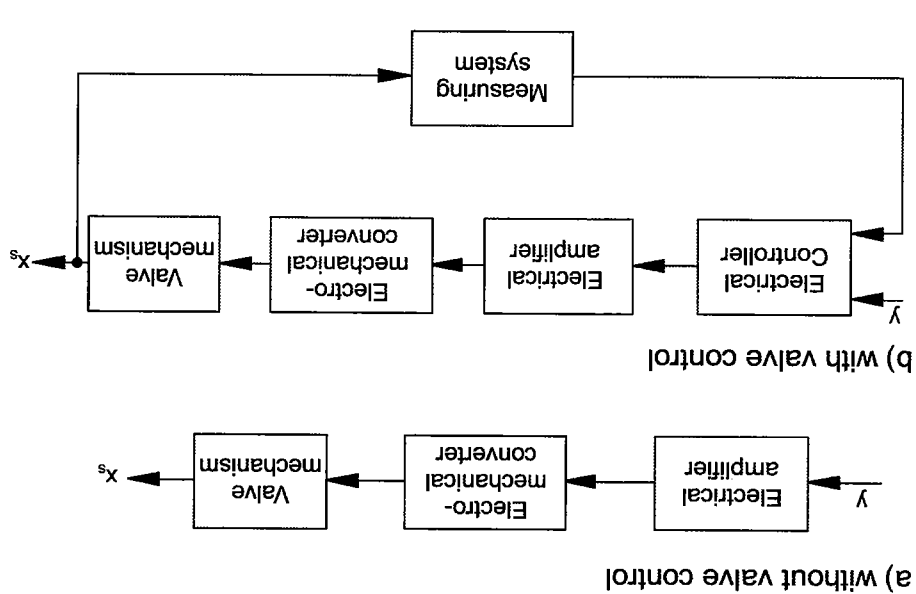
Fig. B5.4:
Directional control valve
with
integrated electronics
(Festo MPYE 5-1/8)



5.3 Mode of operation of a dynamic 5/3-way valve

The figure below shows the signal flow in a dynamic directional control valve.

Fig. 5.5:
Signal flow in a
dynamic directional control
valve



As regards signal flow, a distinction is made between

- valves without closed-loop control of the valve spool position and
- valves with closed-loop control of the valve spool position

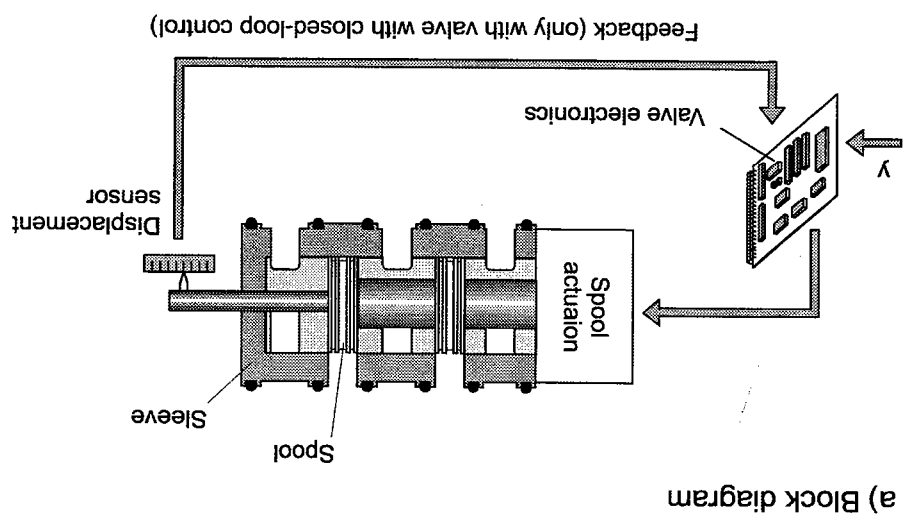
Signal flow in a valve without integrated closed-loop control

In the case of a valve without integrated closed-loop control (Fig. B5.5a), the correcting variable y acts directly on the electrical amplifier, which in turn feeds the valve slide actuator with current. This actuator may be, for example, a plunger coil, a torque motor or a proportional solenoid. The higher the current, the higher the actuating force and the further the slide is deflected.

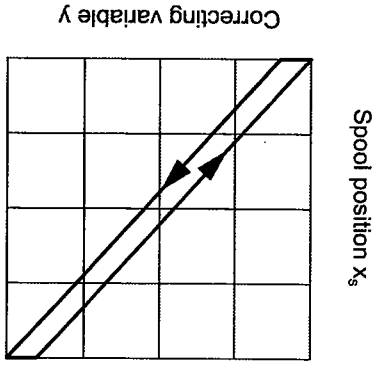
Signal flow in a valve with closed-loop control

In the case of a valve with integrated closed-loop position control, the position of the valve slide is measured continuously. The measured signal is compared with the correcting variable. The electrical amplifier is energised not directly by the valve input signal but by the controller output signal.

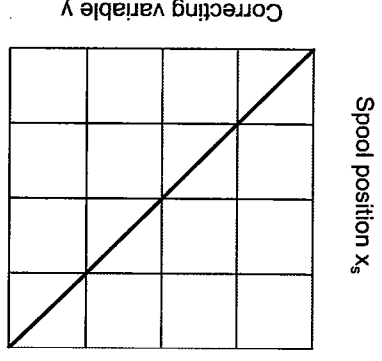
Fig. B5.6:
Valve spool position of a
dynamic directional control
valve as a function of the
correcting variable



b) Characteristic without closed-loop control



c) Characteristic with closed-loop control



Influence of frictional and flow forces

Fig. B5.6 shows schematically the relationship between the correcting variable y and the valve spool position x_s in the form of characteristics. Without closed-loop control of the valve spool, two different characteristics branches are described for a rising and falling correcting variable respectively (Fig. B5.6b). Frictional and flow forces also have a pronounced effect.

■ In the case of a valve with a closed-loop-controlled spool, the direction of the change in the correcting variable has scarcely any effect on the spool position (Fig. B5.6c). The influence of flow and frictional forces is largely compensated out. Closed-loop-controlled valves are always used in cases where a high degree of accuracy is crucial.

Signal flow with a closed-loop-controlled valve

Fig. B5.7 shows the signal flow for a closed-loop pressure control circuit with a closed-loop-controlled directional control valve. The signal flow diagram shows two closed-loop control circuits, one inside the other:

- The outer closed-loop control circuit is for pressure.
- The inner closed-loop control circuit is for the position of the valve spool.

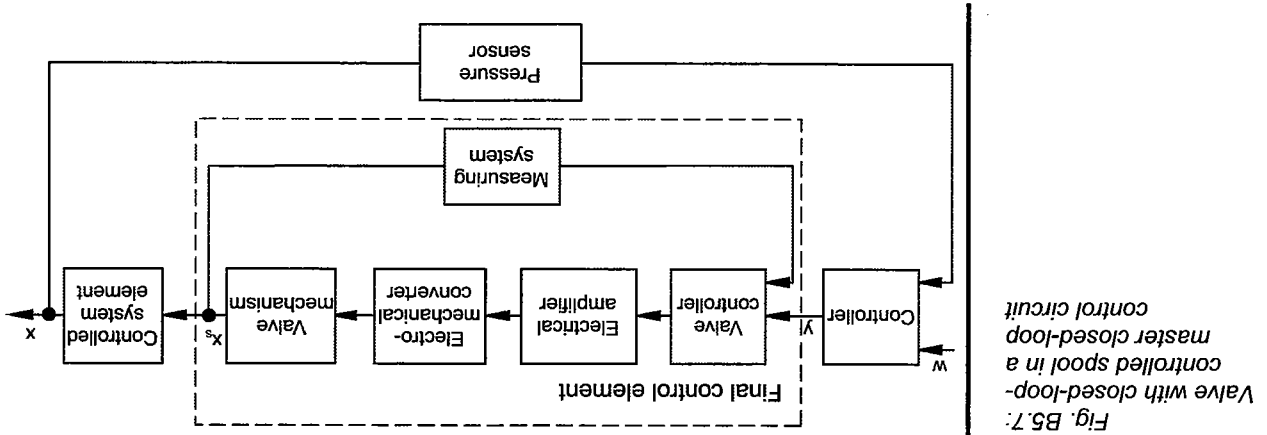


Fig. B5.7: Valve with closed-loop-controlled spool in a master closed-loop control circuit

Valve-spool positions

Figs. B5.8 and B5.9 show valve-spool positions for various selected correcting signals.

Fig. B5.8:
Slide positions of a dynamic
directional control valve for
selected correcting signals

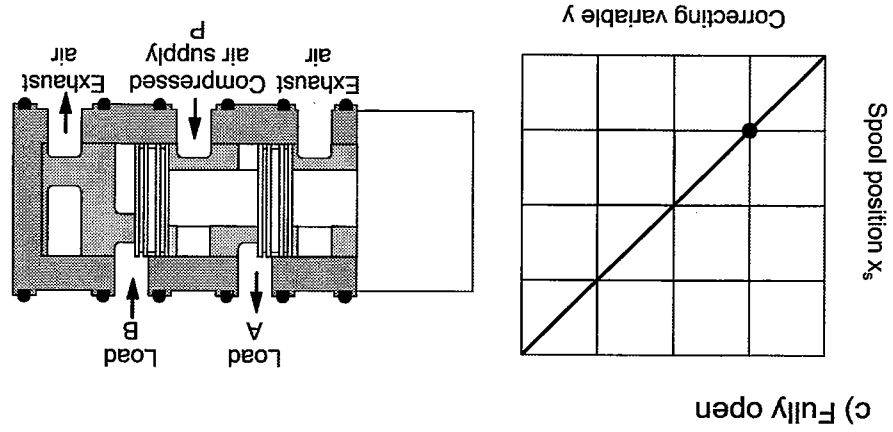
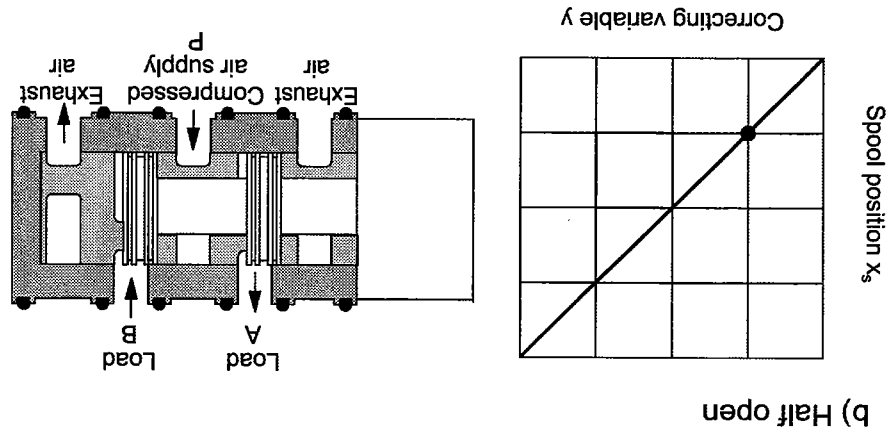
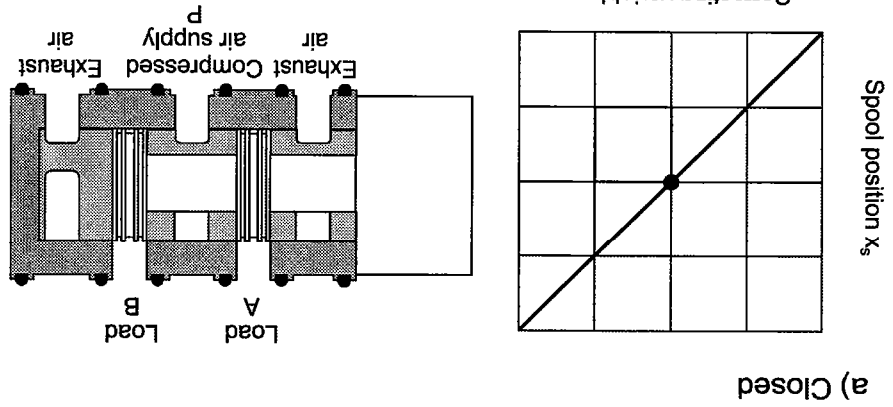
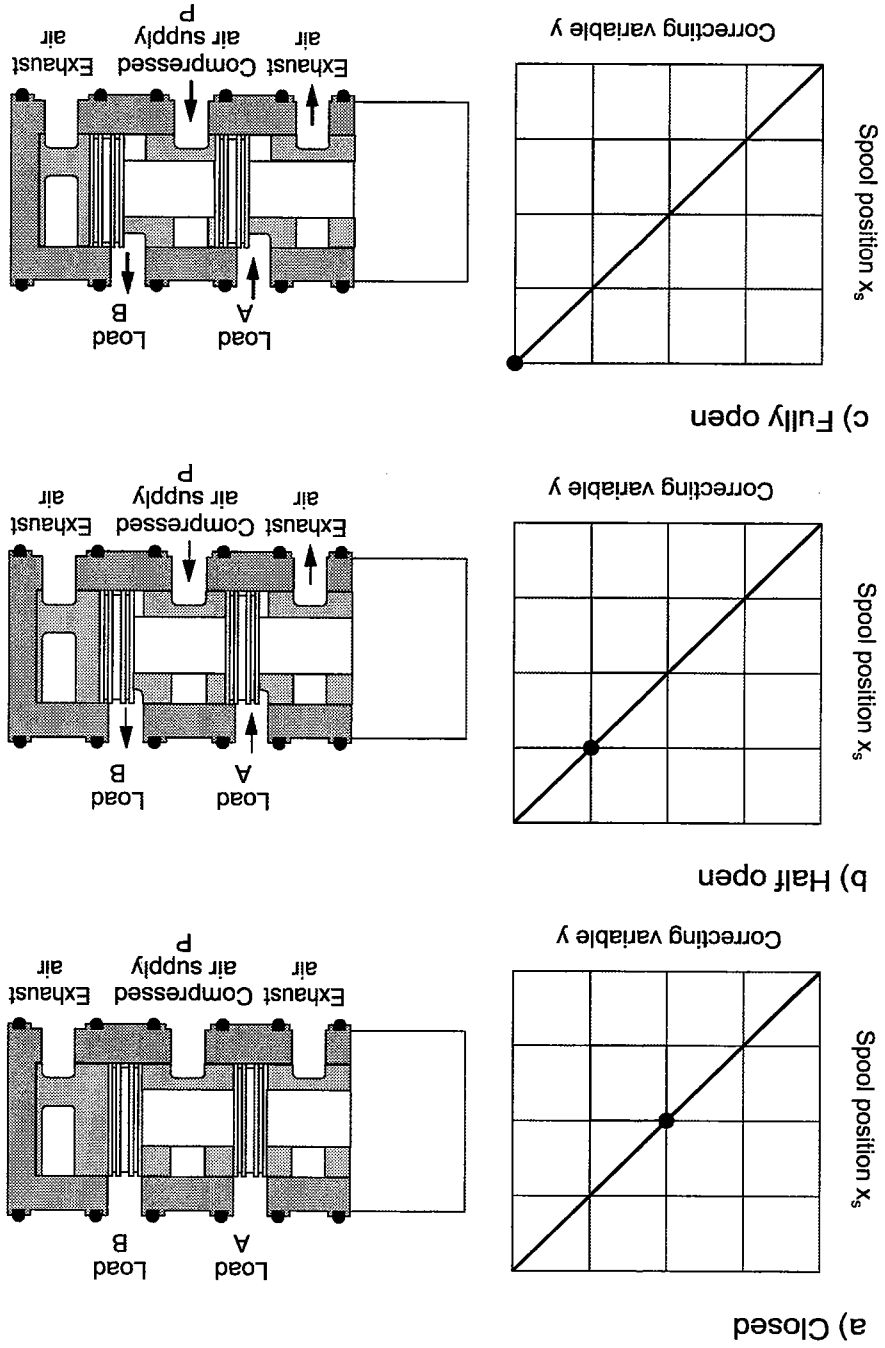


Fig. B5.9:
Slide positions of a
dynamic directional control
valve for selected
correcting signals



- When an actuating signal is applied whose value lies in the mid-correcting range, the valve spool moves into its mid-position (Fig. 5.8a). In the valve mid-position, all control edges are closed. Accordingly, no air passes through the valve apart from a very slight leakage.

- If the actuating voltage is varied in the negative direction, the valve spool will move to the left. Figs. B5.8b and 5.8c show examples of the valve-spool positions half value and full value actuating signals. In these two spool positions, air flows from the supply port to working port A, while working port B is connected to the exhaust port of the valve. A comparison of Figs. B5.8b and B5.8c shows that the flow cross-sections become larger when the valve spool is moved further to the left. The larger the flow cross-sections at the control edges, the higher the flow rate through the valve.

- If the actuating voltage is varied in the positive direction, the valve spool will move to the right (Figs. B5.9b and B5.9c). Working port A is connected to the exhaust bore and working port B to the supply port. Once again, the further the spool is moved away from its mid-position, the larger the open cross-section and thus the air flow.

Due to the dynamic operation of the valve, the valve spool can assume not only the positions shown in Figs. B5.8 and B5.9 but also any other desired intermediate positions.

Advantages of a dynamic directional control valve in comparison with a switching valve

A dynamic 5/3-way valve of the type described above 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 both large-size and small-size switching valves.

5.4 Characteristic features and symbols for dynamic directional control valves

Proportional and servo valves

Electrically-actuated dynamic valves are known as proportional or servo valves, depending on their design and technical data. The most important criteria used to distinguish between these two classes of valves are listed in the following table.

Table B5.1:
Properties of
proportional and
servo valves

Criteria	Proportional valves	Servo valves
Dynamic properties	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 whether to call the valve a proportional valve or a servo valve.

Directional control valve MPYE 5-1/8

The MPYE 5-1/8 valve used in the Technology Package has

- some characteristic features of a proportional valve, such as a simple, robust and inexpensive design, and
- some characteristic features of a servo valve, such as good dynamic properties and accuracy

The valve can thus not be clearly assigned to one of the two categories. Because of its directly-controlled spool, the valve is described by Festo as a proportional valve.

Characteristic features of a dynamic directional control valve

The dynamic directional control valve described in section B5.3 has three possible flow states, depending on the spool position:

Two opposed flow directions, depending on the direction of movement of the valve spool (Figs. B5.8 and B5.9).

Since the valve has 5 ports, it is a 5/3-way dynamic valve.

Symbols for a dynamic directional control valve

■ The symbol for a dynamic directional control valve differs from the symbol for a switching valve by having two additional features (Fig. B5.10):

■ Two straight lines, one above and one below the directional control valve symbol

■ An inclined arrow pointing upwards running through the electromagnetic converter

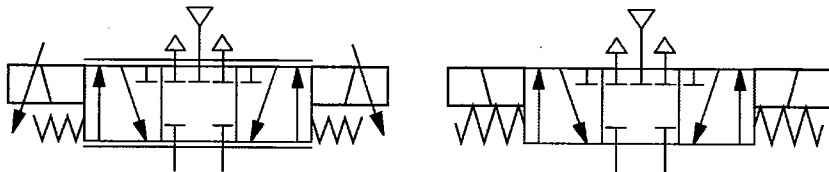


Fig. B5.10:

Symbols for switching and dynamic valves

Examples of symbols

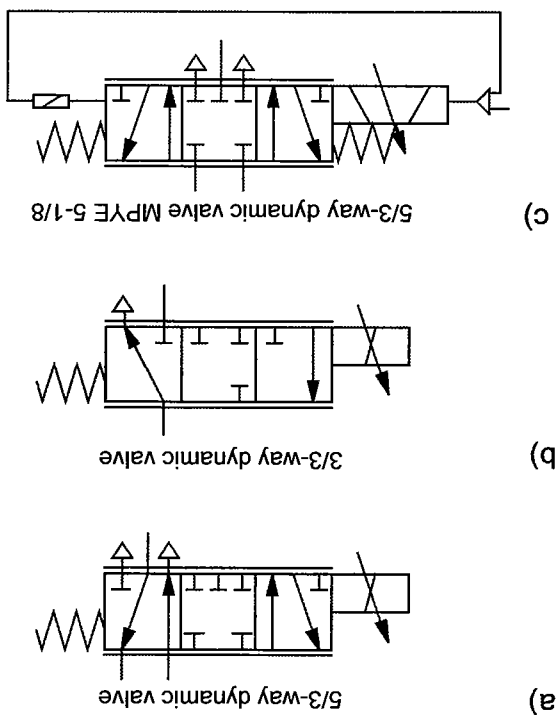
Fig. B5.11 shows three examples of symbols for dynamic valves:

■ Fig. B5.11a shows the symbol for a dynamic 5/3-way valve. The valve spool is actuated by a proportional solenoid. The return force is provided by a spring.

■ Fig. B5.11b shows the symbol for a dynamic 3/3-way valve. It is actuated in the same way as the valve in Fig. B5.11a.

■ Fig. B5.11c shows the symbol for the dynamic directional control valve MPYE 5-1/8. In contrast to the valves in Figs. B5.10a and B5.10b, the valve spool is position-controlled and is actuated by a linear electric motor. The linear motor can, in contrast to the proportional solenoid, exert a force on the valve spool in both directions.

Fig. B5.11:
Symbols for dynamic
directional control valves

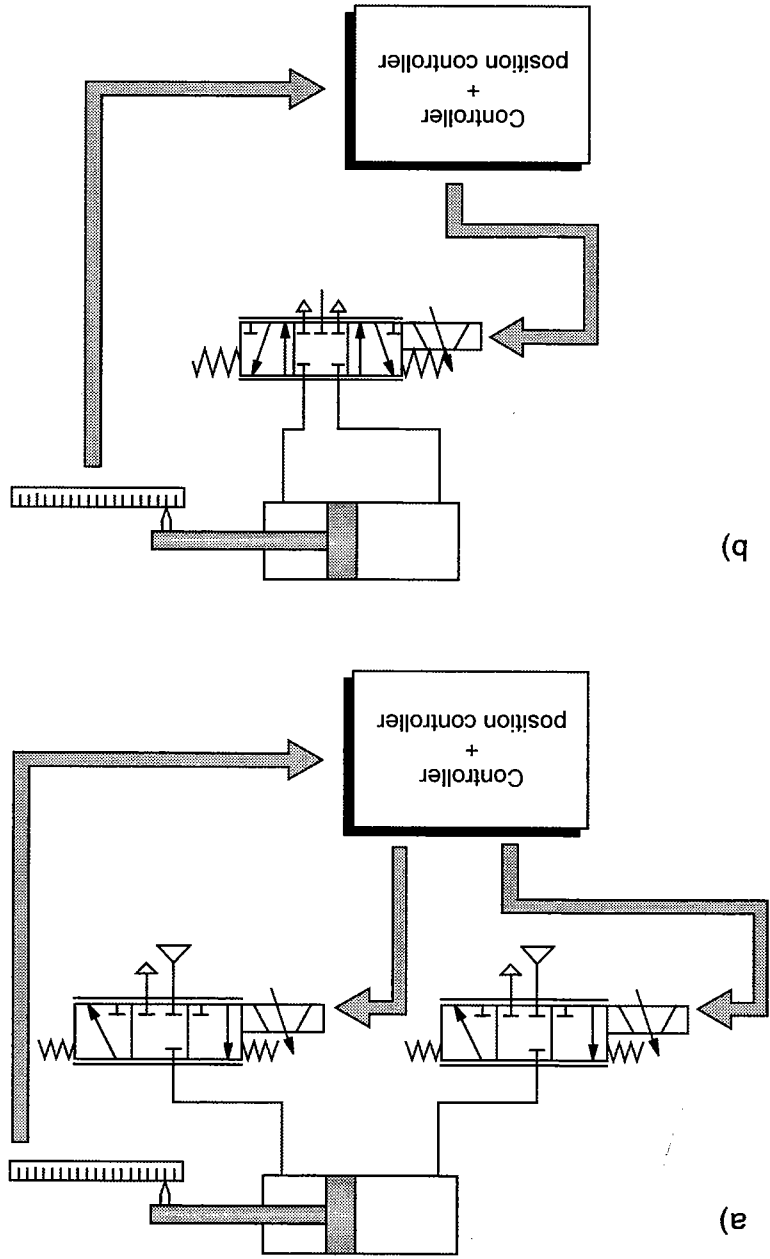


Circuit variants

Many applications, such as closed-loop pressure control systems, require a valve with a consuming-device port. The preferred valve here is a 3/3-way valve.

In the case of a pneumatic positioning actuator, the air flow for the two cylinder chambers must be controlled in opposite directions. As the following figure shows, a pneumatic positioning actuator can be operated with either two dynamic 3/3-way valves (Fig. B5.12a) or with one dynamic 5/3-way valve (Fig. B5.12b).

Fig. B5.12:
Valve configurations
for pneumatic
positioning actuators



5.5 Steady-state characteristics for dynamic directional control valves

Two steady-state characteristics are usually given in data sheets for dynamic directional control valves:

dynamic directional control valves

■ Flow rate/signal function

■ Pressure/signal function

These characteristics are used

■ to compare the properties of several different valves

■ to select a suitable valve for a given application

Flow rate/signal function

The flow rate/signal function for a directional control valve is determined using the circuits in Figs. B5.13a and B5.13b.

■ The circuit in Fig. B5.13a is used for the measurement of the flow rate from port 1 to port 2.

■ The circuit in Fig. B5.13b is used for the measurement of the flow rate from port 2 to port 3.

For each of the two flow directions, various correcting variable values are set and the resulting flow rate measured. The two flow control valves should be set during the measurement so as to produce the following pressures:

■ 6 bar in the direction of flow upstream of the valve

■ 5 bar in the direction of flow downstream of the valve

Following this, the measured values are plotted in the graph and linked to form a characteristic.

The following relationships can be read from the characteristic:

■ The valve is closed in its mid-position. No air can flow through the valve.

■ The flow rate rises as the valve opening increases, starting at the mid-position (Fig. B5.13d).

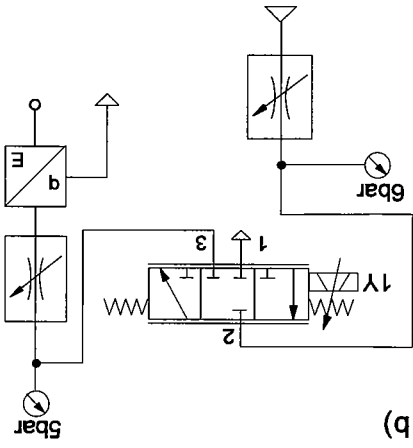
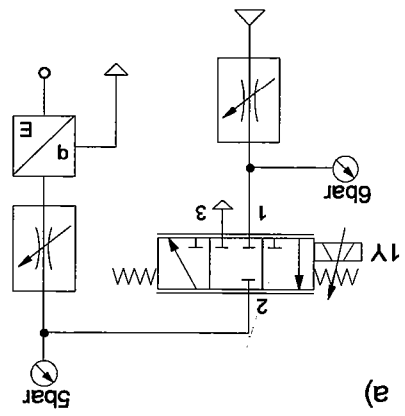
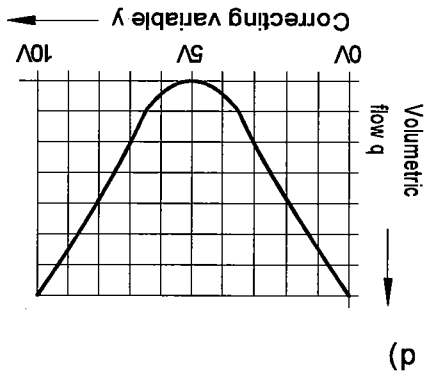
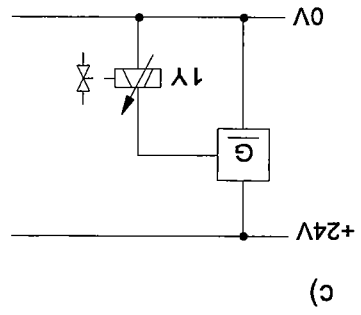


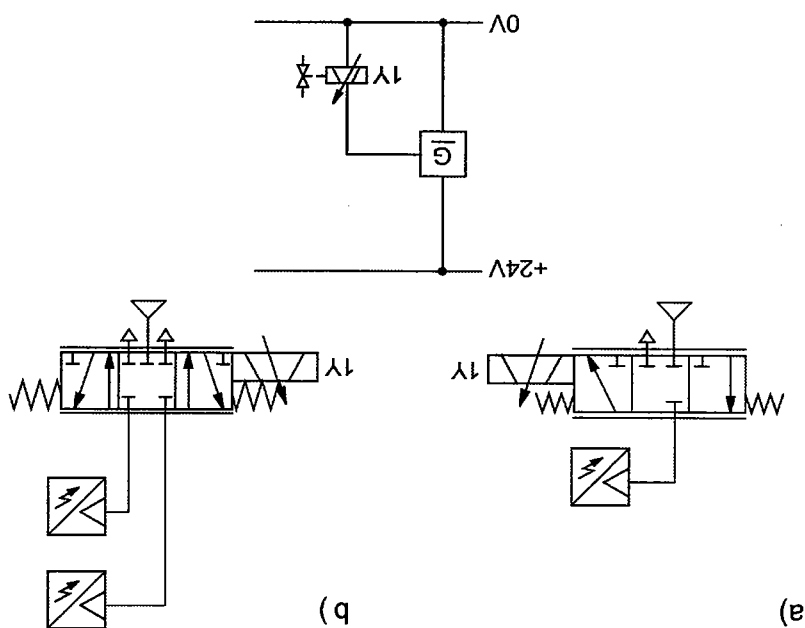
Fig. B5.13:
Flow rate/signal function

Measuring the pressure/signal function

In order to measure the pressure/signal function, a pressure sensor is connected to each outlet port of the directional control valve (Figs. B5.14a and B5.14b). The correcting variable is varied across the entire correcting range. The resulting pressure is 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 5/3-way valve

Fig. B5.14:
Test assembly for
pressure/signal function



Pressure/signal function with negative overlap

Fig. B5.15a shows the valve spool and cartridge for a 5/3-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 overlap 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 restrictors. The pressure at each of the outlet ports lies between the supply pressure and ambient pressure. The precise value will depend 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 right (Figs. B5.8b and B5.8c). In this case, port A will be linked to the supply port. Maximum pressure is present here. Port B is linked to the exhaust port, at which ambient pressure is present.

