Course

Fundamentals

Solutions

Appendix

090166

Sensors for handling and processing technology

Sensors for force and pressure

R. Schulé • P. Waiblinger

Order No.:	090166
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Table of contents

Introduction

Course

Exercises

Force measurement

Pressure measurement

Fundamentals

Solutions

Exercises

Force measurement

Pressure measurement

Appendix

Data sheets

Layout of the workbook

This workbook is part of the Learning System for Automation by Festo Didactic KG. The book has been designed for both course training as well as self-tuition.

The workbook D.LW-FP1130-GB (Order No. 090166) was designed for equipment set D.CP-FP1130 (Order No. 150531) of function package FP 1130.
The core subject of function package FP 1130 is sensors for force and pressure. The components are assembled on an aluminium profile plate. The measurements can be carried out by means of a digitial multimeter. Practical and theoretical knowledge is conveyed regarding analogue force and pressure sensors as well as pressure switches. The sensor characteristics can be determined by means of experiments, e.g. accuracy, resolution, linearity and hysteresis.

The book is divided into:

- Section A "Course"
- Section B "Fundamentals"
- Section C "Solutions"
- Section D "Appendix"

Section A – Course
The course provides the required subject knowledge with the help of selected exercises. The contents of the topics have been coordinated in that the exercises supplement one another, yet can be carried out independently. References point out further and more detailed information contained in both the fundamentals section as well as in the collection of component data sheets.

Section B – Fundamentals
This part contains the theoretical fundamentals on the subject. Topics are arranged according to subject area. The fundamentals section can be worked through by chapter or used for reference.

Section C – Solutions
This section features the solutions to the exercises in the course section.

Section D – Appendix
The final section of the book contains a collection of component data sheets relating to the equipment set.

The book can be incorporated into an existing training program.

What are sensors?

1. Sensors and sensory organs

A