- If a strongly positive correcting signal is present, the valve spool will have been displaced from its mid-position to the right (Figs. B5.9b and B5.9c). Ambient pressure will be present at port A, while maximum pressure will be present at port B.

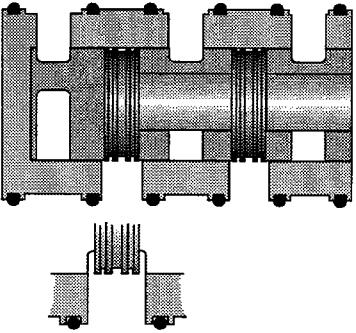
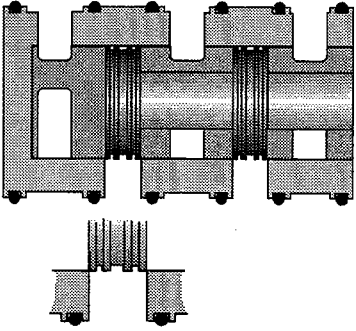
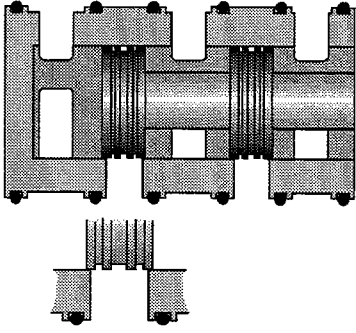
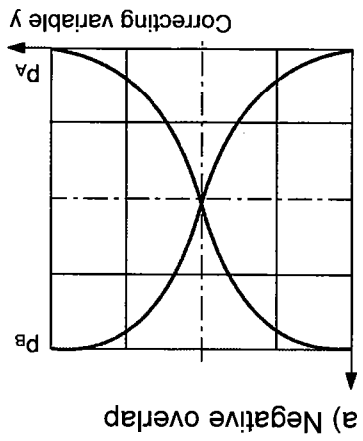
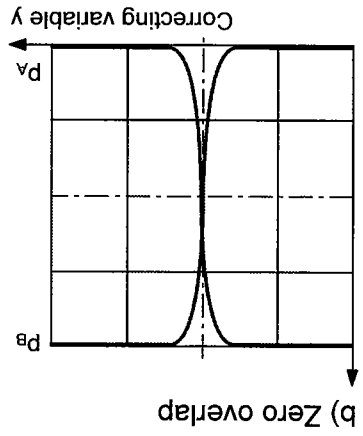
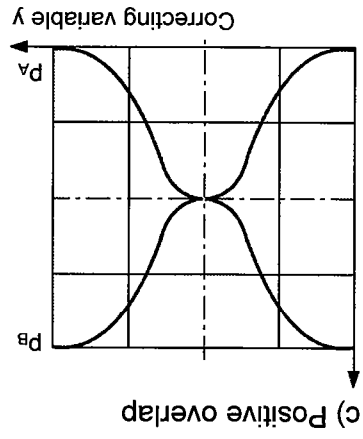
Pressure/signal function with zero overlap

With zero overlap, the edges of the spool in its mid-position coincide exactly with the edges of the cartridge (Fig. B5.15b). Even when the valve spool is deflected only slightly, one outlet port will be connected to the supply port and the other to the exhaust port. The pressure-signal gradient accordingly exhibits a very steep gradient in the vicinity of the mid-position.

Pressure/signal function with positive overlap

In the case of positive overlap, the control edges of the spool and cartridge overlap (Fig. B5.15c). 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 characteristics in the vicinity of the mid-position.

Fig. B5.15
Overlap
and
pressure/signal function



Overlap and leakage

Switching valves are fitted with rubber or plastic seals between the spool and cartridge. The leakage rate is therefore very low. In the case of dynamic valves, the spool and cartridge run against each other without additional seals in order to reduce friction. The annular gap which results means that the leakage rate is considerably higher.

Overlap has a strong influence on the leakage rate of a dynamic directional control valve:

- With negative overlap, the leakage rate with the spool in its mid-position is very high. This means high energy consumption.
- With zero overlap, there is a noticeable leakage with the spool in its 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

Valves with negative overlap are not used in practice, due to their high leakage rate and the high energy consumption which would result. The properties of valves with zero and positive overlap are summarised in Table B5.2.

Advantages of zero overlap		Advantages of positive overlap
Better accuracy when used in a closed-loop control circuit		
Valves cheaper to manufacture		Lower leakage rate
Properties of directional control valves with zero and positive overlap		

Table B5.2:

Properties of directional control valves with zero and positive overlap

Dynamic directional control valves used in pneumatic systems generally have a slight positive overlap. Typical overlap values are between 5 and 25 m. Overlap conditions depend not only on design specifications but also on production tolerances. There may therefore be noticeable differences between different valves of the same series.

5.6 Dynamic behaviour of dynamic directional control valves

In many applications, such as pneumatic positioning actuators, the position of the valve spool must follow the energisation signal not only as accurately as possible but also 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, they have to be activated with a sine-wave correcting variable (Fig. B5.16). The position of the valve spool is measured with a sensor. The correcting variable y and the spool position x_s are displayed in graphic form on an oscilloscope. As Fig. B5.16 shows, the valve spool oscillates at the same frequency as the energisation signal.

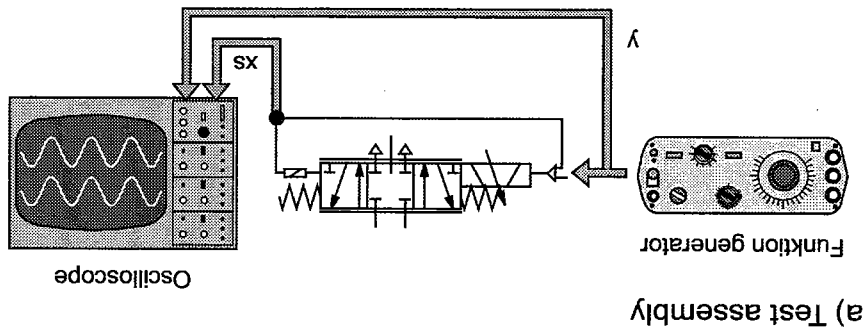
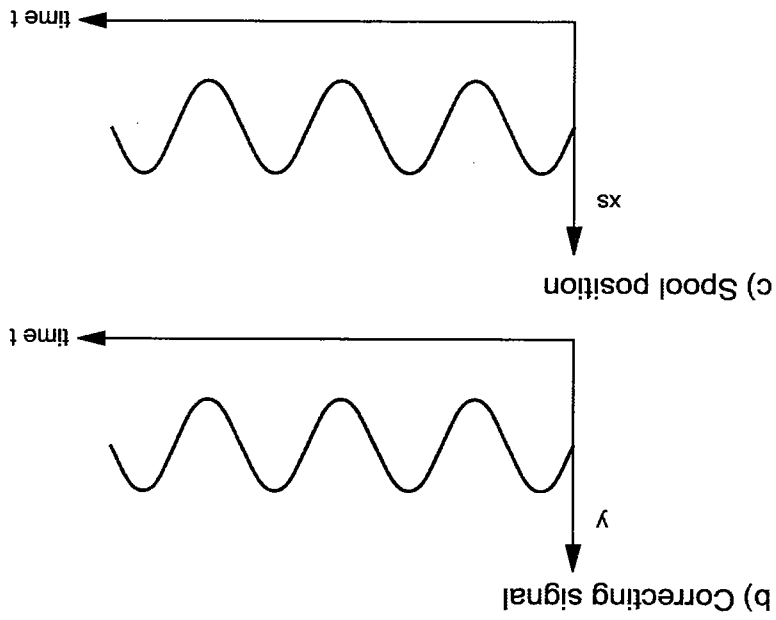


Fig. B5.16:
Measuring the
transmission characteristics
of a dynamic
directional control valve



If the energisation frequency is increased while leaving the energisation amplitude unchanged, the frequency at which the valve spool oscillates will also increase (Fig. B5.17).

At a very high energisation frequency, the valve spool can no longer follow the rapid changes in the correcting signal. This can be seen by comparing Figs. B5.17d and Fig. B5.17e; amplitude A2 is noticeably smaller than amplitude A1.

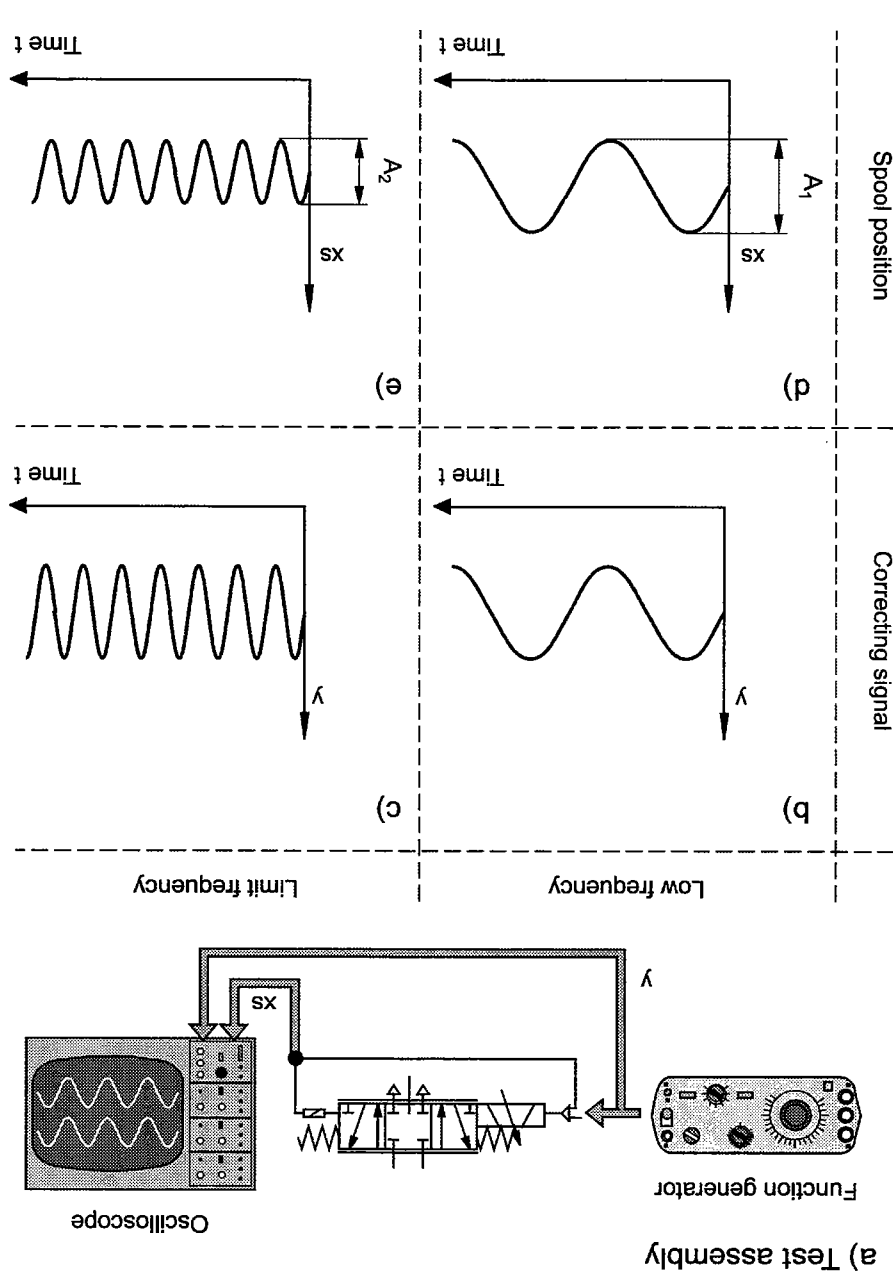
Limit frequency

The limit frequency is generally specified as an indication of the dynamic properties of a valve.

The limit frequency is the frequency at which the amplitude of the valve oscillation has fallen to 70.7% of the amplitude at very low frequencies. In order to determine the limit frequency, the frequency of the input signal is increased until the amplitude of the output signal has fallen to 70.7% (Fig. B5.17).

The limit frequency is also quoted in data sheets as the -3dB frequency. The expression "-3 dB" (minus three decibels) indicates that the amplitude has fallen to 70.7% of its initial value.

Fig. B5.17:
Measuring the limit
frequency of a dynamic
directional control valve



Limit frequencies of dynamic directional control valves

The limit frequencies of dynamic pneumatic valves lie between approx. 5 and 200 Hz, depending on the 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 correcting variable and the position of the valve spool are measured for a large number of different frequencies. At high frequencies, the oscillation amplitude becomes smaller and a phase shift occurs. Two graphs are produced by plotting the amplitude and phase shift across the entire frequency range:

- The amplitude response
- The phase response

The two graphs together describe the frequency response of the valve.

Amplitude response

The valve spool oscillates with a certain amplitude at the measuring frequency. This amplitude is compared with the amplitude with which the valve spool oscillates at a very low frequency. The ratio of the amplitude at the measuring frequency and the amplitude at a very low frequency is given in dB. An amplitude ratio of -20 dB, for example, means that the amplitude has fallen 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 of 100 Hz results from the frequency response in Fig. B5.17.

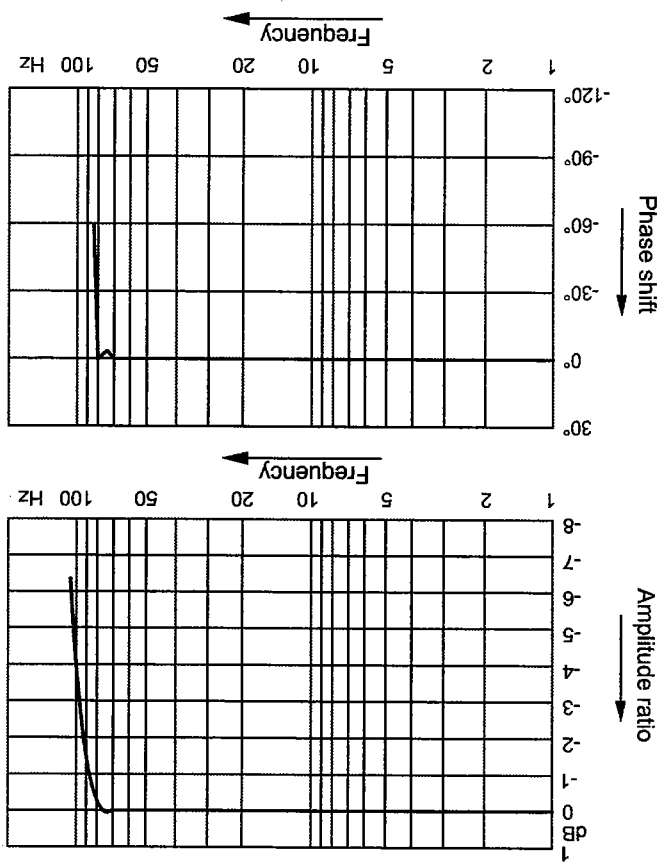
Phase response

The delay of the output signal relative to the input signal is quoted 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.

Bode diagram

A Bode diagram is obtained by plotting a graph of the amplitude and phase response against the frequency.

Fig. B5.18:
Frequency response
of a valve



5.7 Selection criteria for directional control valves

Table B5.3 summarises the selection criteria for directional control valves.

Operating conditions	Control quality
Ambient temperature	Pressure/signal function
Filtration of compressed air	Flow rate/signal function
Dust	Limit frequency
Humidity	Hysteresis
Power supply	Installation dimensions
Interface	
Correcting variable	Response to compressed air supply failure
Nominal valve size	Response to electrical power failure
Cost	
Mechanical components	
Electrical components	

Tabelle B4.5:
Kriterien für die
Reglerauswahl

Pressure regulators

6.1 Purpose of a pressure regulator

With a pressure regulator, a handwheel, adjusting screw or electrical signal is used to adjust the pressure at the outlet port of the valve.

Purpose of a pressure regulator in a pneumatic closed-loop control circuit

A pneumatic pressure regulator has the following functions in a closed-loop pressure control circuit:

- Controller
- Final control element
- Measuring system

Fig. B6.1 shows the signal flow diagram for a closed-loop control circuit 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 outlet of the valve, acts as a further signal.
- The controller built into the valve adjusts the valve opening x_s as a function of these two signals.

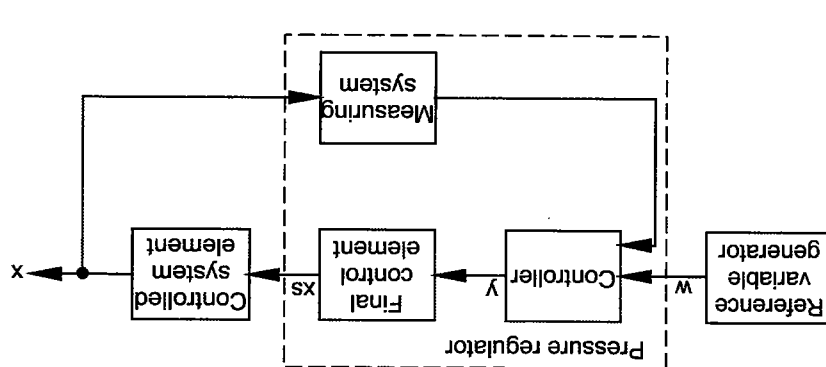


Fig. B6.1:
Signal flow diagram
for a closed-loop control
circuit with
a pressure regulator

Adjustment of pressure and torque

A pressure regulator is often used to adjust force or torque. This is illustrated by the following two examples of applications:

- The contact pressure of a cylinder on an object is adjusted by controlling the pressure in the cylinder.
- The torque of a power wrench is kept to a constant value by controlling the motor air supply pressure.

6.2 Designs of pressure regulators

A distinction is made between two classes of pressure regulators:

- Manually-operated valves
- Electrically-actuated valve

The advantages of manual operation and electrical actuation are compared in Table 6.1.

Table B6.1: Manual and mechanical generation of reference variable		Reference variable input	Manual	Advantages Less expensive	Can be adjusted automatically (e.g. by a PLC)
			Electrical		

Pressure controllers

Pressure controllers may be of mechanical or electrical design. The advantages of electrical and mechanical pressure control are shown 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	Better control dynamics

Table B6.3 lists various designs of valves.

Reference variable generation	Manual	Electrical	Electrical
Controller	Mechanical	Mechanical	Electrical
Pressure sensor	-----	-----	Integrated into valve
Example	Festo LFR-A	Festo MPP	Festo MPPE
Control accuracy [bar]	ca. +/- 0.2	Approx. +/- 0.3	Approx. +/- 0.1

Table 6.3:
Types of
pressure regulators

Interfaces

In the case of electrically-actuated pressure regulators, the reference variable is usually supplied from a signal source as a voltage or current. The input of the pressure regulator and the output of the signal source must be matched to each other, i.e. the voltage or current range must be the same.

The following interface is often used:

0 V corresponds to minimum pressure

10 V corresponds to maximum pressure.

The maximum valve required will depend on the compressed-air consumption of the consuming device. If this consumption is known, the nominal size of the valve and valve type required can be determined from data sheets.

6.3 Mechanical pressure regulator

The service unit of a pneumatic installation is a combination of several components; these are usually

- a pressure regulator
- an air filter with a water separator, and
- a pressure gauge to show the pressure
- A service unit will also frequently incorporate a lubricator

Mode of operation

The purpose of a pressure regulator is to keep the supply pressure constant. Fig. 6.2 shows the mode of operation of this valve:

- If the pressure at consuming-device port is lower than the desired pressure, the diaphragm is pushed upwards by a pre-tensioned spring (Fig. 6.2a). The valve opening is increased, allowing more air to flow to consuming-device port. The pressure at port rises.
- If the pressure at consuming-device port is too high, the diaphragm is pressed downwards (Fig. 6.2b). The plunger is then no longer in contact with the diaphragm. Air flows through the openings provided into the atmosphere. The pressure at port A falls.
- If the pressure at the consuming-device port corresponds to the pre-set value, the valve remains closed.

Generation of reference variable

- The reference variable can be adjusted by means of a handwheel.
- When the handwheel is turned to increase the pre-tension of the spring, the spring presses against the diaphragm with greater force. A higher pressure is then required at output in order to re-establish an equilibrium of forces. An increase in the pre-tension of the spring thus produces an increase in the reference variable.
- When the handwheel is turned in the opposite direction, the pre-tension of the spring decreases. The force acting on the diaphragm becomes less. A lower pressure is then sufficient to establish an equilibrium of forces, i.e the reference variable is reduced.

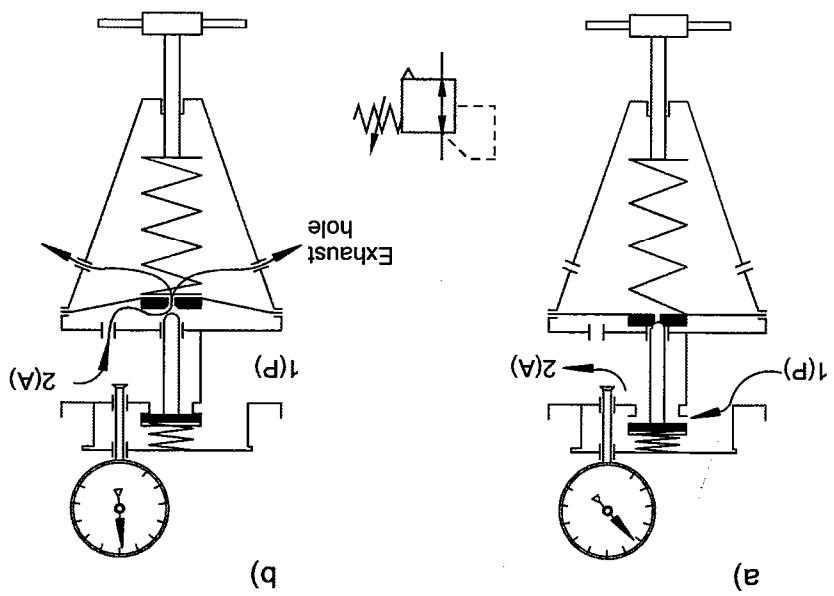


Fig. B6.2:
Mechanical
pressure regulator
(schematic)

Signal flow diagram for closed-loop pressure control circuit

Fig. B6.3 shows the signal flow in a mechanical pressure regulator. The final control element is incorporated into the pressure regulator.

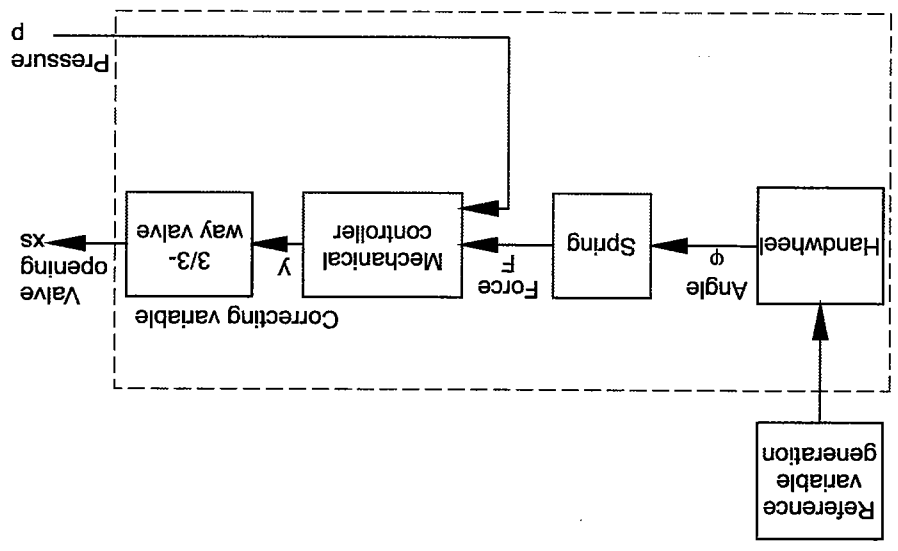


Fig. B6.3:
Signal flow diagram for a
mechanical
pressure regulator

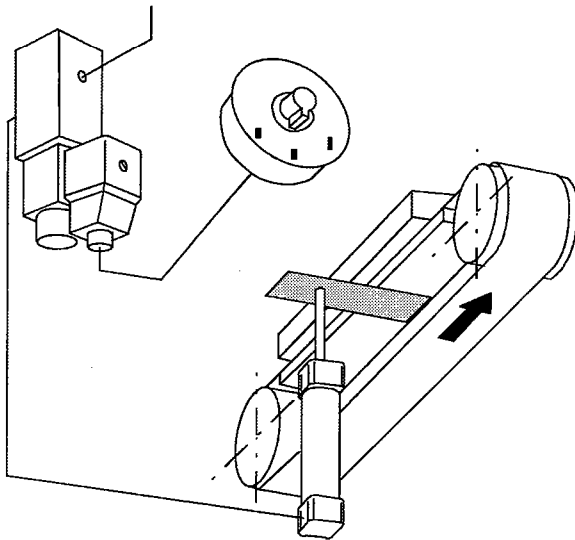
6.4 Electrically-actuated pressure regulator with mechanical compensation

Electrically-actuated pressure regulators are used in cases where pressure is to be controlled from an electrical circuit.

Example of application

Fig. B6.4 shows a belt sander. The sanding belt is pressed against the workpiece by a pneumatic cylinder. The force which the cylinder is required to exert depends on the workpiece. For this purpose, it is necessary to vary the pressure in the cylinder. The reference variable for the pressure is generated by an electrical control system. The function of the pressure regulator is to adjust the pressure in the cylinder to the desired value.

Fig. 6.4:
Controlling contact pressure
with a pressure regulator

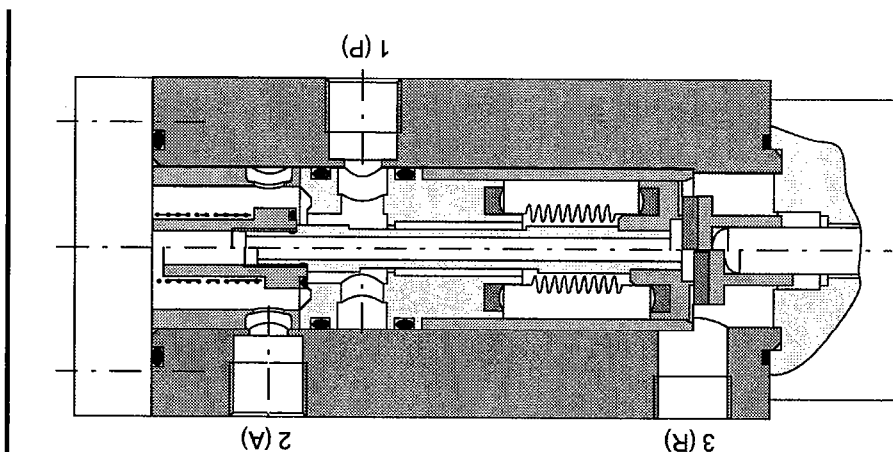


Depending on its performance data, a pressure regulator with electrically generated reference variable is described as a proportional pressure or servo pressure valve.

Proportional pressure valve with mechanical pressure compensation

The figure below shows a sectional view of a proportional pressure valve with mechanical pressure compensation.

Fig. B6.5:
Sectional view of a
pressure regulator with
mechanical adjustment
(Festo MPP)



Mode of operation

The valve is energised by a voltage. The voltage is converted into a current. This current flows through the valve solenoid. The higher the current, the more the solenoid plunger presses against the valve spool. The pressure at consuming-device port A produces a counter-force. A distinction is made between three operating states:

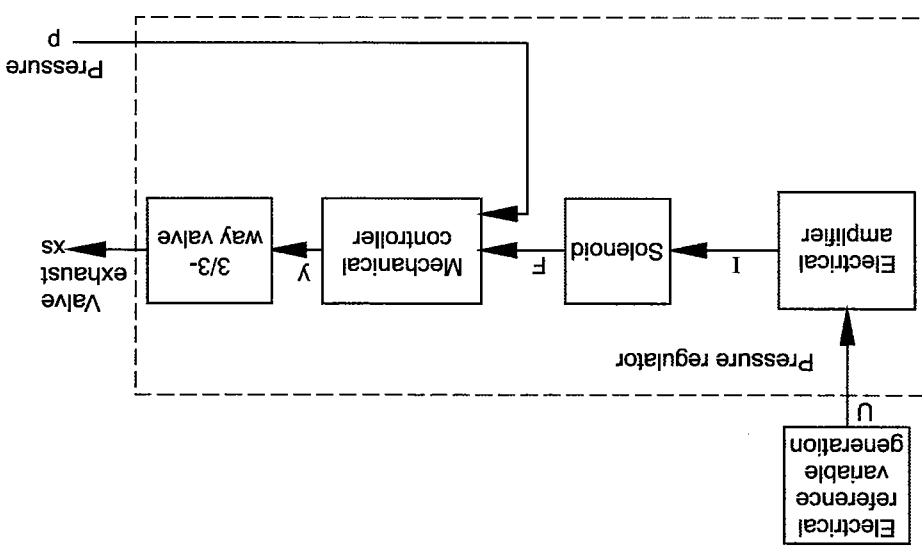
- If the pressure at the consuming-device port is too low, the spool moves to the right. This is shown in the lower part of Fig. B6.5. The supply port and consuming-device port are linked to each other. The pressure at the consuming-device port rises.
- If the pressure at the consuming-device port is too high, the solenoid plunger lifts away from the valve spool. This operating state is shown in the upper half of Fig. B6.5. The consuming-device port is linked to the exhaust port via the longitudinal hole in the valve spool. The pressure at the consuming-device port falls.

- If the pressure at the consuming-device port corresponds to the pre-set value, the two control edges of the valve remain closed.

Signal flow diagram for closed-loop control circuit

Fig. B6.6 shows the signal flow diagram for a pressure regulator with mechanical pressure compensation.

Fig. B6.6:
Signal flow diagram for
a pressure regulator with-
mechanical pressure
adjustment



6.5 Electrically-actuated pressure regulator with electrical compensation

High requirements are often placed on the precision of steady-state control of a closed-loop pressure control circuit. In cases of this kind, a pressure regulator with pressure measurement and electrical compensation is used.

Mode of operation

The mode of operation of a valve with electrical pressure compensation is shown in Fig. B6.7.

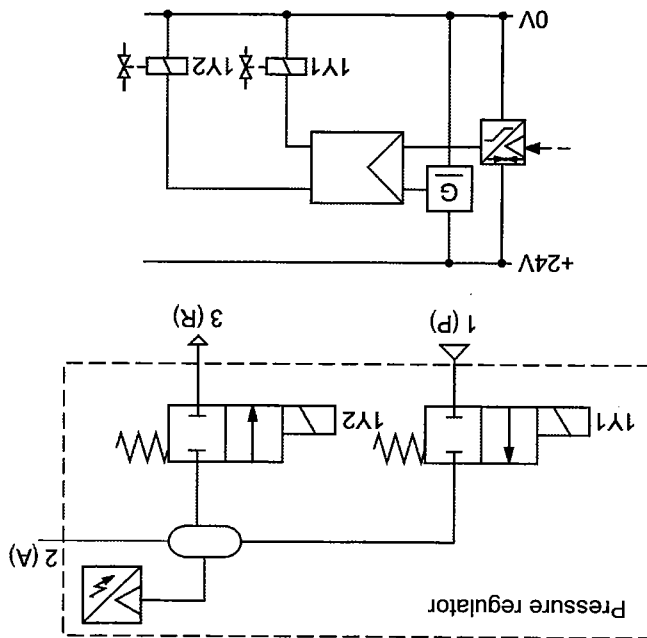


Fig. B6.7:
Pressure regulator with
integrated sensors and
control electronics

The reference variable acts on the electrical controller. A pressure sensor measures the pressure at the outlet port to the consuming device. The sensor output signal is fed to the controller. The two switching valves are energised as a function of the system deviation. The pressure at the outlet port is varied by opening and closing these switching valves.

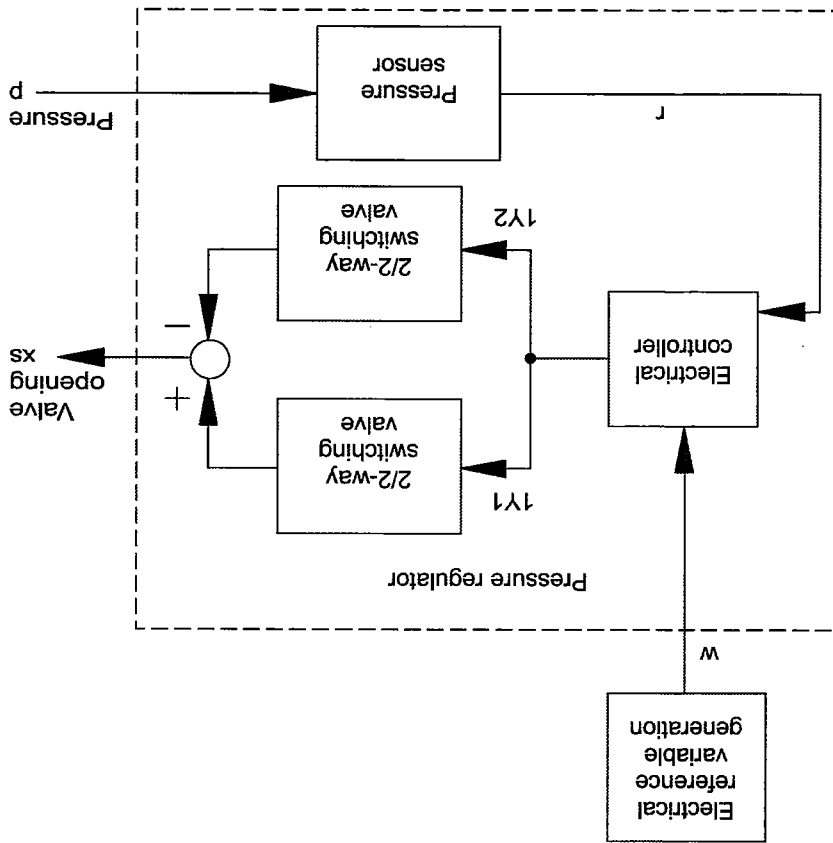
The electrical control of the pressure means that the steady-state system deviation is no more than 0.1 bar.

Signal flow diagram

Fig. B6.8 shows the signal flow diagram for the pressure regulator. The valve incorporates the following closed-loop control circuit functions:

- Controller (electrical)
- Final control element (two 2/2-way valves)
- Measuring system (pressure sensor)

Fig. B6.8:
Signal flow diagram for a
closed-loop control circuit
with
pressure regulator
(electrical pressure
adjustment)



Characteristics for an electrically-controlled pressure regulator

Fig. B6.9 shows the steady-state characteristics for a pneumatic pressure regulator. The characteristics show how the pressure at the valve output varies as a function of the valve flow rate. Each characteristic links the points with the same reference variable. The characteristics for four different reference variables are plotted: 9 bar, 7 bar, 5 bar and 3 bar.

The characteristics exhibit the following behaviour:

- With a low flow rate through the valve, the reference variable and controlled variable are the same.
- If the flow rate through the valve increases while the reference variable stays the same, the controlled variable falls. This means: As the flow rate increases, the steady-state system deviation becomes larger.

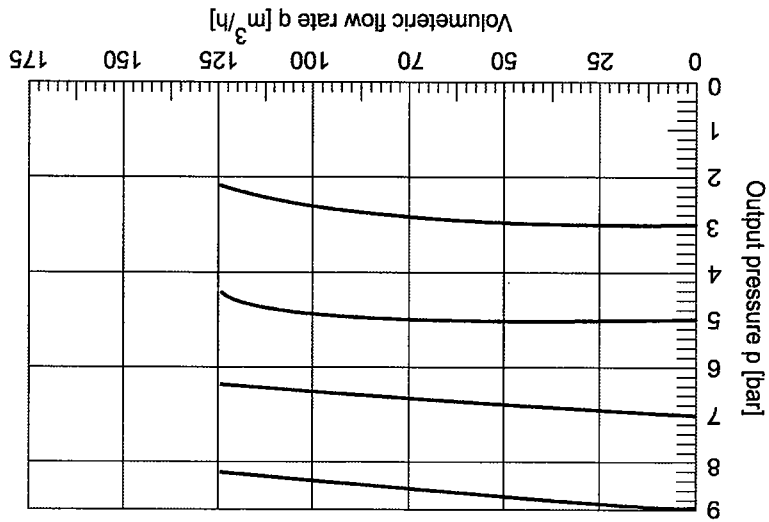


Fig. B6.9:
Characteristics for an
electrically controlled
pressure regulator

6.6 Pressure regulation with a directional control valve

A pressure regulator combines several functions of a closed-loop control circuit in a single component. Closed-loop pressure control circuits may also be of discrete design, i.e. they may consist of several separate components:

- A directional control valve as a final control element
- A pressure sensor as a measuring system
- An electrical controller

This type of solution is more expensive. It is used only in cases where requirements cannot be fulfilled by a pressure regulator. The reasons for this may be as follows:

- Very high steady-state control accuracy is required. A control accuracy of 0.02 bar can, for example, be achieved using an MPYE directional control valve, a pressure sensor and an electrical pressure controller.

- It is desired to measure and control the pressure not directly at the valve output but at another point in the controlled system.

Signal flow diagram for closed-loop control circuit

Fig. B6.10 shows the signal flow diagram for the closed-loop control circuit. In contrast to the case of a pressure regulator, the directional control valve assumes only the function of a final control element. The pressure sensor and pressure controller are not integrated into the valve.

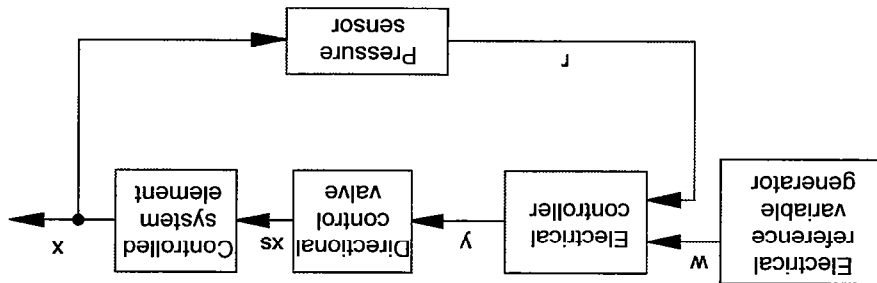


Fig. B6.10:
Signal flow diagram for a
closed-loop pressure
control circuit with
a directional control valve

6.7 Selection criteria for pressure regulators

Table B6.4 summarises the selection criteria for pressure regulators.

Operating conditions	Control quality	Table B6.4: Selection criteria for pneumatic pressure regulators
Ambient temperature	Characteristics	
Compressed air filtration	Hysteresis	
Dust	Limit frequency	
Humidity	Controller structure used	
Power supply	Installation dimensions	
Interface		Safety requirements
Correcting variable	Response to compressed air supply failure	
Nominal valve size	Response to electrical power supply failure	
Cost		
Mechanical components		
Electrical components		

Measuring systems

7.1 Purpose of a measuring system

A measuring system converts an input signal into an output signal of a different form which can be evaluated more easily. This process is known as measurement.

The input signal may, for example, be a pressure or a velocity, while the output signal may be a current or voltage.

Purpose of a measuring system in a closed-loop control circuit

The purpose of a measuring system in a closed-loop control circuit is to

- record the controlled variable and
- generate the feedback variable

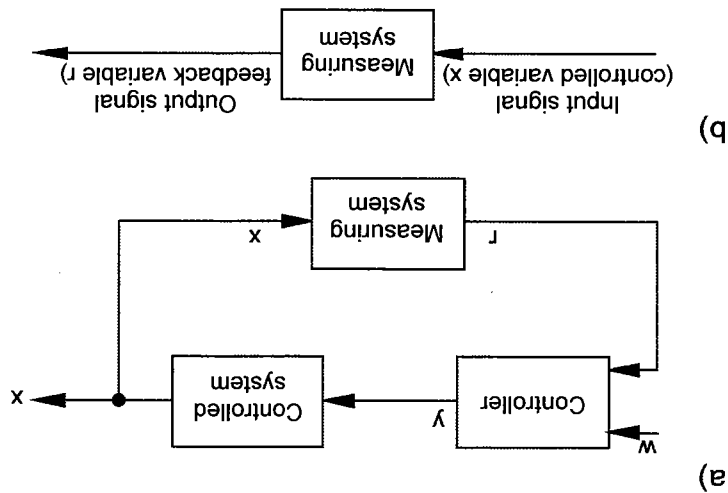


Fig. B7.1: Function of a measuring system in a closed-loop control circuit

A measuring system is required in a closed-loop control circuit in all cases where an electrical controller is used. In the case of closed-loop control circuits with pneumatic or mechanical feedback, the controlled variable frequently acts directly on the controller. This means that the measuring-system function is integrated into the controller, and a separate measuring system is therefore not required.

7.2 Measuring-system designs and interfaces

A measuring system consists of two components:

- A sensor
- A measured-value processing unit

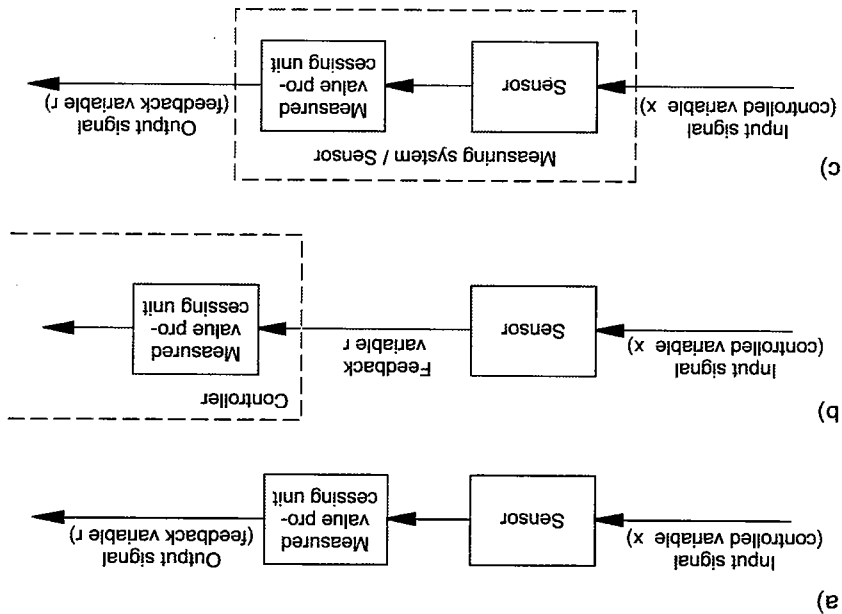
Fig. B7.2 provides an overview of measuring-system designs.

- Fig. B7.2a shows the signal flow diagram for a measuring system in which the sensor and measured-value processing unit are two separate devices. Inductive position sensors are constructed on this principle. In addition to the 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 often used for digital positioning 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 a single unit (Fig. B7.2c). This design is very common, due to the ease with which it can be handled. Examples include pressure sensors and gap sensors.

Fig. B7.2:
Structure of a
measuring system



Input signal

In closed-loop control circuits, the controlled variable forms the input signal of the measuring systems. Table B7.1 gives an overview of measuring systems used in closed-loop pneumatics.

The title given to a measuring system is generally determined by the type of input signal concerned.

Input signal	Title	Example of application
Pressure	Pressure sensor	Pressure-controlled gripper
Force	Force sensor	Force-controlled pneumatic press
Rotary speed	Tachometer	Pneumatic screwdriver
Angle of rotation	Rotary encoder	Pneumatic rotary actuator
Position	Position sensor	Pneumatic positioning actuator

Table B7.1:
Measuring systems for
closed-loop pneumatics

Measuring range

Measuring systems which measure the same physical variable can be distinguished by their measuring range. The measuring range specifies the range within which the input signal of the sensor can vary and still be correctly detected.

Table B7.2 lists three pressure sensors with different measuring ranges.

Measuring range	Sensor type
0 - 2.5 bar	SDE-2.5-10V-20mA
0 - 10 bar	SDE-10-10V-20mA
0 - 16 bar	SDE-16-10V-20mA

Table B7.2:
Measuring ranges of
one series of
pressure sensors (Festo)

Example of application illustrating measuring range

A pressure sensor is to be selected for a pneumatic closed-loop pressure control system. The controlled variable may vary within the range of 0 and 7 bar.

- If the pressure sensor SDE-2.5-10V-20mA is selected, pressure above 2.5 bar will not be detected.
- If the pressure sensor SDE-16-10V-2.5A is used, only a relatively small part of its measuring range will be used.
- Use of a pressure sensor SDE-10-10V-2.5A allows the entire pressure range of the controlled variable to be detected. A larger part of the measuring range is used than in the case of the pressure sensor with a measuring range of 16 bar. This sensor is therefore the most suitable type for the given application.

Output signal

On the basis of the output signal concerned, a distinction can be made between

- binary measuring systems
- analogue measuring systems, and
- digital measuring systems

Table B7.3 shows the combinations of controllers and measuring systems used in practice.

- Binary measuring systems are used only in combination with non-dynamic controllers. A pressure sensor can, for example, 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. Speedometers and pressure sensors are examples of analogue measuring systems.
- Digital measuring systems are used in combination with digital controllers. Examples are digital positioning systems and digital rotary angle sensors in CNC machine tools.

Interface

The output signal of the sensor acts on the controller as an input signal. Sensors with an analogue output signal are used with analogue electrical controllers. Assuming that signal processing is carried out within the measuring system, the output signal will be a

- current or
- voltage

The output signal of the measuring system and the input signal of the controller must be matched. This means:

Same physical variable

Same signal range

Table B7.4 provides an overview of the usual types of interfaces between sensors and controllers.

Interface		Range of measuring system output signal
Current interface		4 – 20 mA
		0 – 10 V 0 – 5 V
Voltage interface		

Table B7.4:
Output signals of
analogue 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

Table B7.3:
Combinations of
controllers and measuring
systems



If the distance between the sensor and the controller is large, a voltage drop in the cable may result. This will falsify the signal in the case of a voltage interface. A current interface should therefore be selected if signal lines are long.

7.3 Selection criteria for measuring systems

Table B7.5 summarises the most important selection criteria for measuring systems.

Table B7.5:
Selection criteria for
measuring systems

Input signal	Cost
Variable to be measured	Cost of sensor
Measuring range	Cost of measured value processing unit
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	Power supply
Resistance to ageing	

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 pneumatic positioning actuator used for palletising.

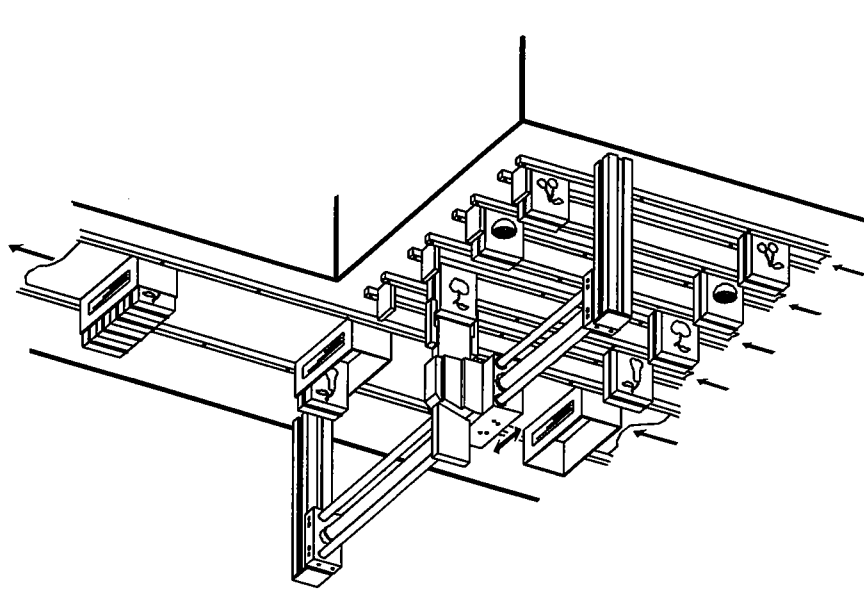
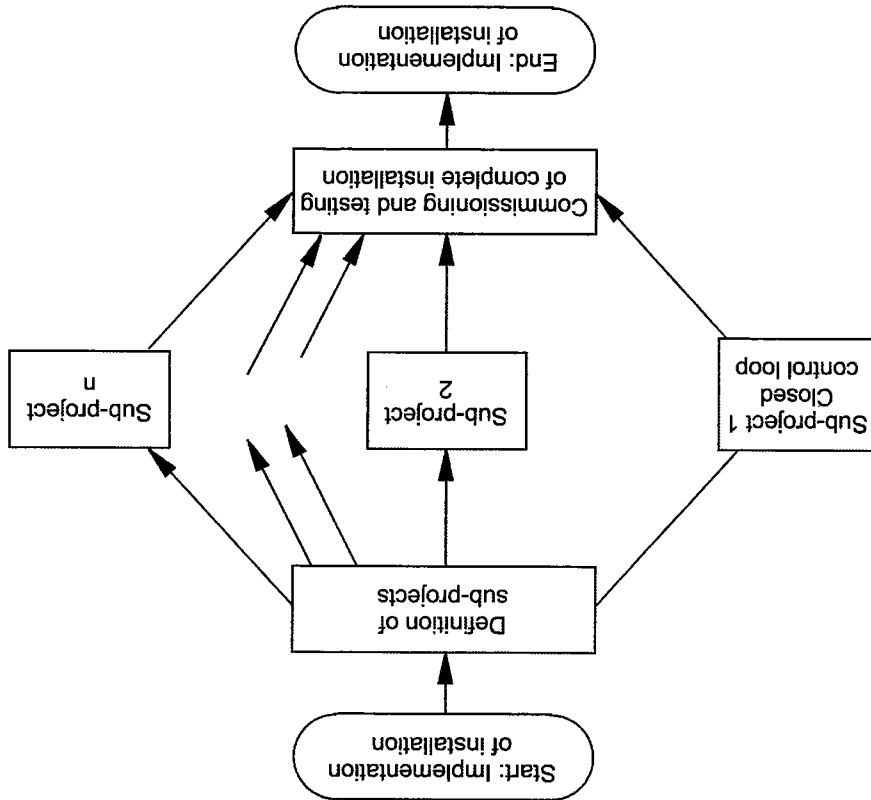


Fig. B8.1:
Closed control loop as part
of a production installation

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.

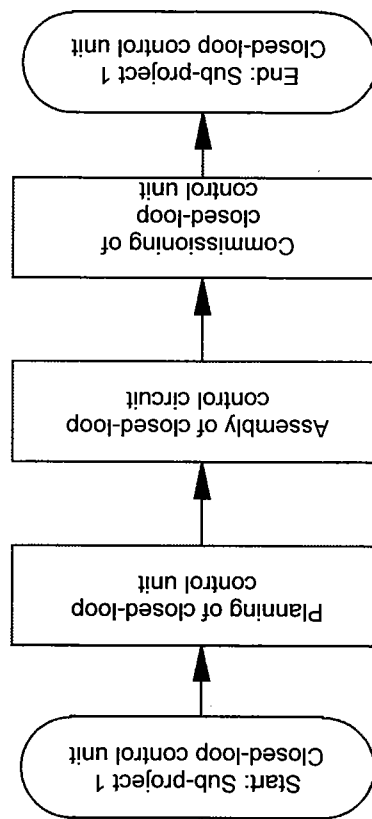


Fig. B8.3:
Working steps for the
implementation of a
closed control loop

8.2 Planning

The flow diagram in Fig. B8.4 shows the various steps in the planning of a closed-loop control circuit.

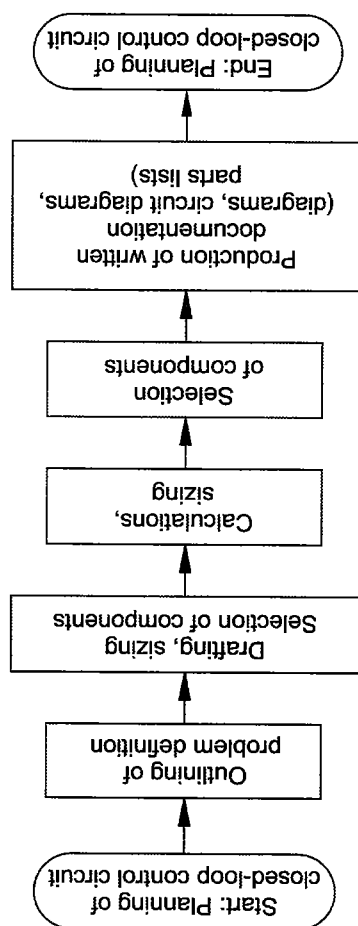


Fig. B8.4:
Planning of a
closed-loop control circuit

Concretisation of 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 in-stallation control system?
- 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 dimensioning

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

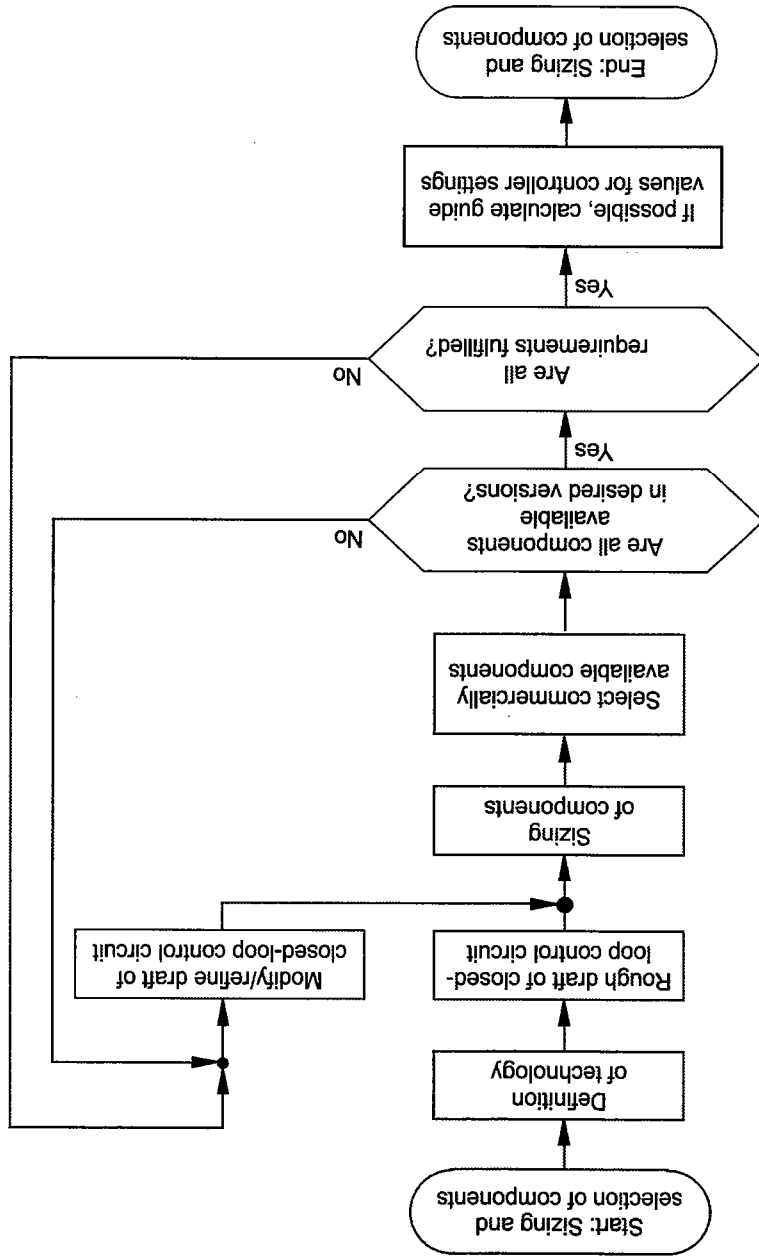


Fig. B8.5:
Flow diagram for drafting,
selection and sizing

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 to 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 compressed-air 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 compressed air 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 fulfill 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 pneumatic 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.
- Device numbers and technical data on 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).

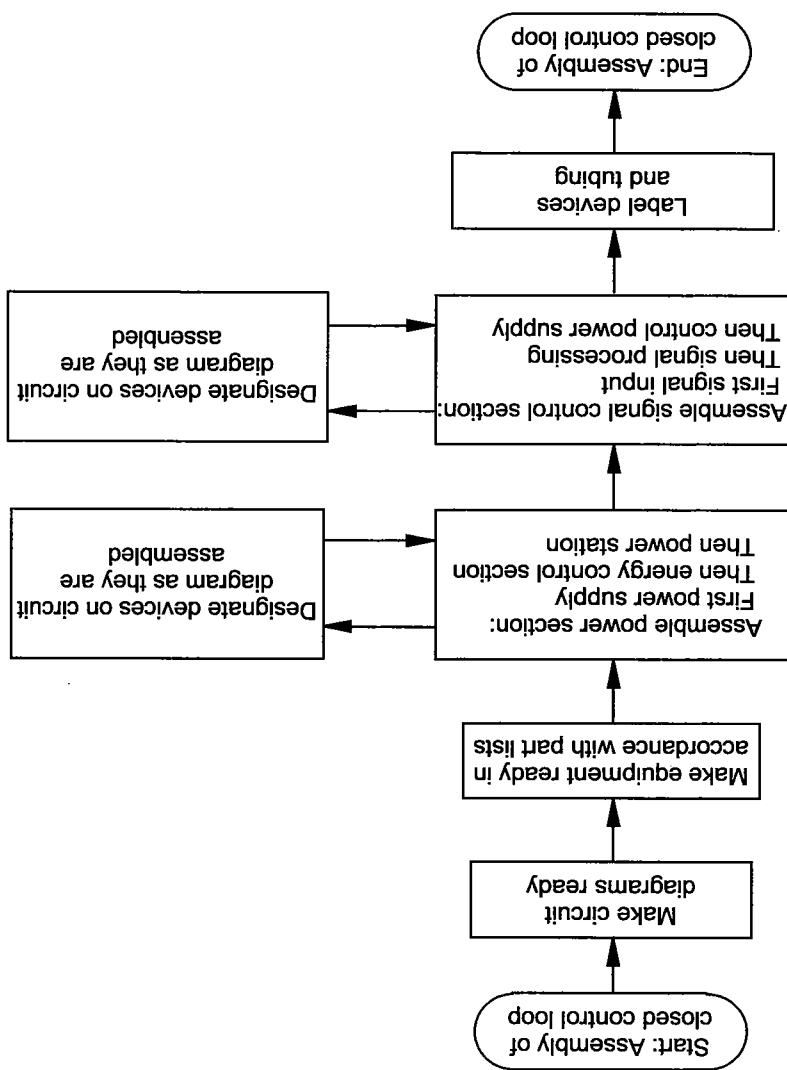
Configuration of devices and tubing

Signals are propagated in air at the speed of sound. This is approx. 330 m/s at 20°C. A piece of tubing 1 m long will produce a signal delay of approx. 3 ms.

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

Distortion and interference may result from the transmission of signals through electrical cables. 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, following 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 Inbetriebnahme

Commissioning a closed control loop

The following flow diagram shows the procedure for the commissioning of a closed control loop.

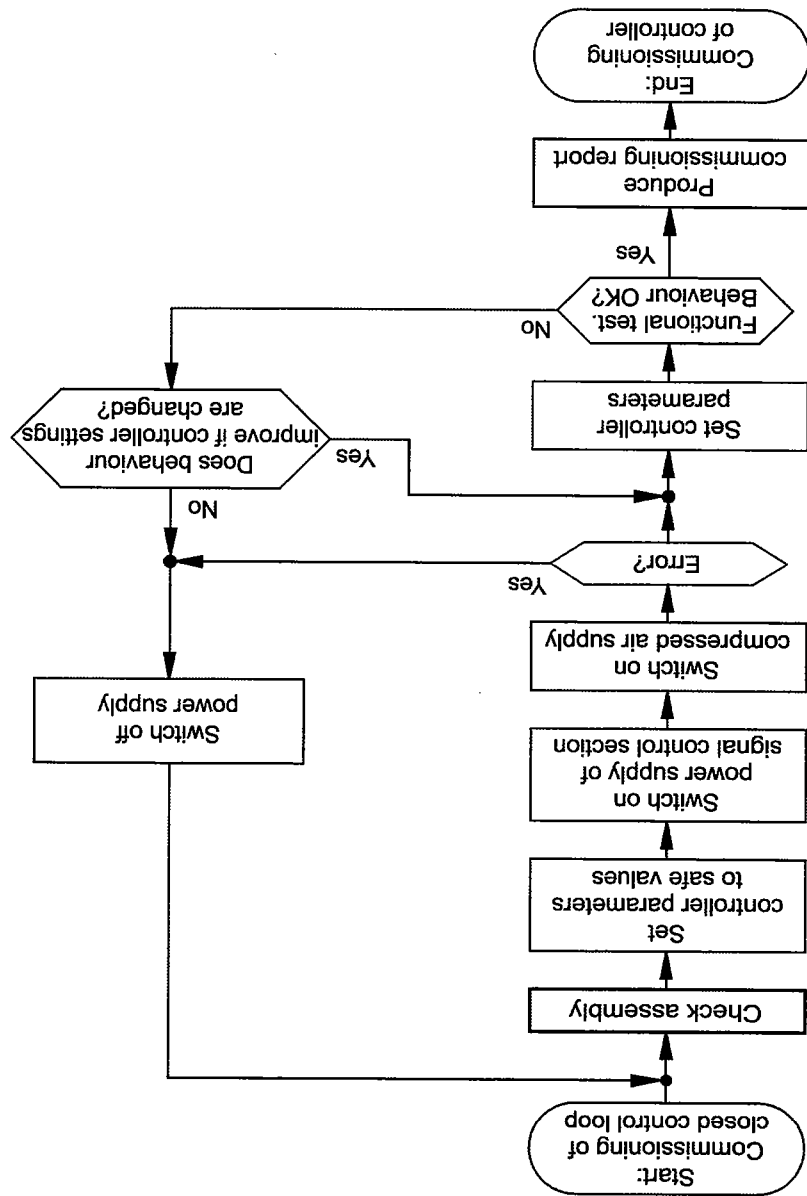


Fig. B8.7:
Flow diagram for
commissioning of a
closed control loop

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 pressure supply 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 compressed air 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.

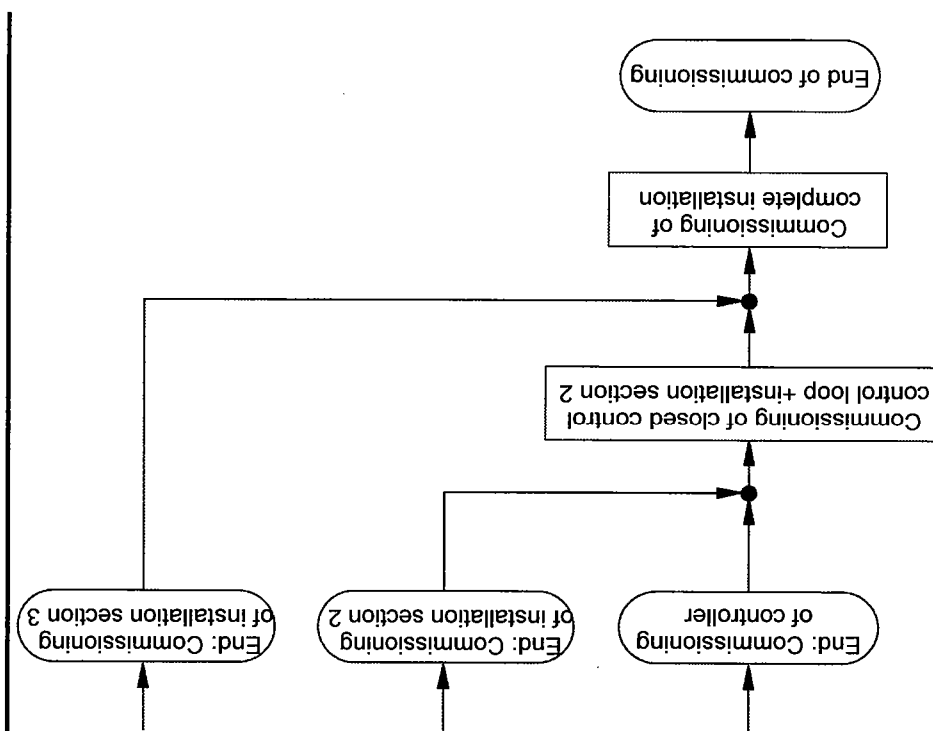


Fig. B8.8:
Flow diagram for commissioning of an installation

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

Controller setting	Mathematical methods	Standard methods	Empirical methods
Advantages	Particularly suitable for complex controlled systems	Same setting method can be used for widely-differing controlled systems	Relative easy to use
	Easy to use		
Disadvantages	Great deal of previous knowledge required	Optimum control behaviour generally not achieved	Different methods used for different controlled systems
Importance for industrial practise	Low	High	High

- 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

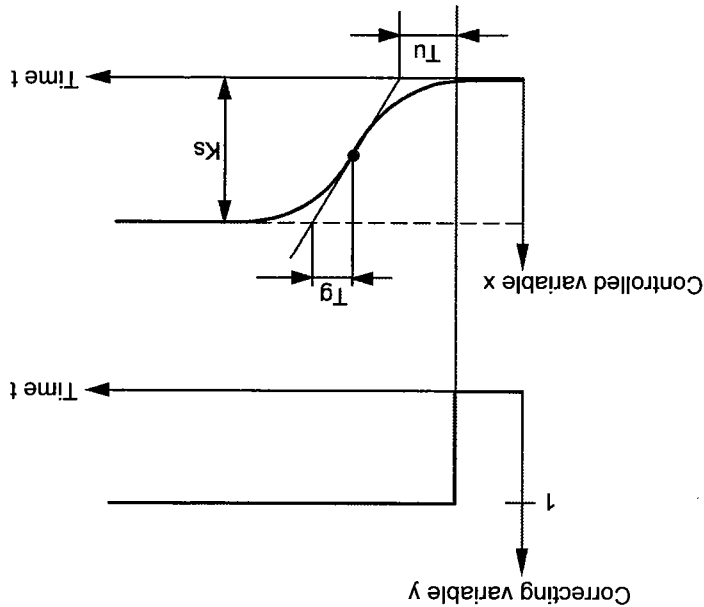
There are two ways of setting controllers using the Ziegler-Nichols method:

- 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 T_t , time constant T_s and controlled-system gain K_s . The controller parameters are calculated from these using Table B8.2b.

Fig. B8.9:
Controlled-system
characteristics for the
Ziegler-Nichols method



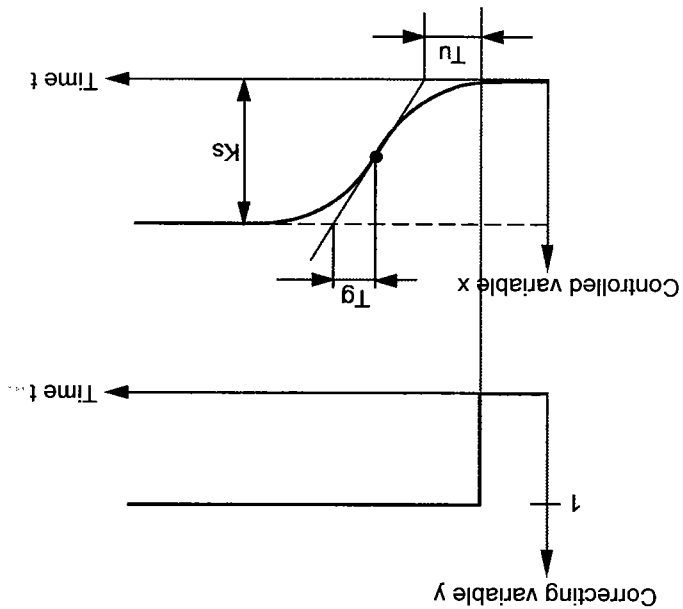
The Ziegler-Nichols method allows optimisation of the response of a closed control loop to interference. When the reference variable is made to execute a step change, controller settings produced using the Ziegler-Nichols method will result in a pronounced overshoot of the controlled variable.

Table B8.2:
Controller setting using the
Ziegler-Nichols method

Controller			T_n	T_v
a)	P	0.5 KRkrit	--	--
	PI	0.45 KRkrit	0.83 Tkrit	--
	PID	0.6 KRkrit	0.5 Tkrit	0.125 Tkrit
Controller			T_n	T_v
b)	P	$\frac{TS}{K_S \cdot T_t}$	--	--
	PI	$0.9 \frac{TS}{K_S \cdot T_t}$	3.3 T_t	--
	PID	$1.2 \frac{TS}{K_S \cdot T_t}$	2 T_t	0.5 T_t

Closed loop control settings according to Chien, Hrones and Reswick

Fig. B8.10:
Delay time T_u and
compensation time T_g



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 T_u and compensation time T_g are determined from this step response in accordance with Fig. B8.1
- If the following applies: $\frac{T_g}{T_u}$ greater than 3, optimised controller parameters can be set on a PID controller in accordance with Table B8.3.

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

Controller	A periodic control curve			Control curve with 20% overshoot		
	Interference variable	Reference variable	Interference variable	Reference variable		
P	KR	$0.3 \frac{T_g}{T_u \cdot K_s}$	KR	$0.7 \frac{T_g}{T_u \cdot K_s}$		
	KR	$0.6 \frac{T_g}{T_u \cdot K_s}$	KR	$0.6 \frac{T_g}{T_u \cdot K_s}$		
	Tn	4 Tu	Tn	2.3 Tu		
PI	KR	$0.6 \frac{T_g}{T_u \cdot K_s}$	KR	$0.7 \frac{T_g}{T_u \cdot K_s}$		
	KR	$0.35 \frac{T_g}{T_u \cdot K_s}$	KR	$0.7 \frac{T_g}{T_u \cdot K_s}$		
	Tn	1.2 Tg	Tn	2.3 Tg		
PID	KR	$0.95 \frac{T_g}{T_u \cdot K_s}$	KR	$1.2 \frac{T_g}{T_u \cdot K_s}$		
	Tn	2.4 Tu	Tn	2 Tu		
	Tv	0.42 Tu	Tv	0.43 Tu		

Table B8.3:

Controller setting using the
Chien, Hrones and Reswick
method

8.6 Fault-finding

Faults in a closed control loop may express themselves in external symptoms. These symptoms are listed in Table B8.4.

Table B8.4: Effects of errors in a closed control loop	
Effect of error	Cause of error in 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 variable	Table B8.8

Possible causes of faults 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	
Supply pressure too low	
Tubing cross-sections too small	
Tubing blocked	
Table B8.6: Possible causes of steady state oscillations	
Controller parameters incorrectly set	
Sensor defective	

Table B8.7: Possible causes if controlled variable runs against a stop	
Control direction incorrect (e.g. cables or tubing crossed over)	
Sensor defective or open-circuit	
Final control element defective/jammed	
Controller defective	

Table B8.8: Possible causes 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 powersection switched off	

Part C – Solutions

I. Non-dynamic closed-loop pressure control circuit

- | | | |
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| Exercise 2: | Spot-welding machine | C-5 |
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| | Transition functions of controlled systems | |
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| | Commissioning of a three-step-action controller | C-13 |

II. Dynamic closed-loop pressure control circuit

- | | | |
|--------------|---|------|
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Exercise 19:	Deburring an engine block	C-51
Exercise 20:	Cake production	C-55
Exercise 21:	Palletizing station	C-59
	Influence of mass load and tubing volume	

Maintenance of a pressure gauge

1.1 Definition of measured variables and selection of measuring system

The given parameters produce the following measured variables:

Input variable: Pressure in bar [bar]

Output variable: Voltage in volts [V]

An analogue pressure sensor is the most suitable type of signal converter.

1.3. Plotting the pressure gauge characteristic

Measurement with increasing pressure

Pressure gauge reading [bar]	Pressure sensor voltage [V]
0	0
1	1.1
2	2.14
3	3.14
4	4.12
5	5.13
6	6.14

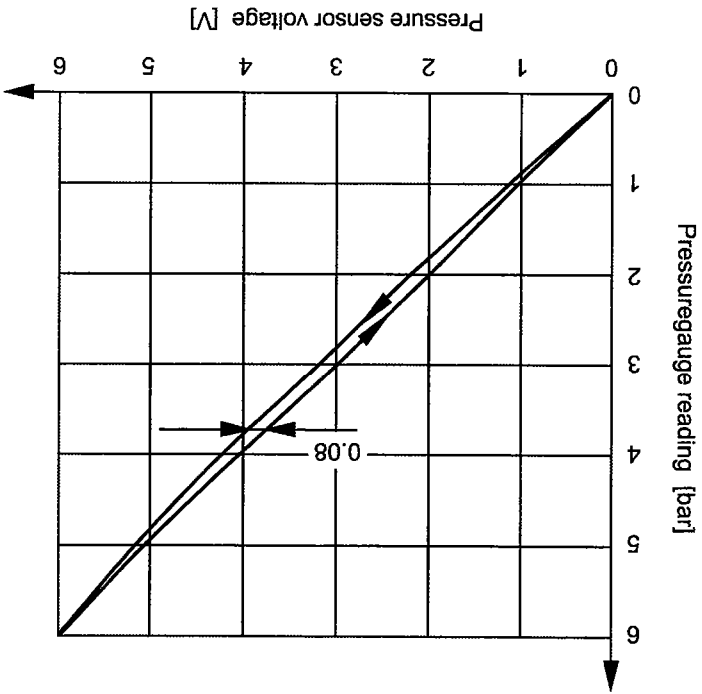
Table C1.1:
Characteristic

Measurement with decreasing pressure

Pressure gauge reading [bar]	Pressure sensor voltage [V]
6	6.14
5	5.05
4	4.05
3	3.06
2	2.06
1	1.08
0	0.007

Table C1.2:
Characteristic

Fig. C1.1:
Pressure gauge
characteristic



1.4 Determining the hysteresis

How great is the hysteresis of the pressure gauge?

$$H = \frac{\text{Max. divergence}}{\text{Input range}} \cdot 100 \%$$

$$H = \text{---} \cdot 100\% = \text{---} \%$$

The hysteresis of the pressure gauge is:

$$H = \frac{0.08 \text{ bar}}{6 \text{ bar} - 0 \text{ bar}} \cdot 100 \% = 1.33 \%$$



Deviations in the measured values are possible. These will in turn produce variations in the characteristic and hysteresis.

Spot-welding machine

2.1 Calculation of setpoints and switching differences

The formula for the chamber pressure is as follows:

$$\text{Chamber pressure [bar]} = \frac{40 \cdot \text{Cylinder force [N]}}{\text{Piston diameter}^2 [\text{mm}^2]} \cdot 3.14$$

The cylinder chamber pressures are obtained by inserting the permissible upper and lower cylinder forces into the above formula consecutively. The difference in chamber pressures is calculated by deducting the upper chamber pressure from the lower.

The associated voltages can be determined from the linear sensor characteristic as follows:

- Find the calculated chamber pressure on the horizontal scale.
 - A vertical auxiliary line should be drawn through this scale value to intersect with the characteristic.
 - A horizontal auxiliary line from this point to the vertical scale will give the desired voltage value.
- The diagram below shows this operation for a chamber pressure of 4 bar.

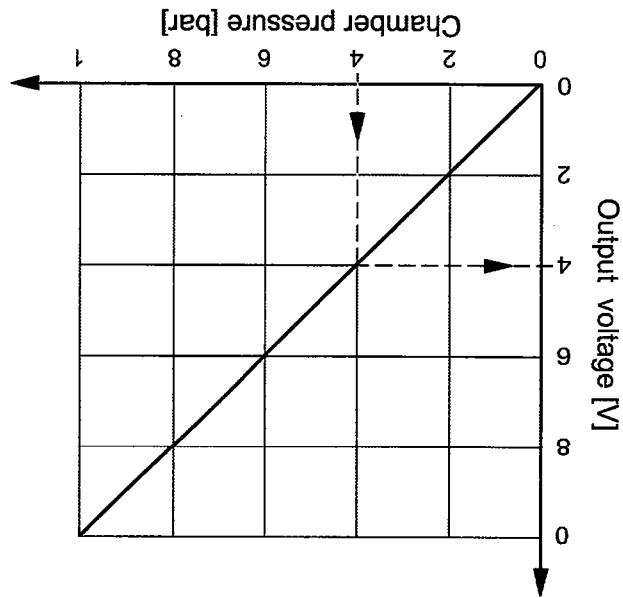


Fig. C2.1:
Characteristic

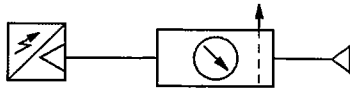
The determined results are as follows:

Table C. 2.1:
Result

Permissible	Permissible		Difference between chamber pressures [bar]	Setpoint [N]	Switching difference [N]
	lower chamber pressure [bar]	upper chamber pressure [bar]			
392.50	471.00	2.0	0.4	2.2	0.4
588.75	745.75	3.0	0.8	3.4	0.8
785.00	981.25	4.0	5.0	4.5	1.0

2.3 Drawing the pneumatic and electrical test circuits

Fig. C2.2:
Pneumatic circuit diagram



Packaging machine

3.2 Determining transition functions and measurement of time constants

Measurements have produced the following transition functions.

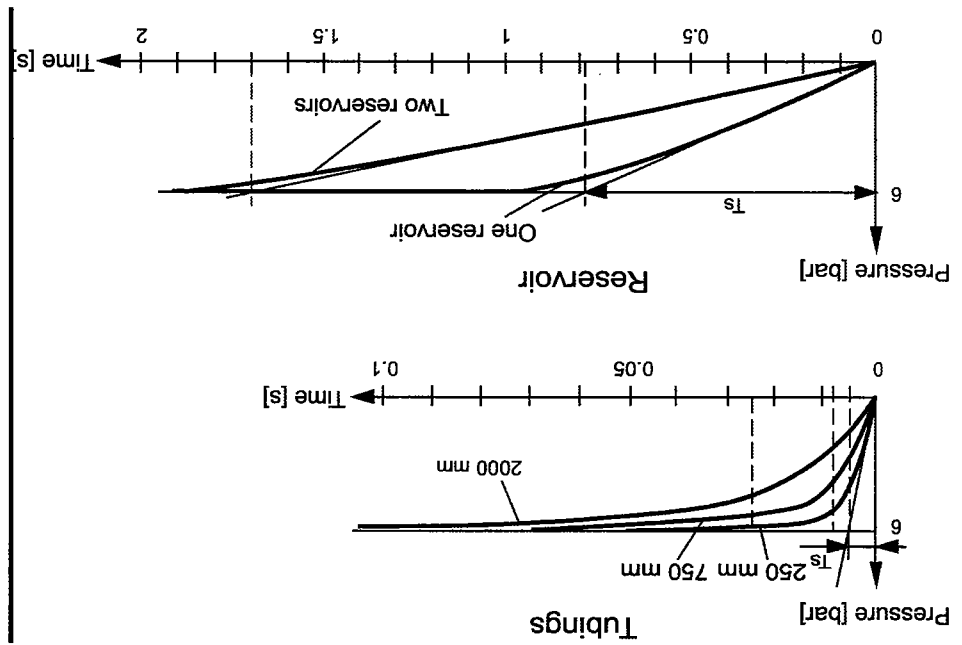


Fig. C3.1:
Transition functions

Table C3.1:
Time constants

Controlled system	Length Volume	Time constant T_s [s]	Recommended oscilloscope setting (time/division)
Tubing	250 mm	0.005	10 ms
Tubing	750 mm	0.008	10 ms
Tubing	2000 mm	0.024	20 ms
One reservoir	0.4 l	0.8	200 ms
Two reservoirs	je 0.4 l	1.7	500 ms

How does the time constant change as the volume of the controlled system increases?

☐ Stays the same

☐ Becomes smaller

☐ Becomes larger

The time constant becomes larger as the volume increases, i.e. it takes longer to compensate for a change in the input variable. We accordingly also speak of fast and slow controlled systems.



The two-reservoir system theoretically has two time constants

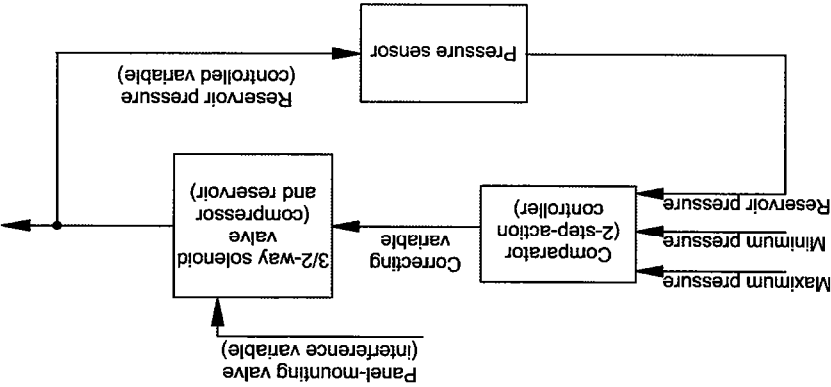
What property of air is the reason for the difference in the time constants?

The difference in the time constants is due to the compressibility of air.

Reservoir-charging circuit

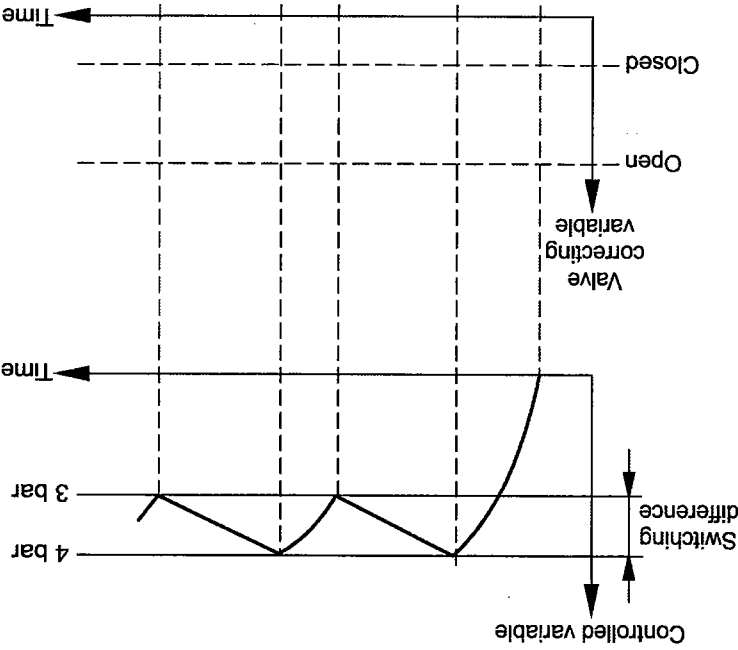
4.1 Drafting of closed-loop control circuit

Fig. C4.1:
Symbol for a closed-loop
control circuit



4.3 Commissioning of closed-loop control circuit

Fig. C4.2:
Curves for controlled and
correcting variables



What do you notice when you compare this correcting variable curve with Fig. A4.3?

The valve correcting variables for the two applications are an exact mirror image of each other.

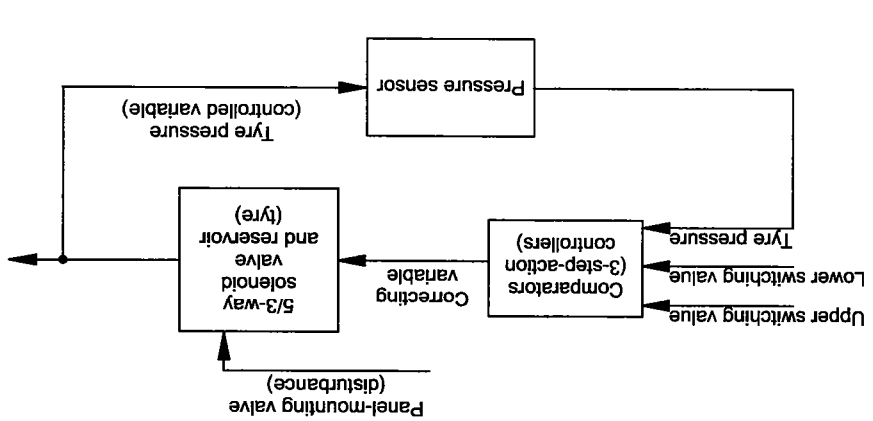
Explain your observations:

The reason for the difference in switching behaviour is that in the case of the charging circuit the switching valve supplies the reservoir with compressed air, while in the discharging circuit the valve exhausts the reservoir.

Tyre test-rig

5.1 Drafting of closed-loop control circuit

Fig. C5.1:
Block diagram for
closed-loop control circuit



5.3 Commissioning of three-step-action controller

Table C5.1:
Criteria catalogue for
closed-loop controllers

Criteria	Two-step-action controller without switching difference	Two-step-action controller with switching difference	Three-step-action controller without switching difference	Three-step-action controller with switching difference	Two-step-action controller with 2 switching differences
Number of setpoints	1	1	1	1	1
Number of switching differences	0	1	0	1	2
Maximum number of correcting variable values	2	2	3	3	3
Number of dead zones	0	0	1	1	1

Pneumatic Press

6.2 Recording of pressure/signal characteristics

Correcting variable [V]	Operating pressure [bar]	U [V]	p [bar]
3	0.04	5.05	3.45
3.5	0.05	5.1	3.7
4	0.07	5.15	3.99
4.5	0.25	5.2	4.24
4.6	0.41	5.3	4.37
4.7	0.73	5.4	4.68
4.8	1.46	5.5	4.77
4.85	1.98	6	4.86
4.9	2.59	6.5	5.11
4.95	3.03	7	5.26
			5.40

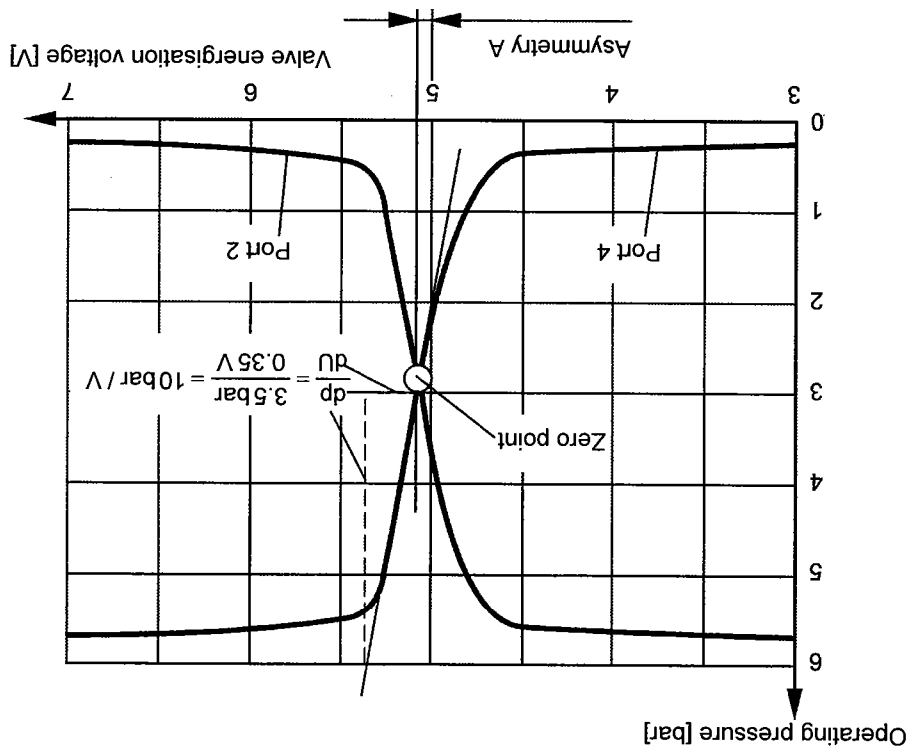
Table C6.1:
Value table for port 4

Correcting variable [V]	Operating pressure [bar]	U [V]	p [bar]
3	5.45	5.05	2.42
3.5	5.33	5.1	1.85
4	5.16	5.15	1.26
4.5	4.80	5.2	0.96
4.6	4.64	5.3	0.67
4.7	4.42	5.4	0.35
4.8	3.99	5.5	0.22
4.85	3.71	6	0.14
4.9	3.32	6.5	0.05
4.95	2.93	7	0.03
			0.03

Table C6.2:
Value table for port 2

The graph shows two pressure-signal characteristics for the MPYE 5 1/8 dynamic valve. It should, however, be noted that the pressure-signal characteristic is subject to the influence of many different factors. Valve production tolerances, for example, may result in noticeable deviations of the pressure-signal characteristic from the curve shown here.

Fig. C6.1:
Pressure-signal
characteristics



6.3 Determining characteristic data and assessment of valve

Table C6.3:
Characteristic data of valve

Characteristic data	Data/tolerances		Measured values at port	
	Asymmetry	Less than 0.5 V	0.05 V	0.07 V
Gradient at zero point	Greater than 5 bar/V	10 bar/V	9.5 bar/V	Negative
Overlap	Not specified	Negative	Negative	Negative

Is the valve suitable for use with the pneumatic press?

☒ Yes, the valve is suitable for use with the pneumatic press, since all tolerances are maintained.

Quality assurance in the production of PID controller cards

7.1 Determining the overload voltage of the differential inputs

Overload voltage	Positive range	Negative range
– of reference variable	10	– 10
– of controlled variable	10	– 10

Table C7.1:
Overload voltage

The measured results may vary due to component tolerances.



7.2 Check of the function of the input summation point

Reference variable voltage w [V]	Controlled variable voltage x [V]	System deviation e [V]
1	0	1
1	1	0
1	– 1	2
0	1	– 1
0	– 1	1
– 1	0	– 1

Table C7.2:
Measured-value table

7.3 Determining the correcting variable offset range

Range selector switch	Minimum value	Maximum value	Difference
on – 10 V ... 10 V	– 7.5	7.5	15
on 0 V ... 10 V	1.25	8.75	7.5

Table C7.3:
Correcting variable offset

7.4 Check of 15 V power supply

What is the pressure when the deviation is equal to zero?

A pressure of 5 bar is present when the system deviation equals zero.

Baffle-plate flow sensor

8.1 Determining the control range x_h of the P controller

Range	Minimum value	Maximum value
Control range x_h	- 14.6 V	13.6 V

Table C8.1:
Control range of the
P controller

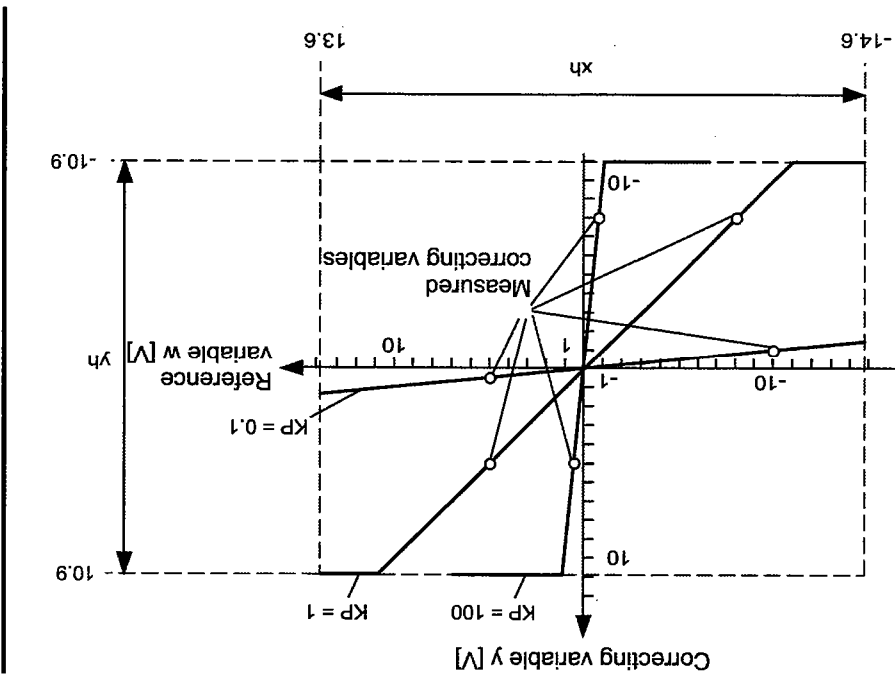
8.2 Determining the correcting range y_h of the P controller

Range	Minimum value	Maximum value
Control range x_h	- 10.9 V	10.9 V

Table C8.2:
Correcting range of the
P controller

8.3 Plotting the P controller characteristics

Fig. C8.1:
P controller characteristics



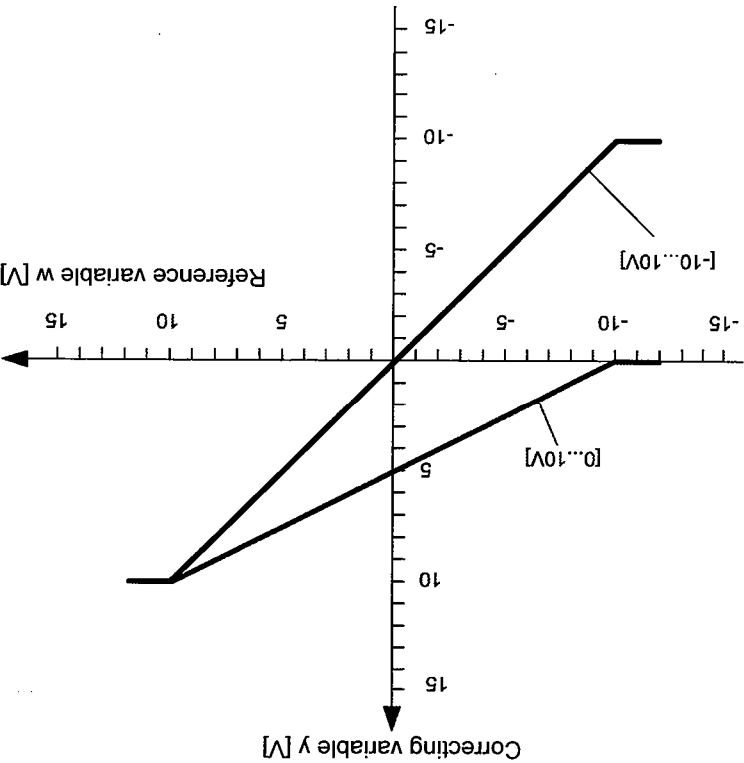
8.4 Plotting the limiter characteristic

Table C8.3: Limiter characteristic		
Reference variable w [V]	(0 ... 10) [V]	Correcting variable y (-10 ... 10) [V]
-12	-0.42	-10.86
-10	0.25	-9.60
-5	2.50	-4.86
-2	4.03	-1.94
0	5.00	0.00
2	5.95	1.93
5	7.39	4.80
10	9.81	9.62
12	10.45	10.92

The measured results may vary slightly due to component tolerances.



Fig. C8.2:
Limiter characteristic



Pneumatic post system

9.2 Check that control direction is correct

Input signal	Output signal	Effect on controlled variable	Assessment of control direction
Increase reference variable	Controlled variable	Controlled variable ☒ rises ☐ falls	Control direction ☒ correct ☐ incorrect

Table C9.1:
Control direction

9.3 Investigation of closed-loop control circuit

Changes	Observations	Explanation
Increase the reference variable to 4 V	The controlled variable ☒ increases ☐ stays the same ☐ decreases	The reference variable produces a larger system deviation. This acts via KP to produce a deflection of the valve spool, with the result that the controlled variable increases.
Set KP = 2	The controlled variable ☐ increases ☐ stays the same ☒ decreases	KP is reduced. The correcting variable accordingly decreases ($y = KP \cdot e$). The smaller correcting variable produces a weaker closed-loop control action, and the controlled variable thus falls.
Turn the correcting variable offset as far as possible to the right	The controlled variable ☐ increases ☐ stays the same ☒ decreases	The correcting variable falls. Working port 4 is closed slowly and port 2 opens

Table C9.2:
Investigation of control circuit

9.4 Investigation of factors influencing the control direction

Table C9.3:
Factors influencing
the control direction

Type of incorrect polarity	Effect on controlled variable
Reference variable signal	The reference variable (RV) is present as a negative value. The controlled variable (CV) falls to zero, as a negative pressure cannot be achieved.
Correcting variable signal	RG falls to zero. The valve is energised in the opposite direction.
Valve ports 2 and 4	CV rises to its maximum value.
Output signal of measuring system	CV rises to its maximum value, since this is added to RV and produces an incorrect direction of action.
Reference and controlled variables	CV falls to zero

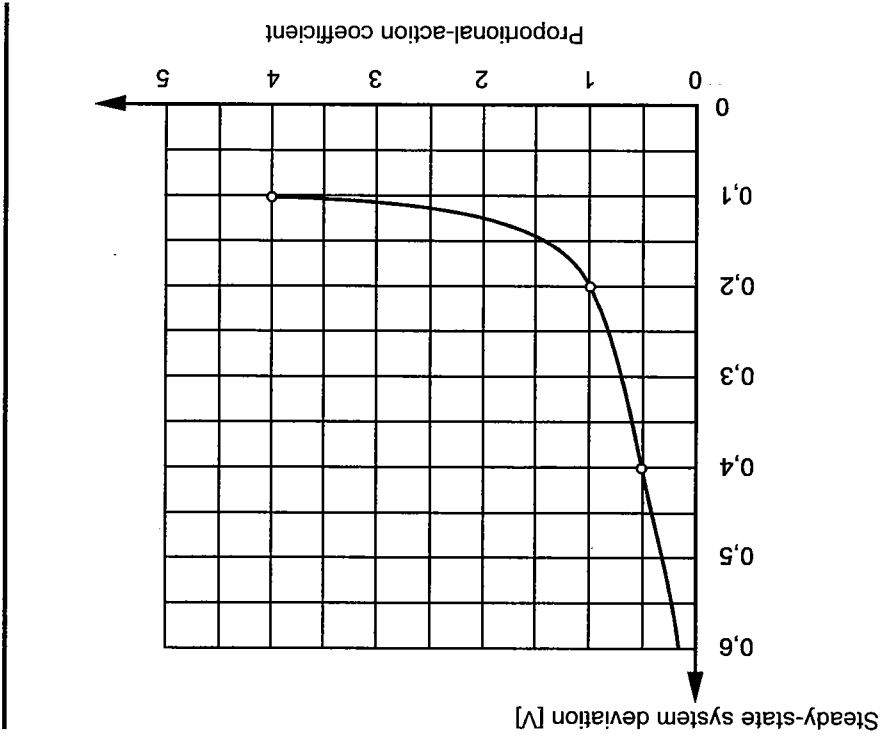
Clamping device

10.2 Plotting the characteristic data for control quality

Table C10.1:
Characteristic data
for control quality

Proportional coefficient K_P	Reference variable w [V]	Controlled variable x [V]	Steady statesystem deviation e_{stat} [V]	Overshoot amplitude x_m [mV]
4.0	3 V	2.9	0.1	0
1.0	3 V	2.8	0.2	0
0.5	3 V	2.6	0.4	0
0.1	3 V	2.3	0.7	0

Fig. C10.1:
Characteristics



How does the steady-state system deviation change as a function of the proportional coefficient?

The larger the proportional coefficient selected for a given reference variable, the smaller the steady state system deviation.

10.3 Determining the limit of stability

Determine the limit of stability for the specified reference variable step changes.

Table C10.2:
Limit of stability

Step range of reference variable	Critical proportional-action coefficient K_{Pcrit}
1 V – 1.5 V	190
2 V – 2.5 V	160
3 V – 3.5 V	140
4 V – 4.5 V	160
5 V – 5.5 V	200

Which step range has the lowest critical proportional coefficient?
In these measurements, the smallest proportional-action coefficients are obtained in the centre step ranges (3 V–3.5 V).

Which step range has the highest critical proportional coefficient?
The largest proportional-action coefficients are obtained in the extreme step ranges (1 V–1.5 V and 5 V–5.5 V).

Which critical proportional coefficient is most important for the design of a closed-loop control circuit?

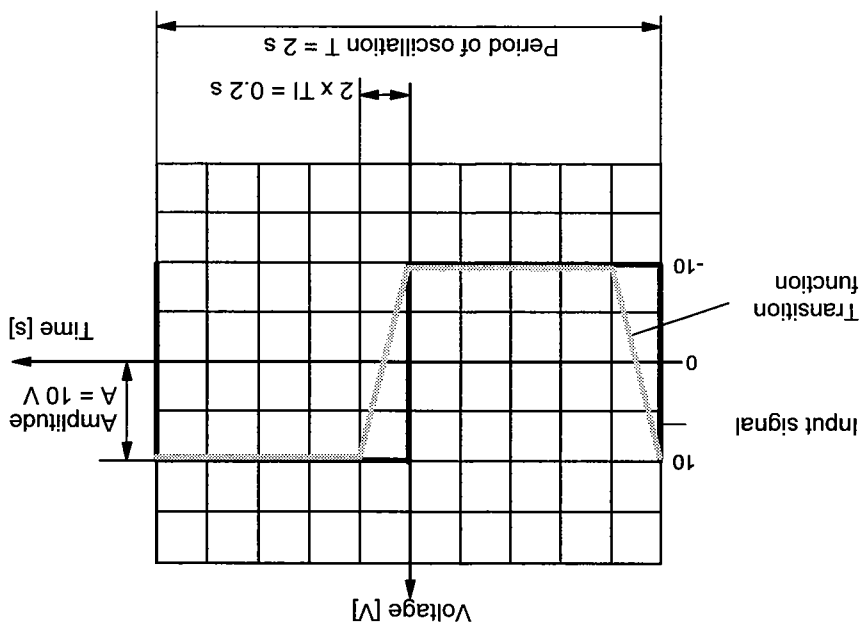
- ☒ Lowest critical proportional coefficient
- ☐ Highest critical proportional coefficient

The lowest critical proportional-action coefficient is the decisive factor in the dimensioning of closed-loop control circuits. Only in this way can it be ensured that the closed-loop control circuit will not oscillate with any reference variable.

Pneumatic screwdriver

11.1 Plotting the transition function with the I controller

Fig. C11.1:
Transition function



11.2 Measurement of the integration time T_I and calculation of the integral-action coefficient

Example of settings

Measured integration time: $T_I = 110 \text{ ms}$

Integral-action coefficient setting: $K_I = 10 \text{ 1/s}$

Calculated integration time: $T_I = 1/K_I \text{ ms}$

Deviation = Measured integration time - Calculated integration time
 $= 10 \text{ ms}$

What percentage setting accuracy results in this case?
 The setting accuracy which results in this case is:

$$(10 \text{ ms} \cdot 100 \%) / 100 \text{ ms} = 10 \%$$

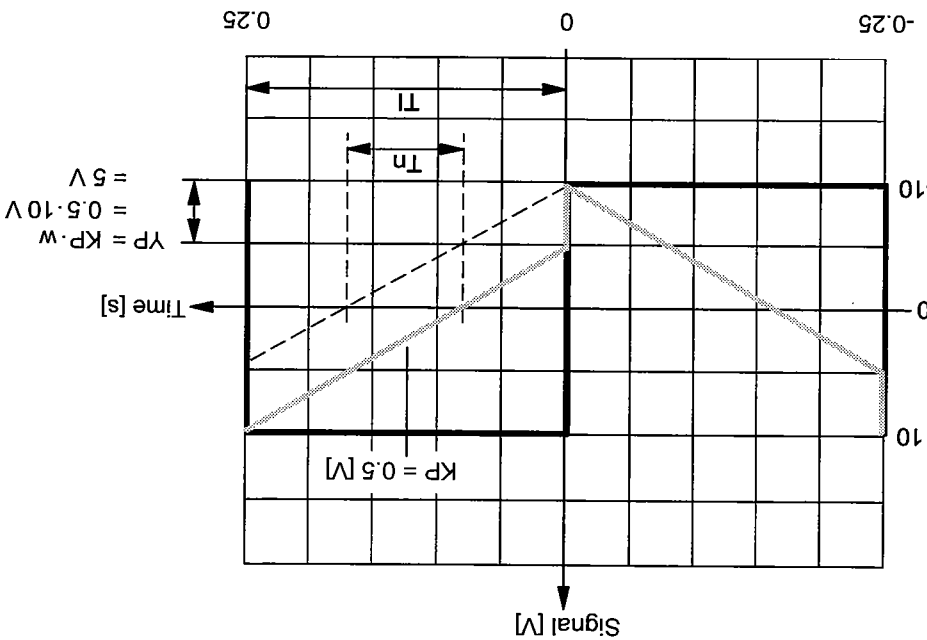
11.3 Determination of the minimum and maximum integration times which can be set

Minimum integration time $T_{\min}$
(with $K_I = 1000 \text{ 1/s}$) = 1 ms

Maximum integration time $T_{\max}$
(with $K_I = 0 \text{ 1/s}$) = Infinite, since the input signal is not integrated due to the fact that $K_I = 0$

11.4 Plotting the transition function with the PI controller

Fig. C11.2:
Transition function



11.5 Measurement of the integral-action time T_n and comparison of this with the values set

Parameter settings $K_P = 0.5$ and $K_I = 6 \text{ 1/s}$:

Integral-action time read: $T_n = 90 \text{ ms}$

Calculated integral-action time: $T_n = 83 \text{ ms}$

Deviation = Read T_n - Calculated $T_n = 7 \text{ ms}$

11.6 Determination of the minimum and maximum integral-action times which can be set

Minimum integral-action time $T_{n \min}$

$$(K_P = 0; K_I = 1000) = 0 \text{ ms}$$

Maximum integral-action time $T_{n \max}$

$$(K_P = 1000, K_I = 0) = \text{infinite due to } 1000 / 0 \text{ s}$$

11.7 Comparison of P, I and PI controllers

Criteria	Controller types		
	P	I	PI
Speed	Fast	Slow	Fast
Steady state system deviation	Yes	No	No

Table C11.1:
Comparison of various
types of controllers

Infection-moulding machine

12.2 Determination of the limit of stability of the closed-loop control circuit with the I controller

Integral-action coefficient K_I [1/s]	Stable?	Maximum overshoot amplitude x_m [V]	
		Upper value	Lower value

0.5	Yes	1	1.4
1	Yes	1	1.2
5	Yes	1.2	1.1
10	No	1.2	1.4
20	No	1.4	1.4
50	No	1.4	1.2
100	No	1.0	1.0

At what K_I value do steady-state oscillations first occur (limit of stability)?

Steady-state oscillations occur even with relatively small integral-action coefficients. With this tests assembly, the value in question is approx. $K_I = 10$ [1/s]. This illustrates the general pronounced tendency of integral-action controllers to oscillation.

How does the overshoot amplitude change when K_I increases?
Consider only those K_I values at which the closed-loop control circuit is stable.

The overshoot amplitude
☒ becomes larger
☐ becomes smaller
☐ stays the same

The overshoot amplitude rises to the limit of stability. It is not meaningful to set the controller above this limit.

Table C12.2:
Parametrisation of the
PI controller

Coefficients		Optimum values
KP	KI	
90 ... 120	30 ... 60	

12.3 Parametrisation of the PI controller

Can the values for KP and KI in this closed-loop control circuit be increased to any desired value?

If the values for KP and KI are too high, the closed-loop control circuit will become unstable, with the result that the controller parameters are limited by the limit of stability.

How do the characteristic data overshoot amplitude, settling time and steady-state system deviation vary if KI is set to zero with KP unchanged?

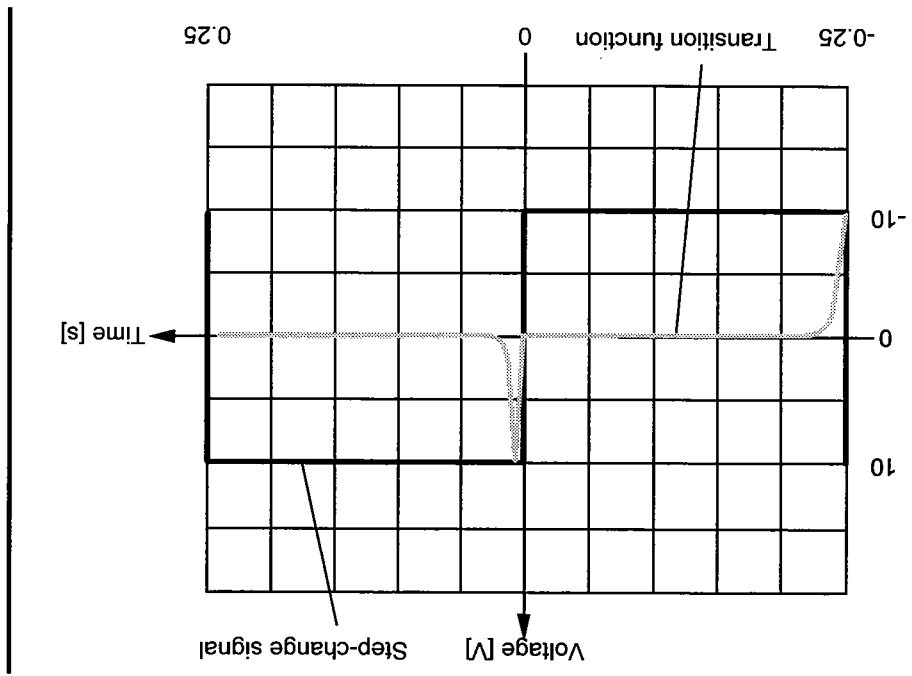
- The characteristic data
- ☐ become noticeably larger
 - ☐ become noticeably smaller
 - ☒ stay roughly the same

The overshoot amplitude, settling time and steady-state system deviation remain roughly the same. This is due to the high value of KP, which in itself produces good control behaviour.

Forming of moulded packaging

13.1 Drawing the transition and ramp responses of the D controller

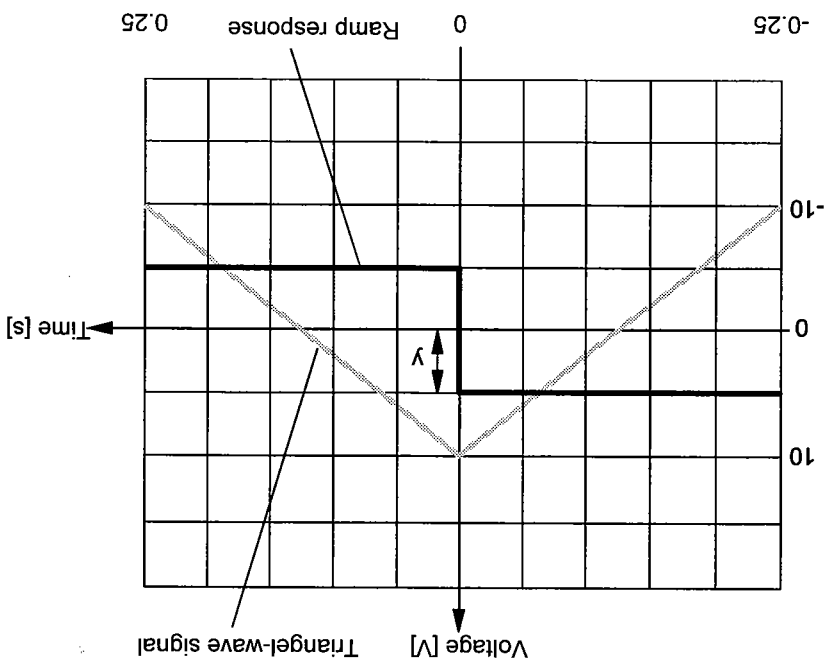
Fig. C13.1
Transition function



How can you explain the shape of the curve for the transition function?

The D controller reacts only to a change in the system deviation. At the moment the square-wave signal executes a step change, this change is infinitely large, with the result that the controller is briefly activated and then returns immediately to its initial position. This controller reaction can be recognised as a peak in the above curve.

Fig. C13.2:
Transition function:



The correcting variable y can be calculated in this case as follows:

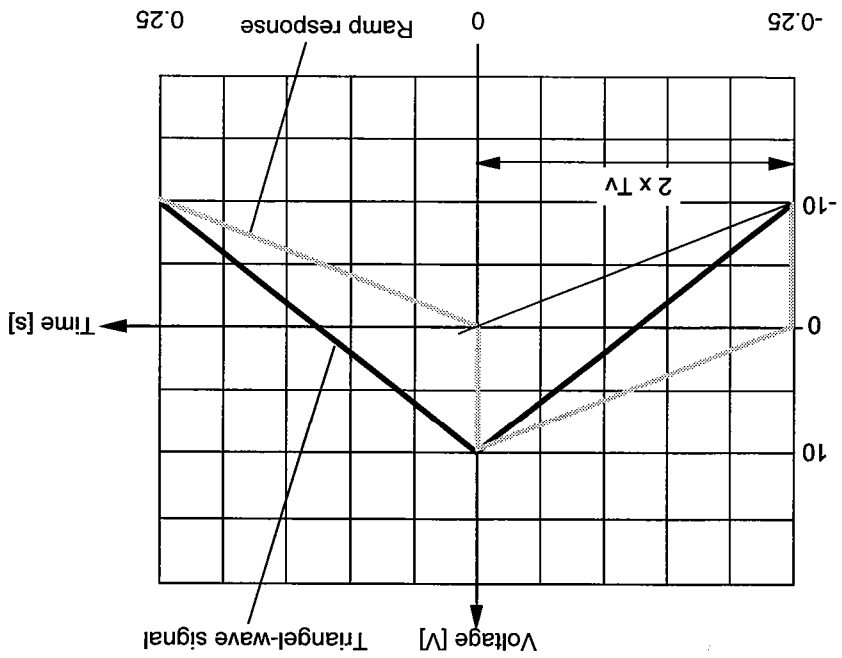
$$y = 0.025 \text{ s} \cdot 4 \cdot 10 \text{ V} \cdot 5 \frac{1}{\text{s}} = 5 \text{ V}$$



The edges of the ramp response may be rounded. This will not affect the results of the measurement.

13.2 Drawing the ramp response of the PD controller and determining the T_v

Fig. C13.3:
Transition function



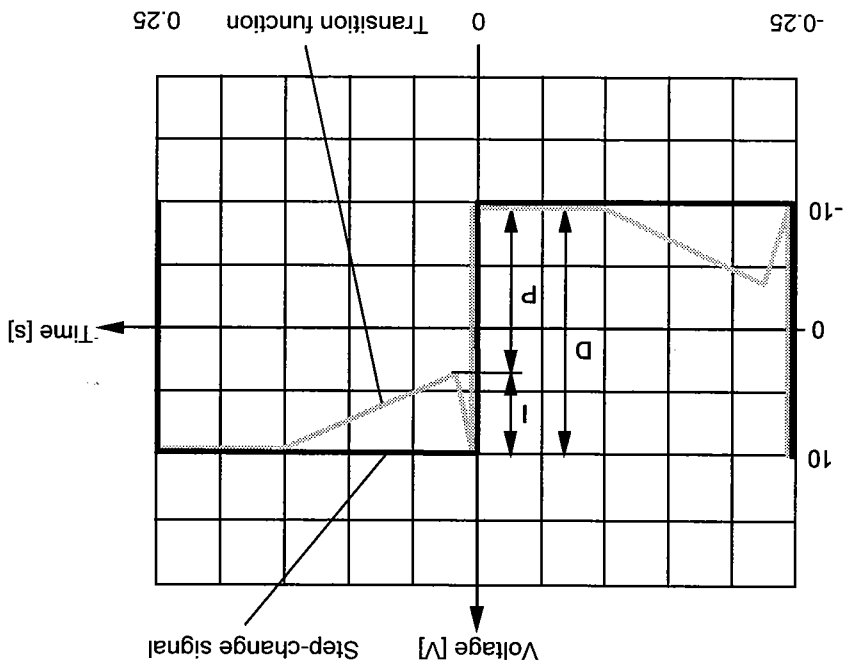
$$\text{Measured derivative-action time } T_v = \frac{100 \text{ ms}}{2} = 50 \text{ ms}$$

$$\text{Calculated derivative-action time } T_v = \frac{K_D}{K_P} = \frac{25 \text{ ms}}{0.5} = 50 \text{ ms}$$

Deviation between measured and calculated derivative-action time = 0 ms

Deviations are possible, depending on the accuracy of the measurements and settings.

13.3 Drawing the transition function of the PID controller

Fig. C13.4:
Transition function

Explain the shape of the curve for the transition function:

The first step change in the transition function is due to the reaction of the D and P controllers. The effect of the D controller, however, soon stops, with the result that the correcting variable becomes smaller. The ramp which follows this is the response of the integrator, which adds up the system deviation present and finally runs against the limiter. The P component of the output signal remains constant until the input signal changes again.

Bending machine

14.2 Investigation of the transient response of the closed-loop control circuit with a PD controller

Characteristic data

Controller	Proportional-action coefficient K_P		Derivative-action coefficient K_D [ms]	Settling time T_a [ms]	Overshoot amplitude x_m [mV]	Steady state system deviation $e_{stat.}$ [mV]
	PD	P				
	90	90	1000	400	100	0
				Steady state oscillations	150	Steady state oscillations

Table C14.1:
Closed-loop control circuit
with a PD controller

Is the closed-loop control circuit still stable after the derivative-action coefficient K_D is switched off?
When the derivative-action coefficient is switched off, the closed-loop control circuit becomes unstable. It is thus not possible to determine the settling time and steady state system deviation.

Which type of controller gives a smaller overshoot amplitude?
Assuming that the proportional-action coefficient K_P is the same in both cases, the PD controller will exhibit a slightly smaller overshoot amplitude. The reason for this is that the derivative-action coefficient K_D suppresses the tendency to oscillation.

14.3 Investigation of the transient response of the closed-loop control circuit with a PID controller

Table C14.2:
Closed-loop control circuit
with PID controller

Characteristic data		Controller
Proportional-action coefficient K_P	90	PD (Schritt 2) P
Integral-action coefficient K_I [1/s]	0	
Derivative-action coefficient K_D [ms]	1000	
Settling time T_a [ms]	400	
Overshoot amplitude x_m [mV]	100	
Steady state system deviation e_{stat} [mV]	0	

Can the steady-state system deviation be reduced by increasing K_I ?

Increasing K_I did not result in any significant reduction in the steady state system deviation. If the value selected for K_I is too high, this will even make the control quality worse.

In this closed-loop control circuit, the steady state system deviation is very small even when a PD controller is used. The reason is the high proportional coefficient of this controller. With other controlled systems, however, much greater differences will be apparent.

Describe the controlled variable curve for the case in which the value selected for KI is too high.

If the value selected for KI is too high, the result will be that the controlled variable will first run far beyond the value of the reference variable and then slowly return to the setpoint (see graph).

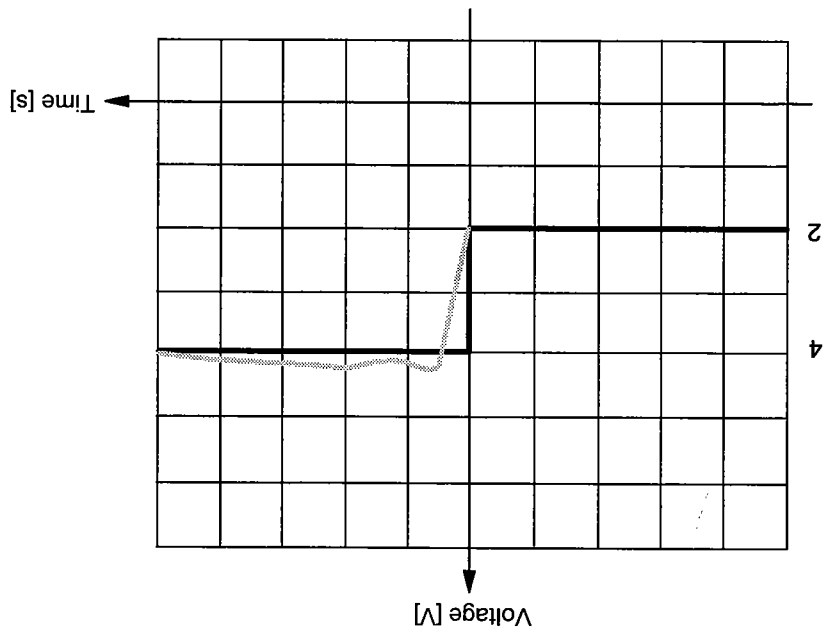


Fig. C14.1:
Transition function

Papermaking machine

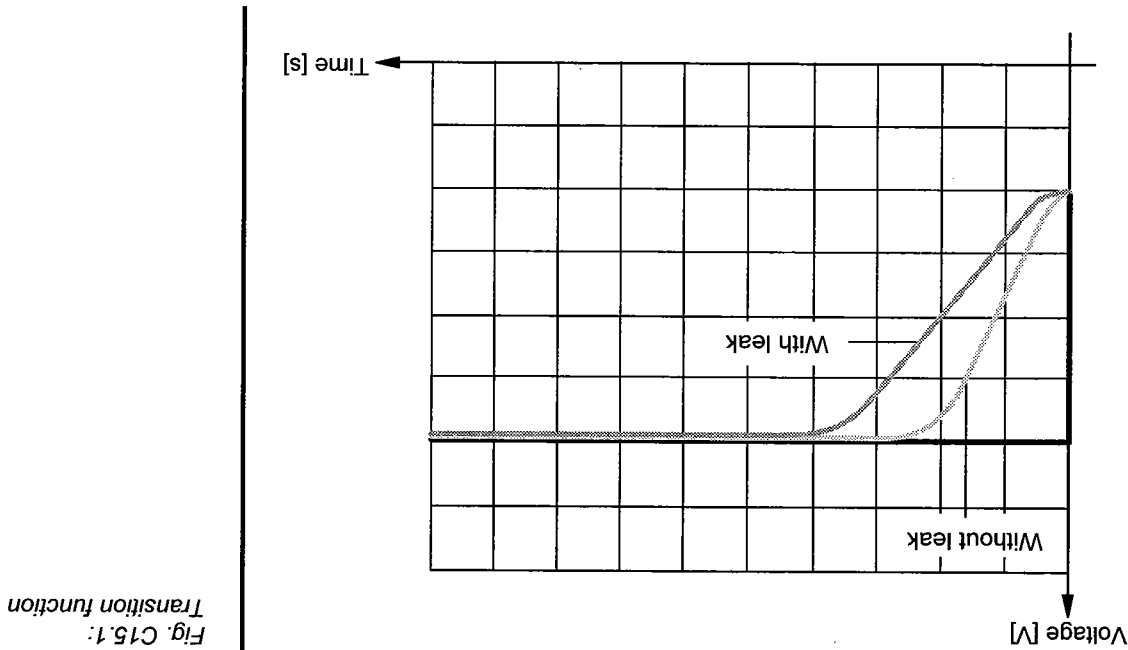
15.2 Investigation of the influence of leaks

Characteristic data		
Without leaks	With leak	
Proportional-action coefficient K_P	20	20
Integral-action coefficient K_I [1/s]	0	0
Derivative-action coefficient K_D [ms]	1000	1000
Settling time T_a [ms]	400	500
Overshoot amplitude x_m [mV]	0	0
Steady state system deviation $e_{stat.}$ [mV]	0	0

Table C15.1:
Leaks

What is the influence of the leak on the settling time?
The effect of leaks is that the settling time becomes longer. The values for the settling time may vary widely, depending on the flow control valve opening.

The transition functions of both measurements are shown below for comparison:



15.3 Investigation of the influence of the compressed-air supply pressure

Table C15.2:
Supply pressure

Characteristic data			
6 bar	5 bar	4 bar	
Proportional-action coefficient KP	20	20	20
Integral-action coefficient KI [1/s]	0	0	0
Derivative-action coefficient KD [ms]	1000	1000	1000
Setting time Ta [ms]	400	600	900
Overshoot amplitude xm [mV]	0	0	0
Steady state system deviation es _{stat.} [mV]	0	0	50

What influence does the pressure level have on the settling time with a constant proportional-action coefficient?

For a constant proportional-action coefficient, the settling time will be come longer as the pressure level falls.

The degree of opening of the flow control valve has a decisive influence on the overshoot amplitude and thus on the control quality. A small valve opening produces a large overshoot amplitude, and vice-versa.

15.4 Investigation of the influence of the measuring point

Characteristic data		Measuring point 1	Measuring point 2
Proportional-action coefficient KP		17	20
Integral-action coefficient KI [1/s]		0	0
Derivative-action coefficient KD [ms]		0	1000
Settling time Ta [ms]		1200	400
Overshoot amplitude xm [mV]		0	0
Steady state system deviation es _{stat} [mV]		200	0

Which measuring point allows a higher proportional-action coefficient KP?

The closed-loop control circuit with measuring point 2 allows considerably higher proportional gain. Different time behaviour for the controlled system is apparently recorded at measuring point 1 (measurement within the controlled system). This leads to instability even with low coefficient values.

At which measuring point can a lower steady-state system deviation be achieved?

A smaller steady state system deviation can be achieved at measuring point 2, since the proportional-action coefficient is considerably higher. An increase in the derivative-action coefficient at measuring point 1 does not produce any improvement in the transient response. The only result is that instability occurs sooner.

Prüfmaschine

16.2 Setting the controller for a controlled system without a delay

Table C16.1:
Controlled system
without a delay

Characteristic data		
P controller	PI controller	
Crit. proportional-action coefficient K_{Pcrit}	10	10
Crit. period of oscillation T_{crit} [ms]	11	11
Proportional-action coefficient K_P	5	5
Integral-action time T_n [ms]		9.35
Integral-action coefficient $K_I = \frac{K_P}{T_n} \left(\frac{1}{s} \right)$		535
Settling time T_a [ms]	120	Unstable
Overshoot amplitude x_m [mV]	30	1000
Steady state system deviation e_{stat} [mV]	500	Unstable

Have the two setting procedures using the Ziegler-Nichols method produced a stable closed-loop control circuit?

☐ Yes

☒ No, the PI controller was not stable.

The closed-loop control circuit with PI controller is not stable. The reason for this is the high integral-action coefficient which results from the calculations using the Ziegler-Nichols method. An I controller is not suitable for the controlled system in this case.

Which controller gave the better results?

☒ P controller

☐ PI controller

☐ Both the same

The closed-loop control circuit with P controller produces a better result.

16.3 Setting the controller for a controlled system with a delay

Table C16.2:
Controlled system
with a delay

Characteristic data		
Crit. proportional-action coefficient K_{Pcrit}	23	23
Crit. period of oscillation T_{crit} [ms]	8	8
Proportional-action coefficient K_P	11.5	13.8
Integral-action time T_n [ms]		4
Derivative-action time T_v [ms]		1
Integral-action coefficient $K_I = \frac{K_P}{T_n} \left(\frac{1}{s} \right)$		3450
Derivative-action coefficient		13.8
Settling time T_a [ms]	4200	Unstable
Overshoot amplitude x_m [mV]	0	500
Steady state system deviation e_{stat} [mV]	0	Unstable

Have the two setting procedures using the Ziegler-Nichols method produced a stable closed-loop control circuit?

☐ Yes

☒ No, the PID controller was not stable.

No, the PID controller is unstable, since the integral-action coefficient calculated for this controlled system in accordance with the Ziegler-Nichols is too high.

Which controller gave the better results?

☒ P controller

☐ PID controller

☐ beide gleich

Due to its instability, the PID controller has clearly worse control quality. If the integral-action coefficient is switched off, the result obtained is roughly the same as with the P controller.

16.4 Setting the controller for a controlled system with a leak

Table C16.3:
Controlled system
with a leak

Characteristic data		PID controller
Crit. proportional-action coefficient K_{Pcrit}	26	
Crit. period of oscillation T_{crit} [ms]	8	
Proportional-action coefficient $K_P = 0.6 \cdot K_{Pcrit}$	15.6	
Integral-action time $T_n = 0.5 \cdot T_{crit}$ [ms]	4	
Derivative-action time $T_v = 0.12 \cdot T_{crit}$ [ms]	1	
Integral-action coefficient $K_I = \frac{K_P}{T_n} \left(\frac{1}{s} \right)$	3.9	
Derivative-action coefficient $K_D = K_P \cdot T_v$ [ms]	15.6	
Settling time T_a [ms]	440	
Overshoot amplitude x_m [mV]	0	
Steady state system deviation e_{stat} [mV]	0	

Has the setting procedure produced a stable closed-loop control circuit?

☒ Yes

☐ No

The setting has produced a stable closed-loop control circuit. Optimum control quality is, however, not achieved with the Ziegler-Nichols method.

What is the difference between the settling times here and in step 3? Briefly describe the reason for this difference.

The settling time is somewhat longer in the case of the controlled system with a leak. The exact difference depends on the opening of the flow control valve. The volume of air which is blown off is then not available to match the controlled variable to the reference variable quickly.

In summary, it can be said that the Ziegler-Nichols for pneumatic controlled systems produces good initial controller settings. Fine adjustments are the required to achieve good control quality. The Ziegler-Nichols also consistently produces integral-action coefficients for these controlled systems which are too high.

Stamping machine

17.2 Approach of positions and calculation of voltage values

The results table below shows the measured and calculated voltages for any desired position.

Number	Position l [mm]	Measured voltage [V]	Calculated voltage [V]
1	20 mm	0.7	0.4
2	70 mm	1.7	1.5
3	140 mm	3.2	3.1
4	210 mm	4.8	4.6
5	280 mm	6.3	6.2
6	350 mm	7.9	7.8
7	430 mm	9.6	9.5

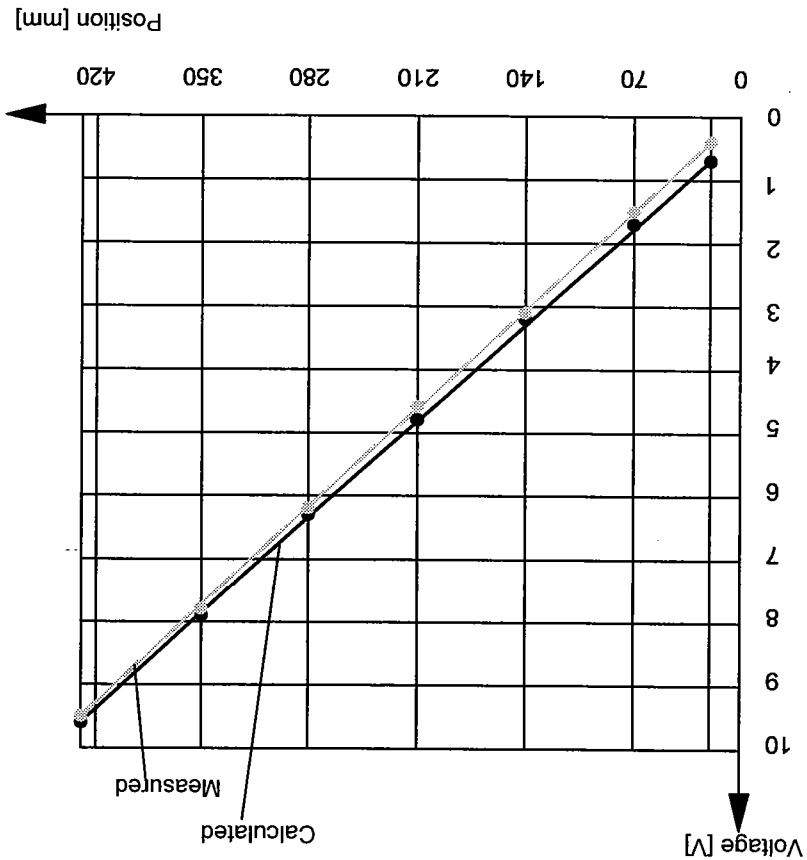
Table C17.1:
Results table



The measured values may vary due to production tolerances affecting the linear potentiometer.

17.3 Plotting of potentiometer characteristic

Fig. C17.1:
Characteristic



What shape do the characteristics have?

The characteristics take the form of straight lines.

How large is the zero-point deviation (offset) of the potentiometer?

The zero point deviation for this test circuit is 0.3 V. This is identical to the voltage measured for the 0 mm position.

The measured values may vary due to differences in the adjustment of the scale or production tolerances affecting the linear potentiometer.

Sorting device

18.1 Production of transition and ramp functions for the position controller

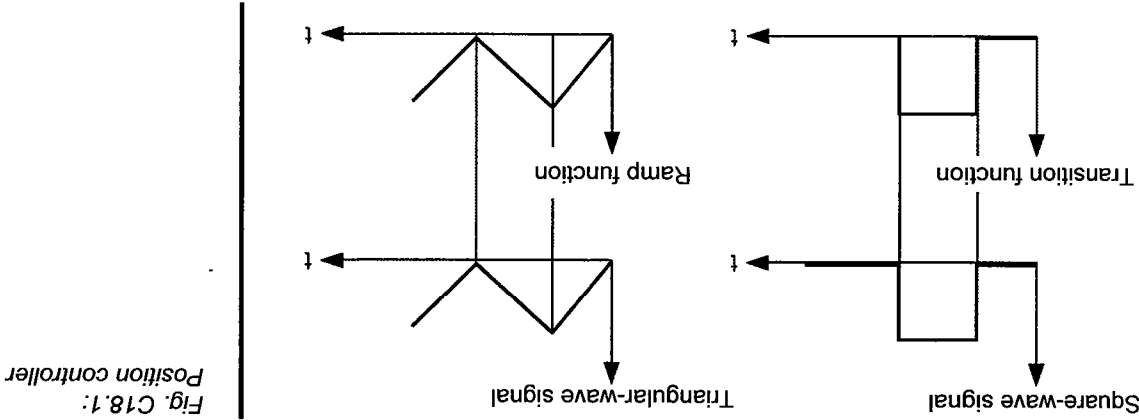


Fig. C18.1:
Position controller

18.2 Production of transition and ramp functions for the velocity controller

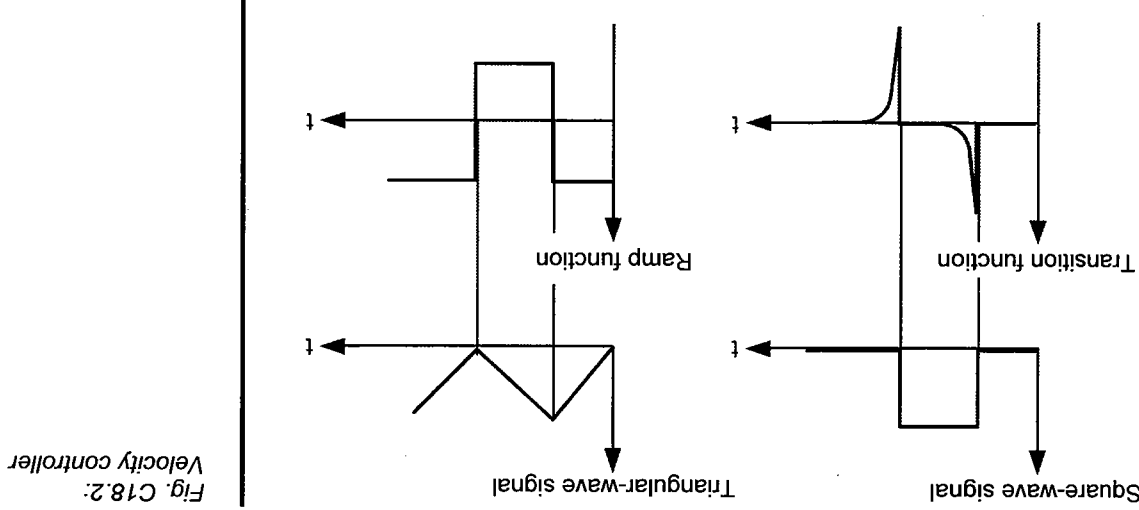


Fig. C18.2:
Velocity controller

18.3 Production of transition and ramp functions for the acceleration controller

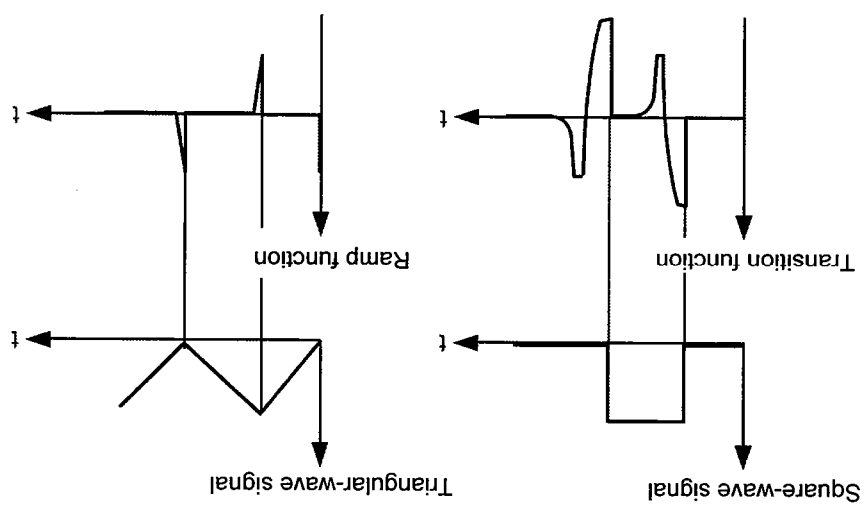


Fig. C18.3:
Acceleration controller

Deburring an engine block

19.1 Assembly and commissioning of the closed-loop control circuit

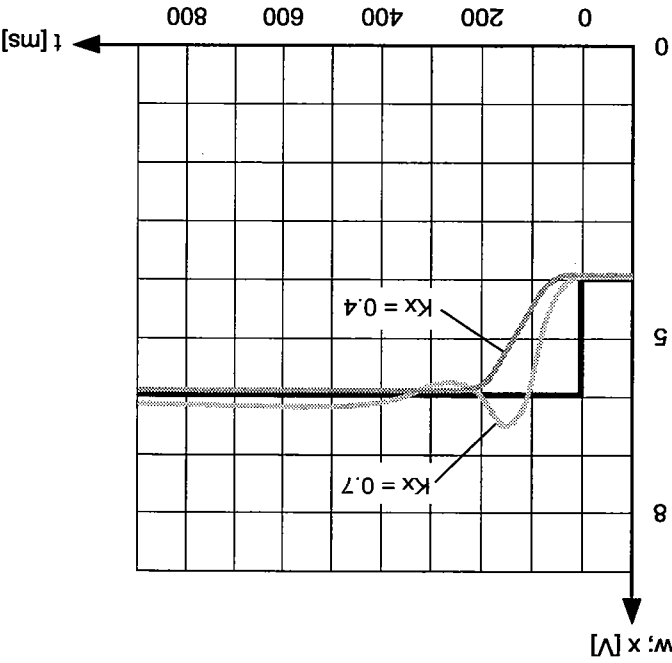
- Square-wave signal of voltage generator:
- Voltage values of potentiometer:
- Input voltage of proportional valve:
- Status controller card:
- Settings on status controller card:
- Reference variable w
- Controlled variable x
- Correcting variable y
- Controller
- Controller coefficients

19.2 Investigation of the transient response for various coefficients

Controller coefficients				
K_x	K_x	0	0	0.7
	K_x	0	0	0.4
	p	8.5	8.5	III

Table C19.1:
Influence of
position coefficient K_x :

Fig. C19.1:
Transition function

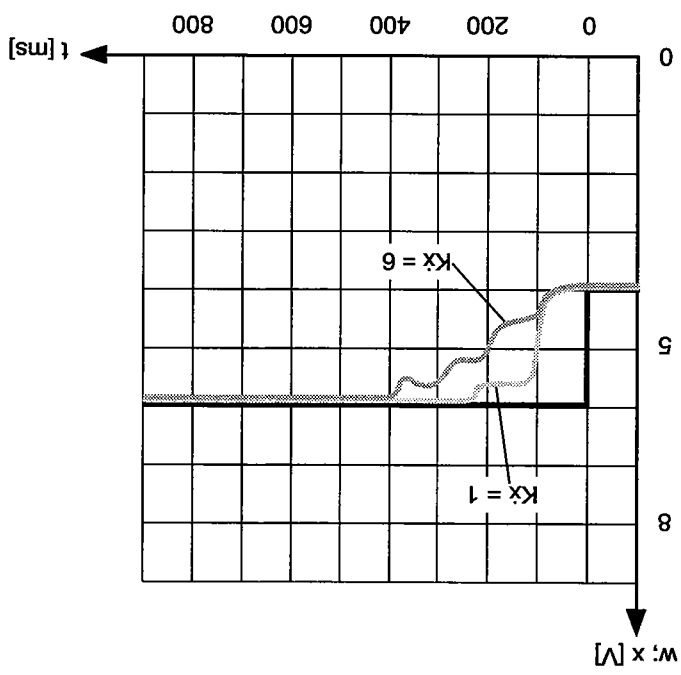


Note The higher the position gain, the greater the overshoot amplitude and the longer the settling time.

Table C19.2: Influence of velocity coefficient K_v :			
K_v	K_v	K_v	Case
1	2.5	0	IV
1	7	0	V

Controller coefficients			
K_v	K_v	K_v	K_v
1	2.5	0	8.5
1	7	0	8.5

Fig. C19.2
Graph of
controlled variables
(2 curves)

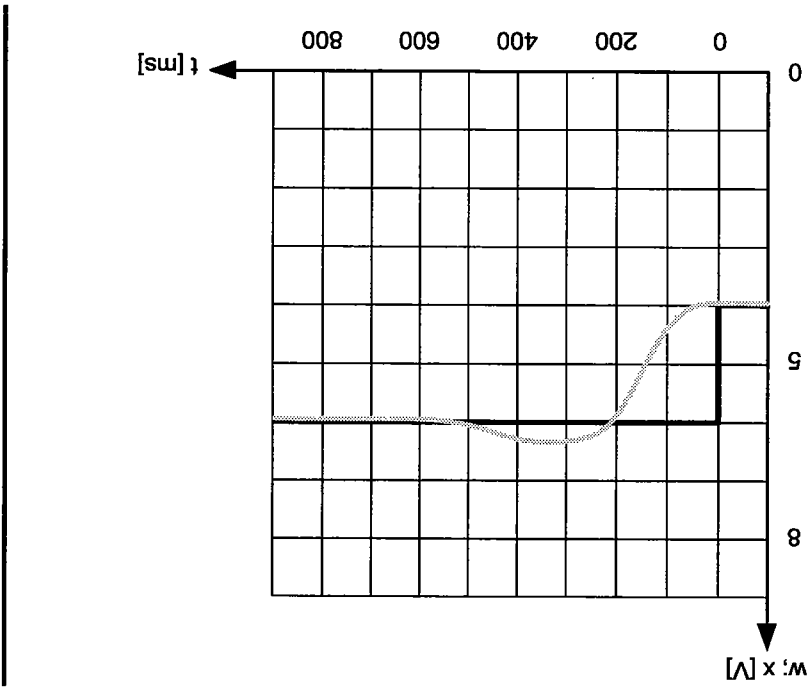


Note A velocity coefficient which is too high will lead to premature braking, which in turn means longer settling times. "Intermediate stops" may even occur.

Controller coefficients			
K _x	K _x	K _x	0.4
	p	8.5	II
Influence of acceleration coefficient K _x :			

Table C19.3:

Fig. C19.3:
Graph of
controlled variable
(t curve)



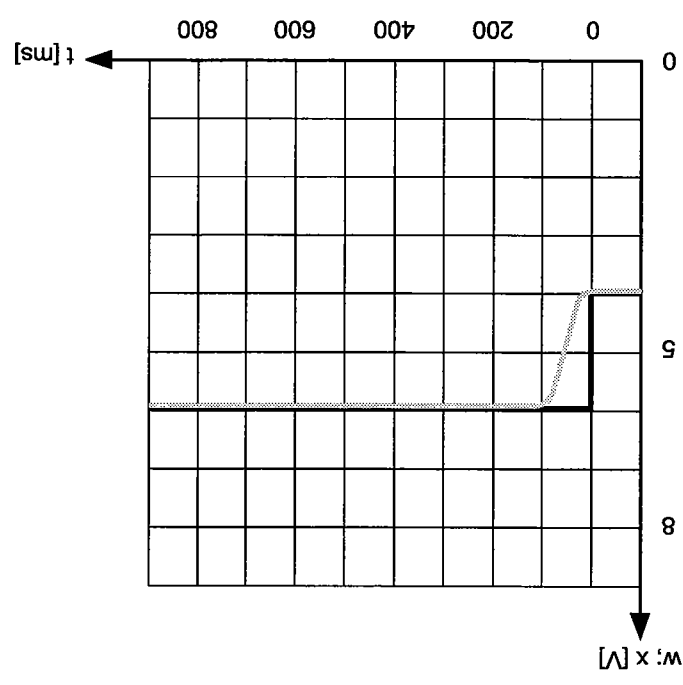
The higher the acceleration coefficient which is selected, the longer the settling time.

19.3 Parametrisation of the status controller using the empirical method

Table C19.4:
Parametrisation of the
status controller

Characteristic data	
Overall gain P	12.1
Position coefficient K _x	1.5
Velocity coefficient K _v	2.4
Acceleration coefficient K _a	1.1
Settling time T _s [ms]	105
Overshoot amplitude x _m [mV]	0
Steady state system deviation [mV]	0

Fig. C19.4:
Graph of optimum
transient response:



Cake production

20.1 Determining the follower behaviour with a ramp function

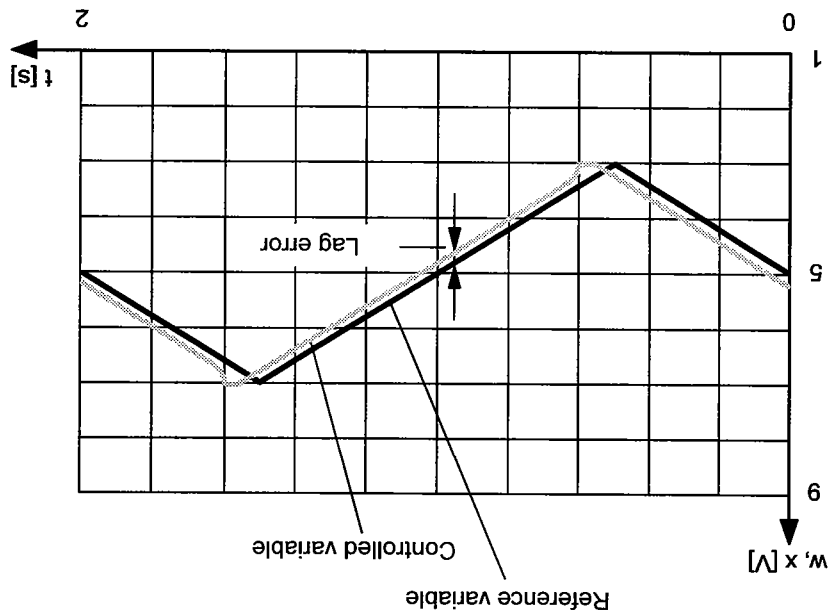


Fig. C20.1:
follower behaviour with a
ramp function

How large is the measured lag error (value in mV)?
The measured lag error is approximately 200 [mV]

How large is the lag error (value in mm)?
 $e = 200 \text{ mV} \cdot 0.045 \text{ mm/mV} = 9 \text{ mm}$

When the frequency is increased, the travel velocity and stroke behave as follows:

The travel velocity

☐ becomes lower

☒ becomes higher

☐ stays the same

The stroke

☐ becomes smaller

☐ becomes larger

☒ stays the same

(only at frequencies below 1 Hz)

When the voltage amplitude is reduced, the travel velocity and stroke behave as follows:

The travel velocity

☒ becomes lower

☐ becomes higher

☐ stays the same

The stroke

☒ becomes smaller

☐ becomes larger

☐ stays the same

20.2 Determining the lag error as a function of velocity

Table C20.1:
Determining the lag error

Frequency setting $f \left[\frac{1}{s} \right]$	Amplitude (measured) $A \text{ [mV]}$	Velocity $v1 \left[\frac{mV}{s} \right]$ $v1 = 4 \cdot A \cdot f$	Velocity $v \left[\frac{mm}{s} \right]$ $v = v1 \cdot 0.045$	Lag error (measured) $e1 \text{ [mV]}$	Lag error $e \text{ [mm]}$ $e = e1 \cdot 0.045$	Closed-loop gain $Kv \left[\frac{1}{s} \right]$ $Kv = \frac{e}{v}$
0.2	2000	1600	72.0	200	9.0	8.0
0.5	2000	4000	180.0	250	11.3	16.0
1.0	1950	7800	351.0	280	12.6	22.2
2.0	1850	14800	666.0	350	15.8	42.2
3.0	1810	21600	972.0	700	31.5	30.9

Is the lag error proportional to the velocity? Explain its behaviour.

At low velocities, the lag error is not proportional to the velocity. This is due to the proportional valve, which does not exhibit linear behaviour at small control-edge openings.

20.3 Determining the lag error as a function of controller gain

Table C20.2:
Determining the lag error

Overall gain	$P[]$	Amplitude (measured)	$A \text{ [mV]}$	Velocity	$v1 = 4 \cdot A \cdot f$	$v1 \left[\frac{\text{mV}}{\text{s}} \right]$	Velocity	$v = v1 \cdot 0.045$	$v \left[\frac{\text{mm}}{\text{s}} \right]$	Lag error (measured)	$e1 \text{ [mV]}$	Lag error	$e \text{ [mm]}$	$e = e1 \cdot 0.045$	$Kv = \frac{e}{v}$	$Kv \left[\frac{1}{\text{s}} \right]$	Closed-loop gain
1			550	1100	49.5	300	13.5	3.7									
2			730	1460	65.7	180	8.1	28.1									
5			1000	2000	90.0	70	3.2	64.3									
10			1000	2000	90.0	30	1.4										

How do the lag error and closed-loop gain vary as a function of the control gain (overall gain)?
The lag error decreases as the controller gain rises. The closed-loop gain increases.

Palletizing station

21.2 Determining the settling time T_a without a mass load

Mass [kg]	K_x	K_v	K_a	P	T_a [ms]
0	1.5	3.5	2.5	11	130

Table C21.1:
Settling time without
a mass load

21.3 Determining the settling time T_a with a mass load

Masse [kg]	K_x	K_v	K_a	P	T_a [ms]
5	0.7	5.4	2.1	11	170

Table C21.2:
Settling time with
a mass load



The optimum controller settings may be different from the values in the table in certain cases.

In which load case (with or without a mass) is the settling time longer?

A mass load prolongs the closed-loop control operation and leads to an increase in the settling time T_a .

How must the velocity K_v and acceleration coefficients K_a be changed in order to obtain good transient response with an additional load?

The parameters K_x and K_v have considerably higher values in the case of the loaded slide unit. The controller thus has more pronounced damping properties in this case.

21.4 Determining the settling time T_a with various lengths of tubing

Table C21.3:
Settling time

Tubing length [mm]	Kx	Kx	Kx	P	T_a [ms]
250	1.5	3.5	2.5	11	40
2000	1.5	3.5	2.5	11	60

What do you observe with regard to the settling time?
The settling time increases with longer tubing.



It can be observed that the settling characteristics become progressively worse with tubing lengths of more than 2000mm and that instability occurs in certain cases.

Section D Appendix

Guidelines and standards

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Comparator

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3/2-way solenoid valve with LED, normally closed

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5/3-way solenoid valve with LED, mid position closed

167077

5/3-way proportional valve

167078

Pressure sensor, analogue

167094

Lineal, 450

525927

Guidelines and standards

DIN ISO1219	Fluidic systems and equipment, 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	Measurement and control: Symbols used in formula in control technology
DIN 19222	Measurement and control: Instrumentation and control, terminology
DIN 19225	Measurement and control: Designation and classification of controllers
DIN 19226	Closed-loop and open-loop control technology: Terminology and designations
DIN 19227	Measurement and control: Graphic symbols and code letters for process instrumentation and control
DIN 19231	Measurement and control: Pressure range for pneumatic signal transmission
DIN 19233	Automatic machines, automation: terminology
DIN 19236	Measurement and control: Optimization, terminology
DIN 19237	Measurement and control: Open-loop control technology, terminology
DIN 19239	Measurement and control: Open-loop control technology, programmable logic controllers, programming
DIN 40719 Part 60	Circuit documentation: Production of function charts for measurement and control
DIN 44300	Data processing: Terminology
DIN 66025	Industrial automation: Program structure for alphanumerically-controlled machines
DIN 66201 Part 1	Process computer systems: terminology
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	ISO 3511-3	1984 Process measurement control functions and instrumenta- tions - Symbolic representation - Part 3: Detailed symbols for instrument interconnection Diagrams	VDI/DE 3844	Drives for actuation of final control elements Characteristic data for pneumatic and electrohydraulic drives	VDI/DE 3685	Adaptive Controllers: Terminology, Properties, Comments und Examples	VDI 2860	Assembly and handling systems, handling functions, handling devices: Terminology, definitions, symbols
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K. H. Zeitz	Regelungen mit Zwei- und Dreipunktreler (Closed-loop control systems with two-step-action and three- step-action controllers) Oldenbourg Verlag

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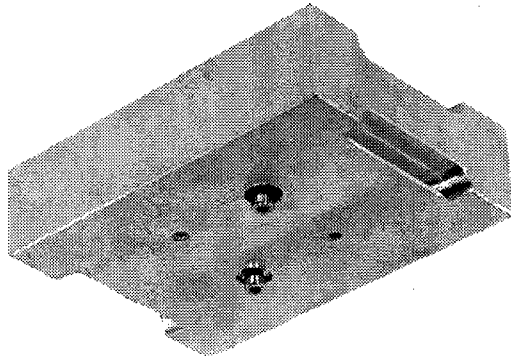
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Design

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

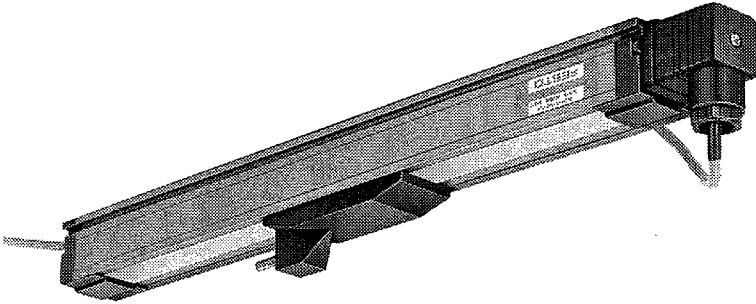
To compensate for different hole patterns, Festo Didactic supplies an intermediate plate (Order no. 019500). To secure, both of the enclosed socket head screws are inserted into the drop bores of the weight and tightened together with the slide. Several weights can be stacked together by laying one upside-down 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

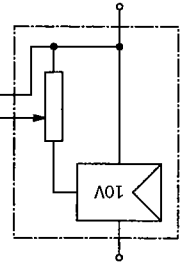
Mechanical			
Mass	5 kg		
Dimensions	Length	150 mm	2 Cheese-head screws M5
	Width	110 mm	
	Height	40 mm	
	Mounting method		





This linear potentiometer is a sliding potentiometer without connecting rod and with connections at each end. It is fitted in an aluminium housing and attached to the linear actuator LA-450 (Order No. 192501) with the aid of a mounting kit (Order No. 178441). The electrical connection is by means of a cable (Order No. 376177). The cable has a rectangular plug at one end for the linear potentiometer and four banana plugs at the other. The cable incorporates a reference power supply and an impedance converter.

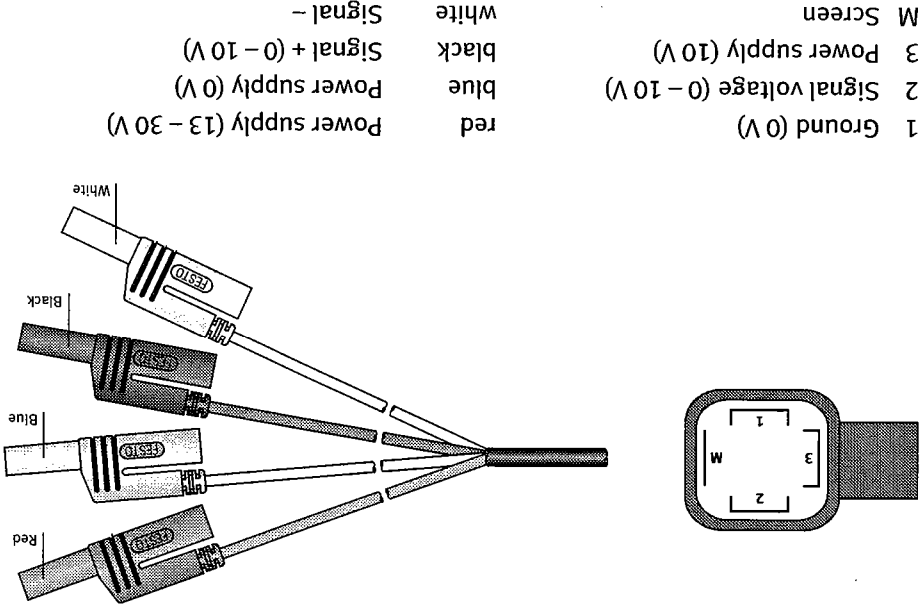
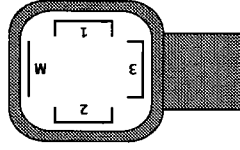
The linear potentiometer supplies an output voltage which is proportional to the supply voltage and the wiper position. Its resistive material consists of a conductive-plastic coating, which has the advantage over wire-wound potentiometers of higher resolution and longer service life.



Design

Function

Pin assignment

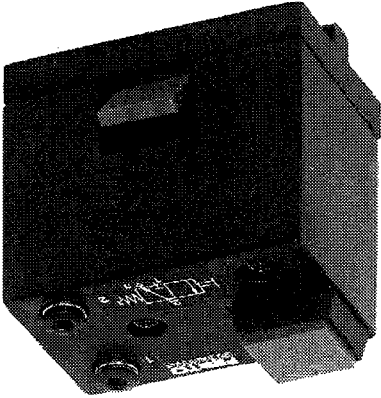
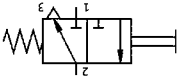


1	Ground (0 V)	red	Power supply (13 – 30 V)
2	Signal voltage (0 – 10 V)	blue	Power supply (0 V)
3	Power supply (10 V)	black	Signal + (0 – 10 V)
M	Screen	white	Signal –

Technical data

Electrical, Mechanical	
Permissible operating voltage **	13 – 30 V DC
Potentiometer resistance	5 kΩ
Resistance tolerance	±20 %
Recommended wiper current	≤1 µA
Effective electrical working distance	457 mm
Output voltage **	0 – 10 V DC
Operating ambient temperature **	-30 – +100 °C
Max. linearity error	±0.07 % FS*
Resolution and reproducibility	≤0.01 mm
Polarity-safe**	yes
Insulation resistance (potentiometer)	<100 MΩ at 500 V; 0.1 bar
Dielectric strength (potentiometer)	500 V _{ms} at 50 Hz; 1 min; 1 bar
Speed of adjustment	≤10 m/s
Acceleration during adjustment	≤200 m/s ²
Actuating force (horizontal)	<1 N
Max. number of actuations	10 ⁸
Material (housing)	Aluminium
Weight	1000 g
Connections	Cable with plugs

* FS = Of full-scale value
** Applies to potentiometer inclusive of impedance converter



Design

The 3/2-way valve with push-in connections is assembled in a polymer housing. The unit is mounted on the profile plate via a quick release detent system with blue lever (mounting alternative "A").

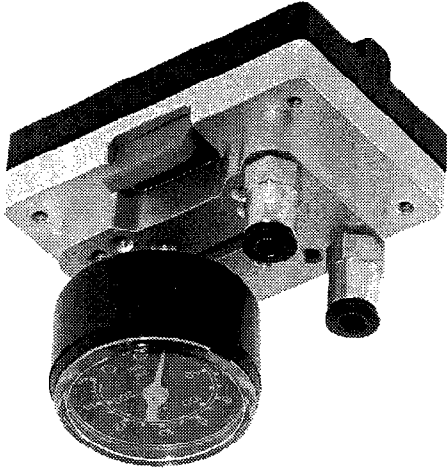
Function

The valve is actuated by pressing the pushbutton. Releasing of the pushbutton returns the valve to the normal position via a return spring.

Technical data

Pneumatic	
Medium	Compressed air, filtered (lubricated or unlubricated) (or vacuum; port 1)
Design	Poppet valve, directly actuated on one side, with return spring
Actuation	Pushbutton
Pressure range	-95 – 800 kPa (-0.95 – 8 bar)
Standard nominal flow rate 1...2	60 l/min
Actuating force at 600 kPa (6 bar)	6 N
Connection	QSM-4 fittings for plastic tubing PUN 4 x 0.75





Design

The pressure gauge is screwed to the function plate which is fitted with two directly linked push-in fittings. The unit is mounted on the profile plate via a quick release detent system with the blue lever, (mounting alternative "A").

Function

The pressure gauge indicates the pressure in a pneumatic control system.

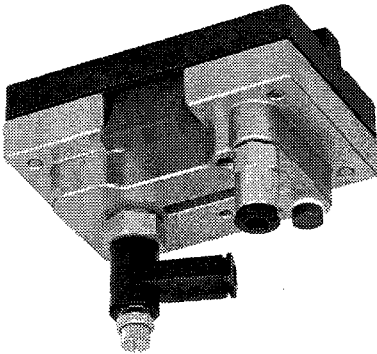
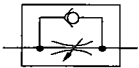
Note

During continuous operation the pressure gauge must only be loaded to 75 % of maximum scale reading, and in the case of an alternating load, 66 % of maximum scale reading.

Technical data

Pneumatic	
Medium	Compressed air, filtered (lubricated or unlubricated)
Design	Bourdon tube pressure gauge
Indicating range	0 – 1000 kPa (0 – 10 bar)
Connection	QSM-M5-4 fitting for plastic tubing PUN 4 x 0.75
Quality grade	1.6





Design

The adjustable one-way flow control valve is screwed into the function plate, incorporating a straight push-in fitting. The unit is slotted into the profile plate via a quick release detent system with a blue lever (mounting alternative "A").

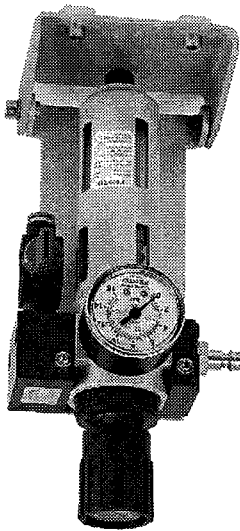
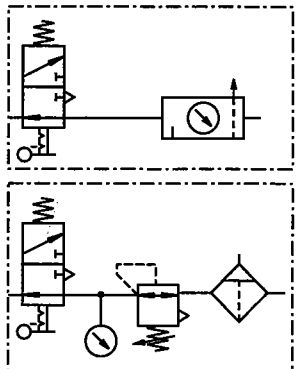
Function

The one-way flow control valve consists of a combination of a flow control valve and a non-return valve. The non-return valve blocks the flow of air in one direction, whereby the air flows via the flow control valve. The throttle cross section is adjustable by means of a knurled screw. The setting can be fixed by means of a knurled nut. Two arrows indicate the direction of flow control on the housing. In the opposite direction, the air flow is unrestricted via the non-return valve.

Technical data

Pneumatic	
Medium	Compressed air, filtered, (lubricated or unlubricated)
Design	One-way flow control valve
Pressure range	20 – 1000 kPa (0.2 – 10 bar)
Standard nominal flow rate	in throttled direction: 0 – 150 l/min free flow direction: 160 l/min (throttle open) 130 l/min (throttle closed)
Connection	QSM-M5-4 for plastic tubing PUN 4 x 0.75





Design

The filter regulator with pressure gauge, on/off valve, push-in fitting and quick coupling plug is mounted on a swivelling retainer. The filter bowl is fitted with a metal bowl guard. The unit is mounted on the profile plate by means of cheese head screws and T-head nuts (mounting alternative "C"). Attached is a quick coupling socket with threaded bush and connector nut for plastic tubing PUN 6 x 1.

Function

The filter with water separator cleans the compressed air of dirt, pipe scale, rust and condensate. The pressure regulator adjusts the compressed air supplied to the set operating pressure and compensates for pressure fluctuations. An arrow on the housing indicates the direction of flow. The filter bowl is fitted with a filter drain screw. The pressure gauge shows the preset pressure. The on/off valve exhausts the entire control. The 3/2-way valve is actuated via the blue sliding sleeve.

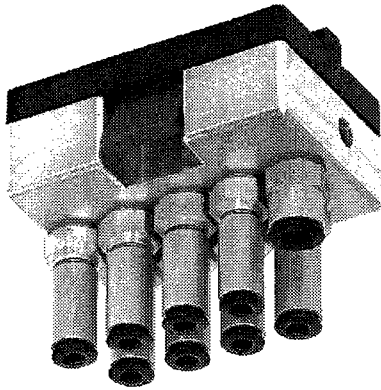
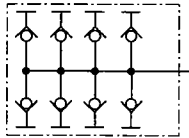
Note

When constructing a circuit, please ensure that the filter regulator is installed in the vertical position. The pressure regulator is fitted with an adjusting knob, which can be turned to set the required pressure. By sliding the adjusting knob towards the housing, the setting can be locked.

Technical data

Pneumatic	
Medium	Compressed air
Design	Sintered filter with water separator, diaphragm control valve
Assembly position	Vertical ±5°
Standard nominal flow rate *	750 l/min
Upstream pressure max.	1600 kPa (16 bar)
Operating pressure max.	1200 kPa (12 bar)
Connection	Coupling plug fore coupling socket G 1/8 QS-plug fitting for plastic tubing PUN 6 x 1

* Upstream pressure: 1000 kPa (10 bar), Operating pressure: 600 kPa (6 bar),
Differential pressure: 100 kPa (1 bar).



Design

The manifold with eight self-sealing push-in fittings is screwed on to a universal plate. The unit is mounted on the profile plate via a quick release detent system with blue lever (mounting alternative "A").

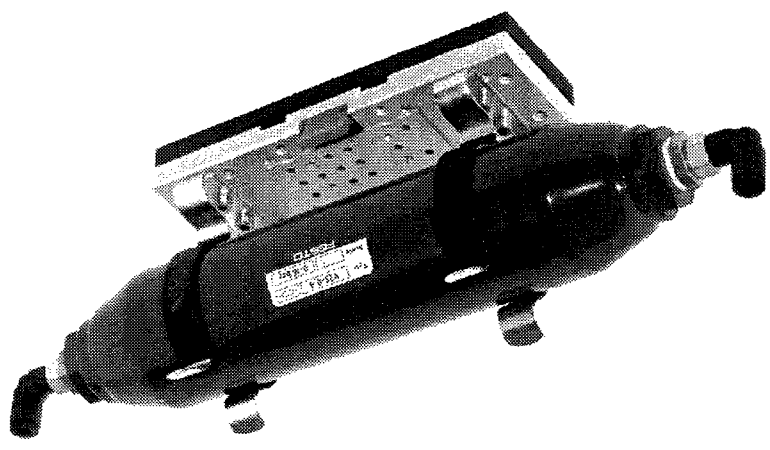
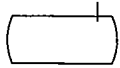
Function

The manifold with a common P-supply enables a control system to be supplied with compressed air eight individual connections.

Technical data

Pneumatic	
Connection	6 1/8 1 QSK-1/8-6 for plastic tubing PUN 6 x 1 8 QSK-1/8-4 for plastic tubing PUN 4 x 0.75





Design

This reservoir is equipped with the quick release detent system (mounting alternative "A") suitable for profile-plate mounting and is equipped with pneumatic push-in fittings at both ends.

Function

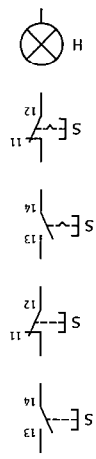
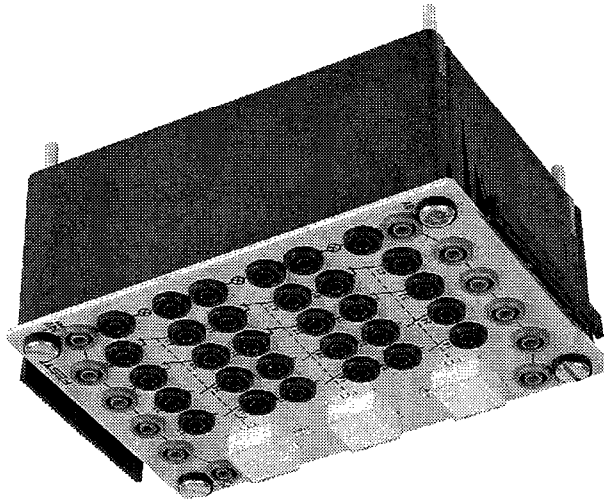
The reservoir can be used for the following functions:

- Generation of static pressures with the aid of a one-way flow control valve.
- Generation of longer delay times in conjunction with time delay and flow control valves.
- Compensation for pressure fluctuations.
- Compensation for rapid pressure drops.
- Creation of a controlled system with a 1st order delay (PT1).

Technical data

Pneumatic	
Type	VZS-0.4
Medium	Compressed air, filtered (lubricated or unlubricated)
Design	Brazed pressure vessel
Mounting method	Retaining clips, detent system for profile plate
Connections	at each end QSL-1/8-4 for plastic tubing PUN 4 x 0.75
Capacity	400 ml
Pressure range	0 – 1600 kPa (0 – 16 bar)
Temperature range	Depends on tubing or piping used
Materials	Blue-painted brass Retaining clips: Spring steel
Weight	730 g





Design

This component consists of two illuminated pushbuttons in the form of momentary-contact switches and one illuminated pushbutton in the form of a detented switch. All electrical connections are in the form of 4 mm safety connectors. The unit can be mounted in a mounting frame or on the profile plate using four plug-in adapters.

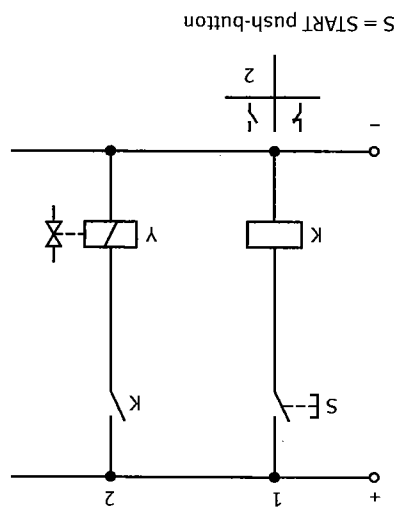
Function

The **illuminated pushbutton** in the form of a detented switch consists of a contact assembly with two normally-open contacts and two normally-closed contacts, together with a colourless transparent pushbutton cap with a miniature lamp. The contact assembly is actuated by pressing this cap. Electrical circuits are opened or closed via the contact assembly. When the cap is released, the switching status is maintained. The contact assembly is returned to its initial position by pressing the pushbutton a second time.

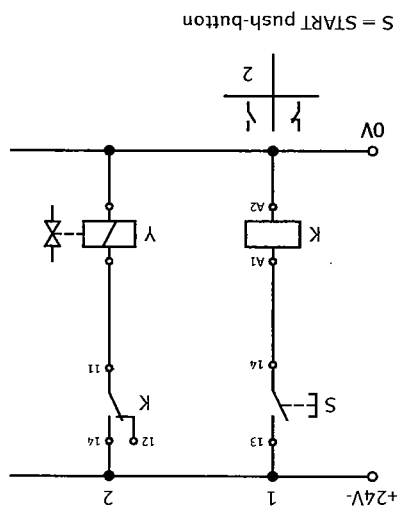
The **illuminated pushbuttons** in the form of momentary-contact switches consist of a contact assembly with two normally-open contacts and two normally-closed contacts, together with a colourless transparent pushbutton cap with a miniature lamp. The contact assembly is actuated by pressing this cap. Electrical circuits are opened or closed via the contact assembly. When the cap is released, the contact assembly returns to its initial position.

Note

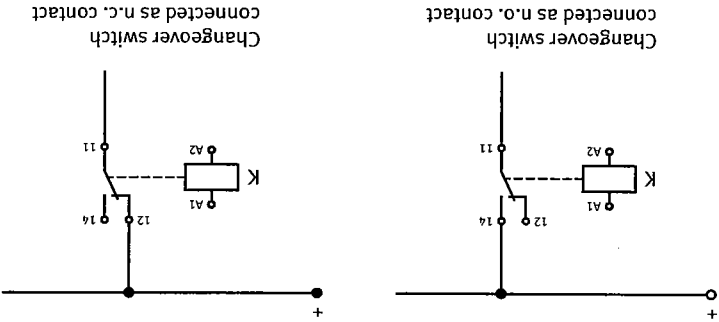
When power is applied to the connections of the visual indicator, the switching status is displayed by the built-in miniature lamp in the pushbuttons.



Example of application: Circuit diagram, electrical



Example of application: Practical assembly, electrical

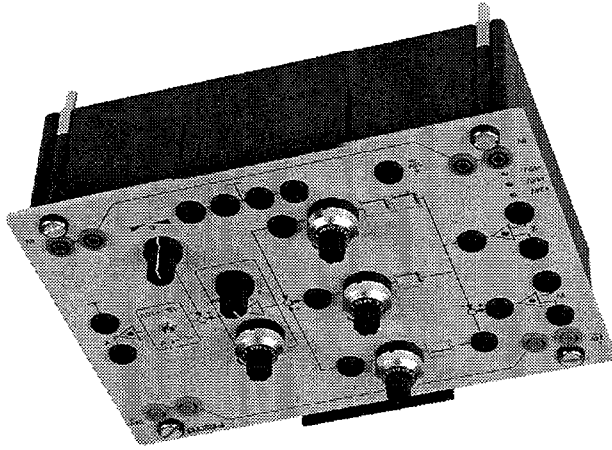
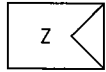


Normally-open contacts, normally-closed contacts: Allocation of contacts on relay plate

Technical data

Electrical	
Voltage	24 V DC
Contact assembly	2 normally-open contacts, 2 normally-closed contacts
Contact rating	Max. 1 A
Power consumption (miniature lamp)	0.48 W
Connections	For 4 mm safety connector plug
Electromagnetic compatibility	
Emitted interference	tested to EN 500 81-1
Noise immunity	tested to EN 500 82-1





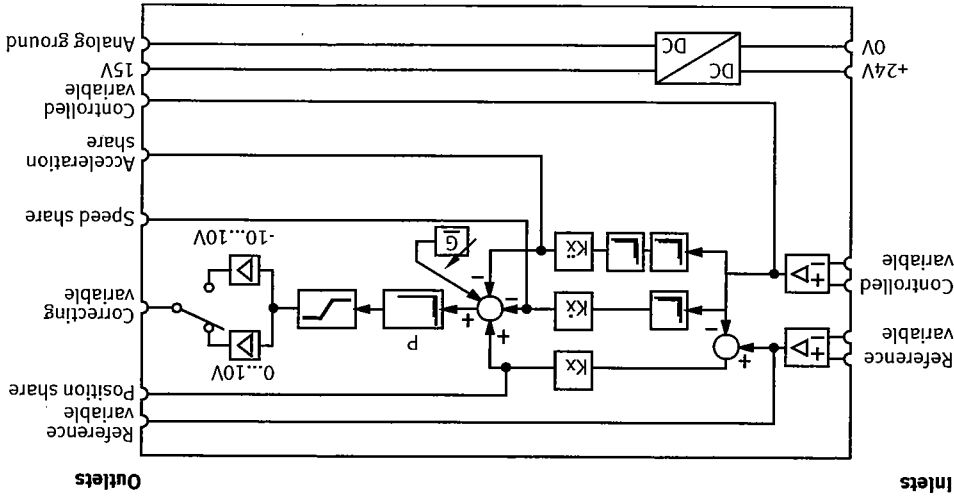
Design

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

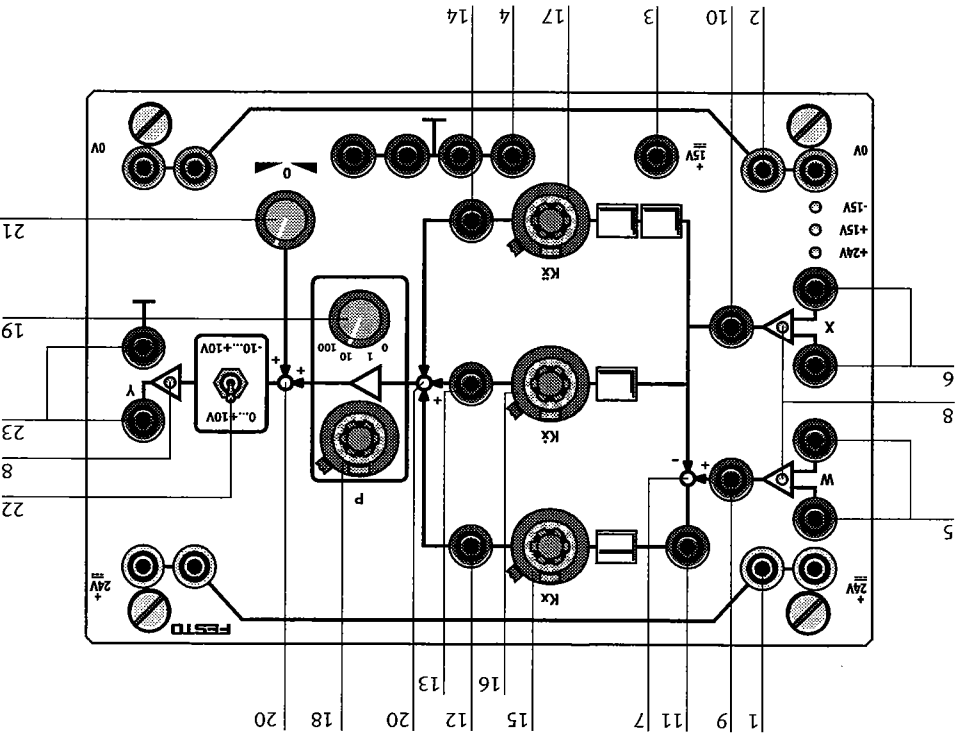
The status controller is used as a controller in pneumatic and hydraulic closed-loop positioning circuits.



Representation in circuit diagram

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



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)).

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.

Note

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 (K_x , K_v und K_a) 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

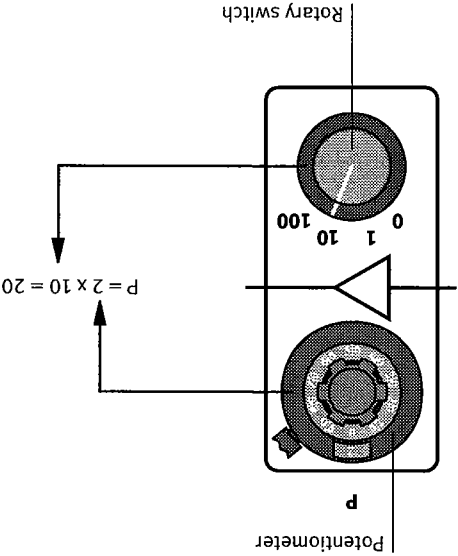
The correcting variable can be tapped against analogue ground at the output.

Test sockets

Various test sockets allow signal voltages to be measured against analogue ground.

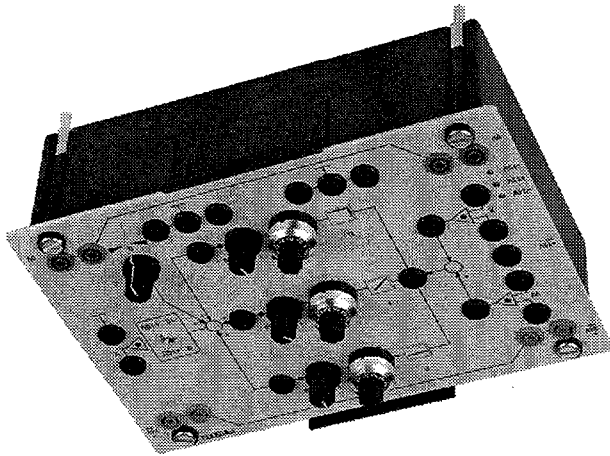
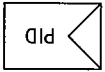
Setting the coefficients

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 $\pm$ 3,5 V bei [0 V – +10 V] 0 V $\pm$ 7 V bei [-10 V – +10 V]
Connection	for 4 mm safety connector plug
Electromagnetic compatibility	
Emitted interference	tested to EN 500 81-1
Noise immunity	tested to EN 500 81-1



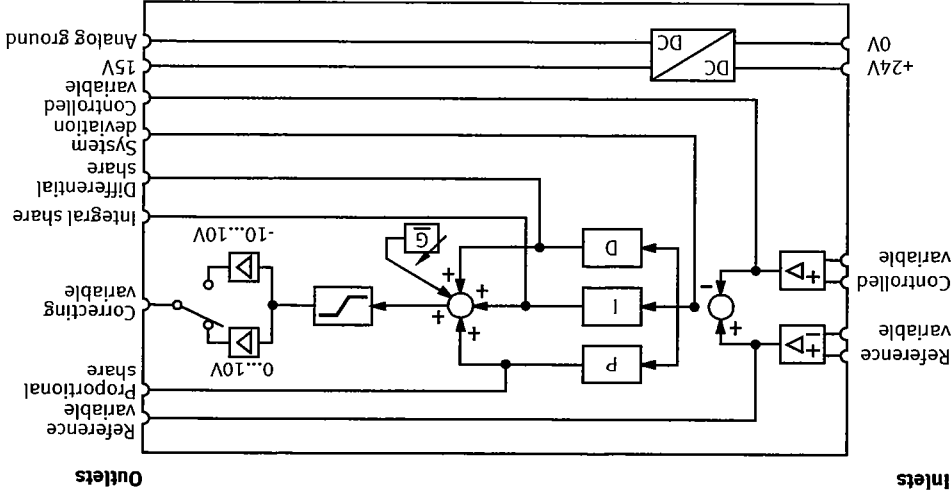
Design

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

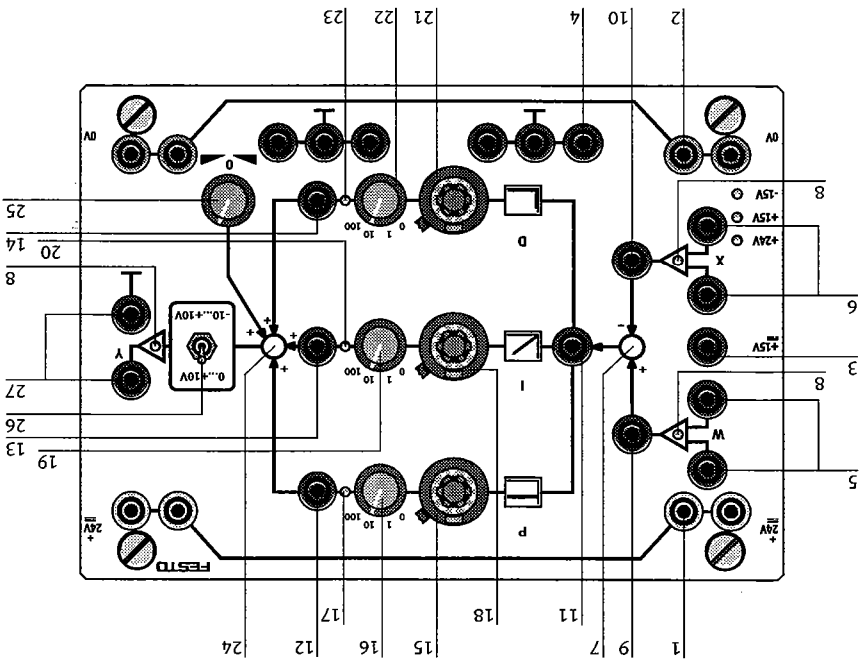
Function

This PID controller can be used, among other things, as a controller for closed-loop pneumatic and hydraulic control circuits.



Representation in circuit diagram

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

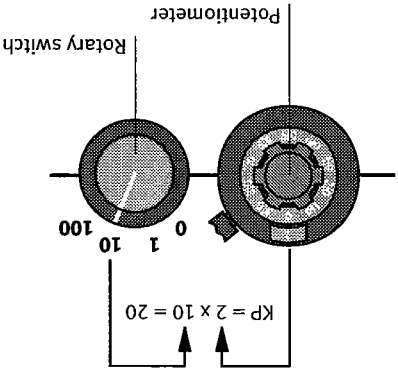
The correcting variable can be tapped against analogue ground at the output.

Test sockets

Various test sockets allow signal voltages to be measured against analogue ground.

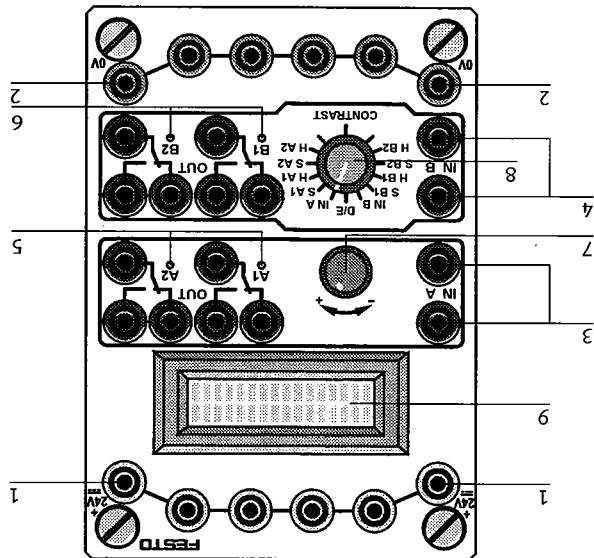
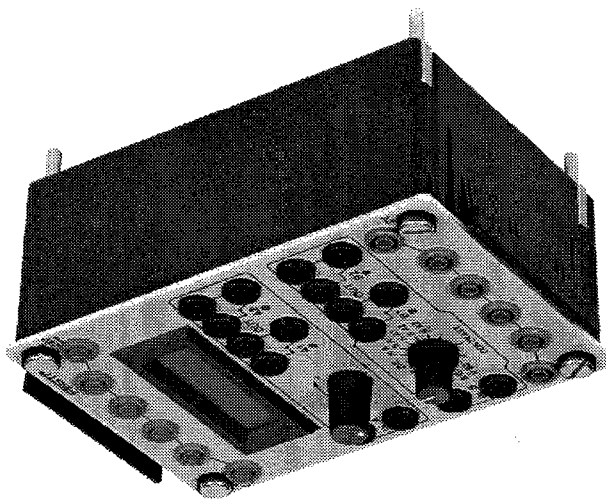
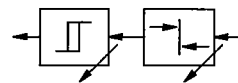
Setting the coefficients

The coefficients K_P , K_I and K_D 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 K_x	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	
Emitted interference	tested to EN 500 81-1
Noise immunity	tested to EN 500 81-1



Key to operator facilities

- 1 Power supply +24 V DC
- 2 Power supply 0 V
- 3 Input A: input voltage 0 – ±10 V
- 4 Input B: input voltage 0 – ±10 V
- 5 Output contacts A1, A2
- 6 Output contacts B1, B2
- 7 Adjusting knob
- 8 Selector switch
- 9 Display

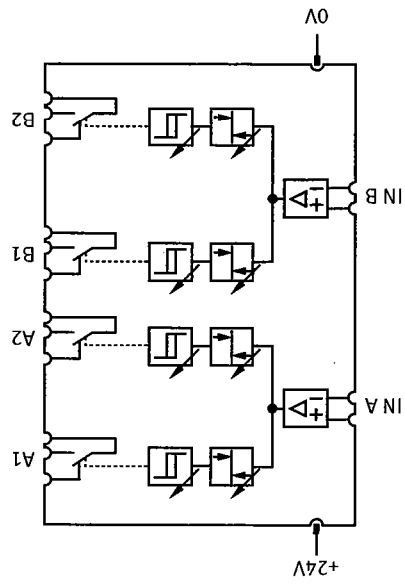
This comparator card has two separate inputs (IN A, IN B), each of which acts on one of two independent comparators. The outputs of these are designated OUT A1, A2 and OUT B1, B2. The activation of outputs is shown by LEDs.

The following values can be set on each comparator:
Setpoint voltage: -10 V ... +10 V,
Hysteresis (switching difference): 0 V ... 5 V.

The switch-on and switch-off values are defined as follows:

Switch-on value = Setpoint + 1/2 hysteresis,
Switch-off value = Setpoint - 1/2 hysteresis.

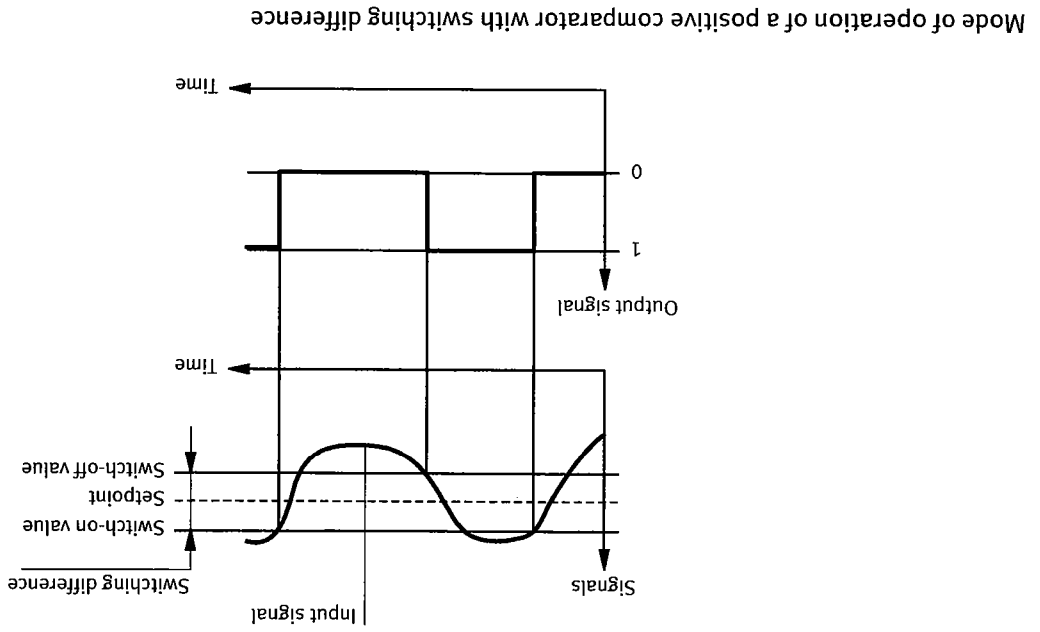
The setpoints and hysteresis values are selected by means of a selector switch. The settings are made with the aid of an adjusting knob. The contrast of the LCD is adjustable. The menu guidance system also offers a choice of German and English language. The power supply for the comparator card is 24 V.



Circuit diagram

Function

- A positive-switching comparator with switching difference has the following characteristics:
- The output is set when the input signal exceeds the switch-on value.
 - The output is reset when the input signal falls below the switch-off value.

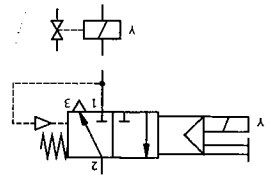
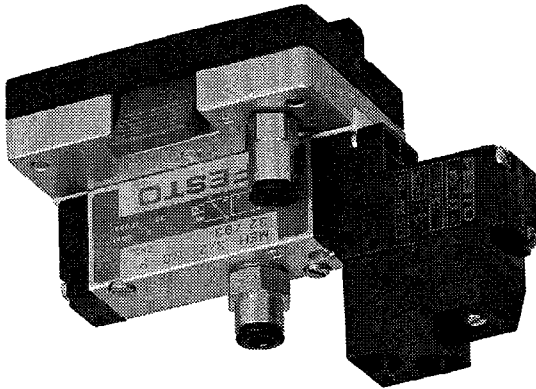


Technical data

Electrical	
Power supply	24 V DC $\pm 10\%$
Input voltage inputs A and B	-10 – +10 V
Input resistance inputs A and B	>10 k Ω
Display accuracy	± 30 mV
Outputs A and B	Floating relay contacts, changeover contacts
Contact rating	24 V DC/2 A 120 V AC/1 A
Connection	for 4 mm safety connector plug
Electromagnetic compatibility	
Emitted interference	tested to EN 500 81-1
Noise immunity	tested to EN 500 82-1

The inputs are short-circuit proof and surge-proof up to 24 V.

167073 3/2-way single solenoid valve, normally closed



Design

This 3/2-way single solenoid valve with push-in fittings is attached to a function plate which is equipped with a P port and silencer. The two electrical connections are equipped with safety connectors. The unit is mounted on the profile plate using a quick release detent system with a blue lever (mounting alternative "A").

Function

The solenoid valve is reversed when voltage is applied to the solenoid coil (1 → 2) and brought back into its initial position (1 → 0) by a return spring when the signal is removed. The switching status is displayed via an LED in the terminal housing. The valve is equipped with a manual override.

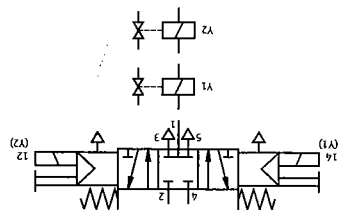
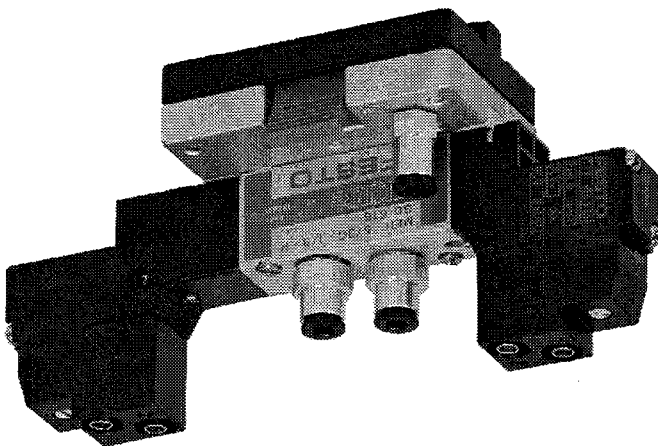
Note

The solenoid coil is characterised by very low power consumption and low heat generation. The electrical connection incorporates protection against incorrect polarity for the LED and a protective circuit.

Technical data

Pneumatic	
Medium	Compressed air, filtered (lubricated or unlubricated)
Design	Spool valve, pilot-actuated, with return spring
Pressure range	250 – 800 kPa (2.5 – 8 bar)
Switching time at 600 kPa (6 bar)	On: 20 ms, Off: 30 ms
Standard nominal flow rate	500 l/min
Connection	QS 3 for plastic tubing PUN 4 x 0.75
Electrical	
Voltage	24 V DC
Power consumption	1.5 W
Duty cycle	100 %
Connection	For 4 mm safety connector plug

167077 5/3-way solenoid valve, mid position closed



Design

This 5/3-way solenoid valve with push-in fittings is attached to a function plate which is equipped with a P port and silencer. The unit is mounted on the profile plate using a quick release detent system with a blue lever (mounting alternative "A").

Function

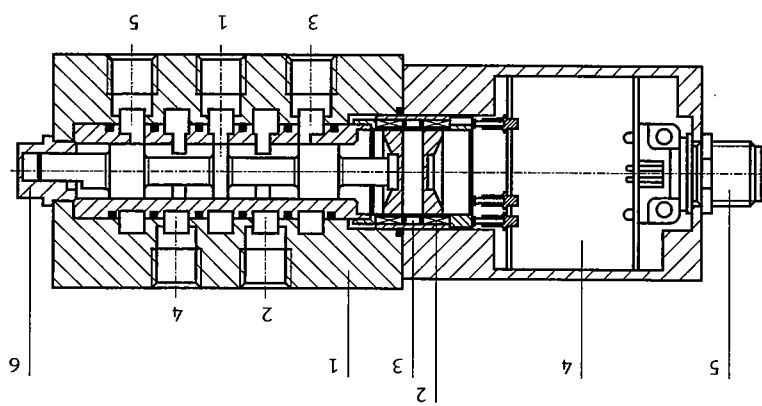
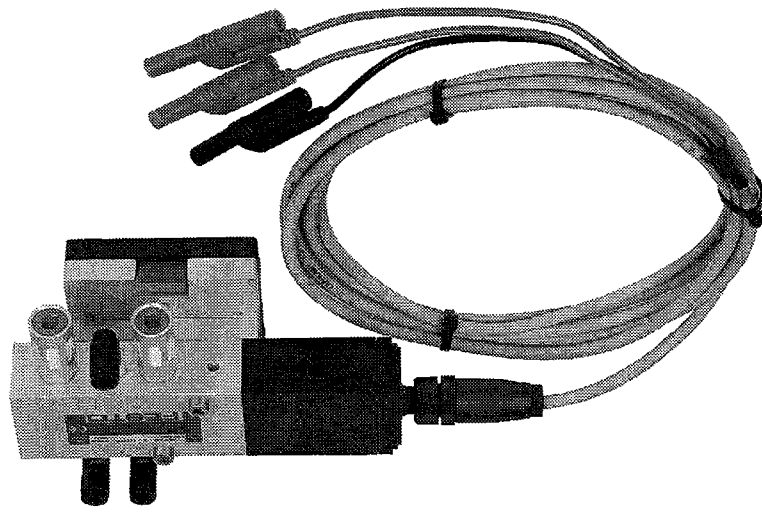
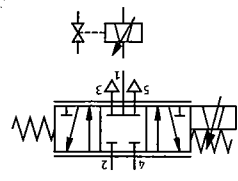
The solenoid valve is actuated in one direction when voltage is applied to coil 14 (1 → 4 and 2 → 3) and brought back to its closed initial position (1 → 0) by a return spring when the signal is removed. When voltage is applied to the other coil 12, the valve is actuated in the other direction (4 → 5 and 1 → 2). The switching status is displayed via an LED in the terminal housing.

Note

The solenoid coils are characterised by very low power consumption and low heat generation. The electrical connections incorporate LEDs with protection against incorrect polarity and a protective circuit.

Technical data

Pneumatic	
Medium	Compressed air, filtered (lubricated or unlubricated)
Design	Spool valve with pilot-actuated return spring
Pressure range	300 – 800 kPa (3 – 8 bar)
Switching time at 600 kPa (6 bar)	On: 15 ms, Off: 40 ms
Standard nominal flow rate	250 l/min
Connections	QS for plastic tubing PUN 4 x 0.75
Electrical	
Voltage	24 V DC
Power consumption	1.5 W
Duty cycle	100 %
Connections	For 4 mm plug and 2-way jack plug



- 1 5/3-way valve
- 2 Plunger-armature drive
- 3 Sensor
- 4 Valve electronics
- 5 Electrical connection
- 6 Valve cover cap

Design

The proportional valve MPYE-5-1/8 is assembled on a base which incorporates the quick release detent system (mounting alternative "A") suitable for profile-plate mounting. The valve is equipped with LCU push-in fittings and two silencers. The major internal components of a proportional directional control valve are:

- A pneumatic 5/3-way valve of spool design, closed in its mid-position (1)
- A plunger-armature drive (2) to position the valve spool
- A sensor (3) to measure the valve spool position
- Integrated valve electronics (4) to control the valve spool position.

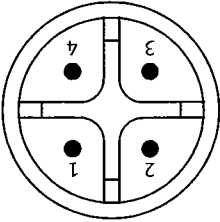
Function

The proportional directional control valve converts an analogue electrical input signal into appropriate cross-section openings to the outputs. At half the nominal voltage, i.e. 5 V, the valve assumes its pneumatic mid-position, in which all control edges are closed, so that no air apart from minimal leakage passes through the valve. At 0 and 10 V respectively, the valve assumes one of its end positions, with maximum opening cross-section.

A plunger-armature drive acting directly on the pneumatic spool valve acts as an electromechanical transducer. An integrated electronic control for the valve-spool travel (subordinate position control loop) allows good static and dynamic characteristics to be obtained, which are reflected in the low hysteresis (below 0.3%), short actuating time (typically 5 ms) and high maximum frequency (approx. 100 Hz). The valve is thus particularly suitable for use as a final control element in conjunction with a higher-level position controller for the positioning of a pneumatic cylinder.

If the valve spool jams, for example due to dirt, the valve cover cap (6) can be removed and the valve spool freed by hand.

Electrical connection

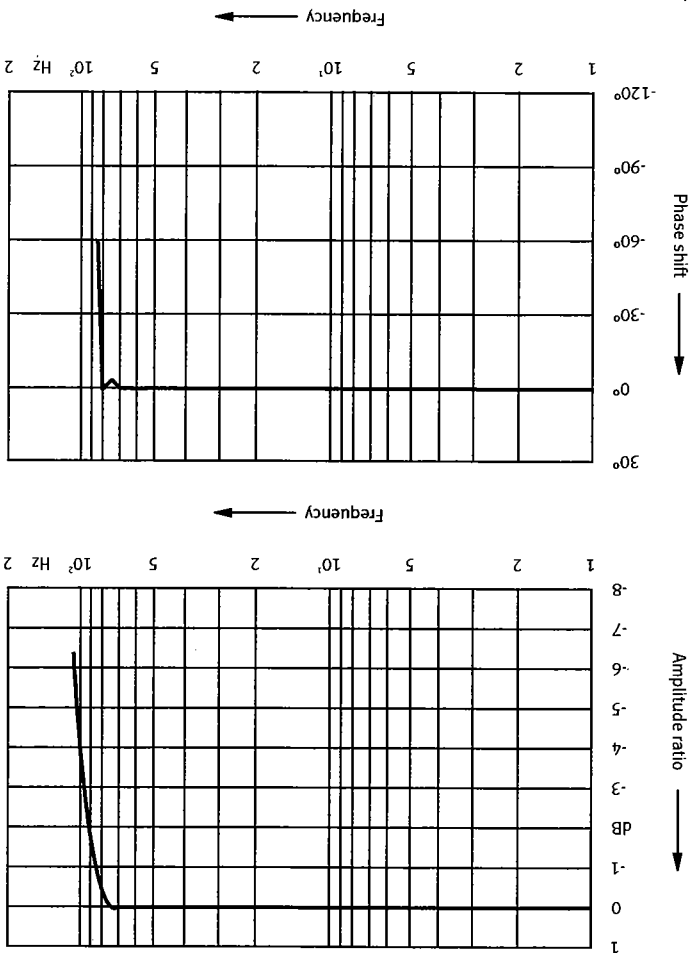


The pin assignment of the housing socket and the colour-coding for the plugs of the cable are shown in the following table.

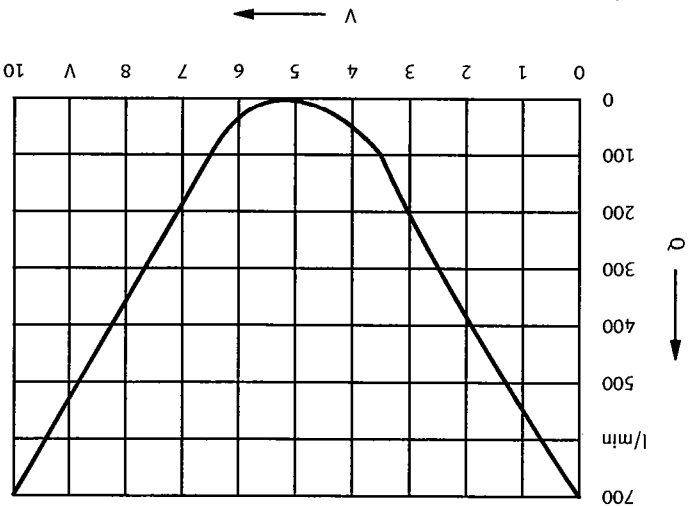
Pin	Connections	Plug
1	Power supply +24 V	Red
2	Power supply 0 V	Blue
3	Signal voltage	Black
4	Signal ground	White



Flow characteristics MPYE-5-1/8

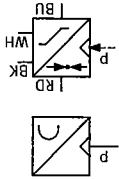
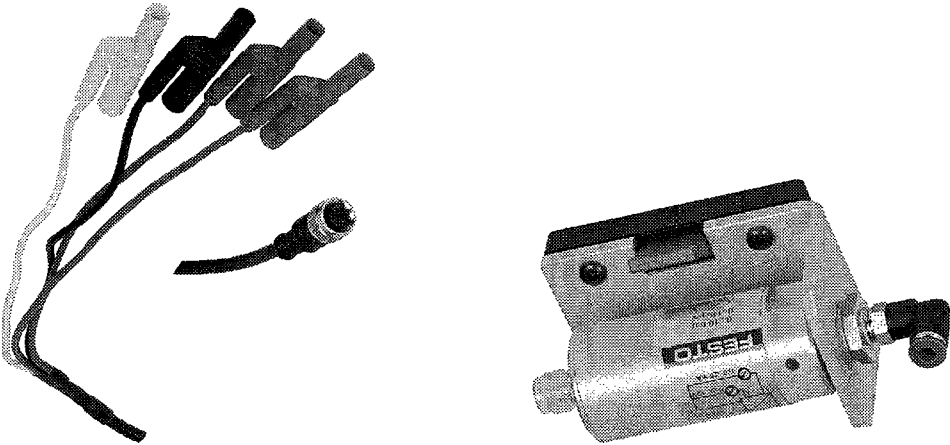


Frequency characteristics MPYE-5-1/8



Technical data

Pneumatic, Electrical	
Medium	Compressed air, microfiltered (unlubricated)
Temperature range of medium	+5 – +40 °C, non-condensing
Nominal bore	6 mm
Operating pressure, nominal/maximum value	6 bar/10 bar
Flow rate at nominal pressure, maximum	700 l/min
Maximum normal leakage (in new condition)	20 l/min
Operating voltage, nominal value	24 V DC
Power consumption, piston mid-position	2 Watt
Power consumption, maximum value	20 Watt
Analogue setpoint voltage	0 – 10 V DC
Nominal value at pneumatic mid-position	5 V DC
Input resistance	70 kΩ
Duty cycle in accordance with VDE 0580	100 %
Degree of protection in accordance with DIN 40.050 in conjunction with plug	IP 65
SIM-GD 18.494	
Limit frequency (-3 dB) at P _{max} and with valve spool stroke 20 % to 80 %	100 Hz
Actuating time at P _{max} and with valve spool stroke 20 % to 80 %	5 ms
Hysteresis relative to valve position	0.4 %
Linearity relative to valve position	1.0 %
Connections, pneumatic	G 1/8, QSL for plastic tubing PUN 4 x 0.75
Connections, electrical	polarity-safe, for 4 mm safety connector plug
Electromagnetic compatibility	
Emitted interference	tested to EN 500 81-1
Noise immunity	tested to EN 500 82-1



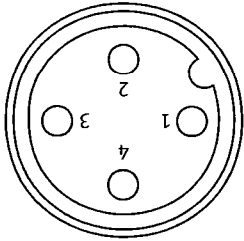
Design

Function

This analogue pressure sensor is mounted on a support bracket which is equipped with the quick release detent system (mounting alternative "A") suitable for profile-plate mounting.

This analogue pressure sensor is a piezoresistive relative pressure sensor with an integrated amplifier and built-in temperature compensation in an aluminium housing. The pressure to be measured acts via a silicon layer on a piezoresistive element. The signal change produced within this element is output via an amplifier as a voltage or current at the plug connector. The output signal is calibrated, thus ensuring that the sensors are readily interchangeable.

Pin assignment

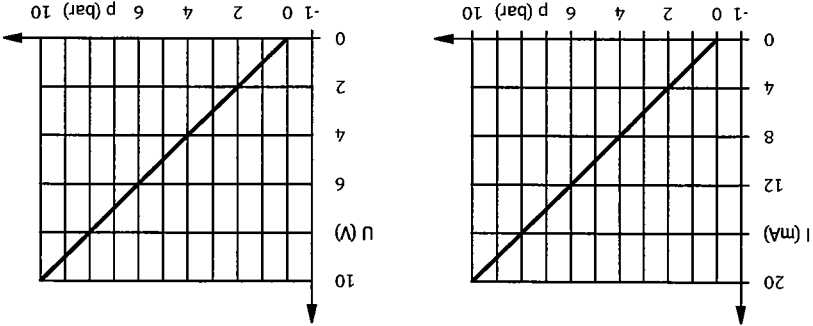


- 1 Power supply (+24 V)
- 2 Ground
- 3 Voltage output
- 4 Current output

Plug colour-coding

The plugs of the cable are colour-coded as follows:	
red	(RD)
blue	(BU)
Black	(BK)
white	(WH)
Current output	
Voltage output	
0 V	
+24 V	

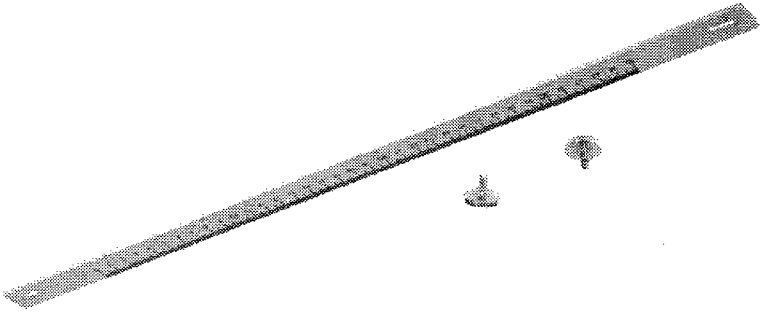
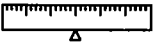
Characteristic curves



Technical data

Pneumatic, Electrical	
Pressure measuring range *	0 – 1000 kPa (0 – 10 bar)
Maximum permissible pressure p_{max}	1400 kPa (14 bar)
Power supply	12 – 30 V DC
Residual ripple of UB	10 % in accordance with DIN 41 755
Current consumption	With current output approx: 35 mA With voltage output approx: 15 mA
Load resistance	Current output: 300 Ω max. RB $\leq$ (UB - 3 V)/30 mA
	Voltage output: 4 k Ω max.
Total error	± 1 % of full-scale value
Temp. drift of zero point	< 0,3 % of full-scale value/10 K
Temp. drift of full-scale value	< 0,3 % of full-scale value/10 K
Maximum frequency	100 Hz
Medium	Compressed air (lubricated or unlubricated)
Operating ambient temperature	0 – +85 °C
Compensated range	+10 – +70 °C
Storage temperature	-25 – +125 °C
Electrical protection	Short-circuit-proof, polarity-safe
Degree of protection	IP 65
Materials	Al, anodised; Silicon
Weight	265 g
Cable	4-core, 2 m
Electrical connection	For 4 mm safety connector plug
Pneumatic connection	G 1/4, QSL for plastic tubing PUN 4 x 0,75

* The sensor will also supply a signal with pressures of < 0 bar. Linearity and proportionality cannot be guaranteed in this case.



Design

Scale printed in millimetres, with two knurled screws.

Function

The scale is used to measure the position of the slide of the linear actuator LA-450 (Order no. 192501).

Mounting

The scale is fitted as follows:

- Push the slide to its end position.
- Place the scale on the side of the linear actuator with the scale uppermost.
- Lightly secure the scale using the two knurled screws supplied and the upper threaded holes in the end plates of the actuator (yokes).
- Adjust the scale until the zero mark lines up with the outer edge of the slide.
- Fully tighten the knurled screws.

Technical data

Mechanical	
Overall length	580 mm
Scale length	450 mm
Scale units	mm
Resolution	1 mm
Mounting method	2 knurled screws
Distance between mounting holes	510 – 565 mm

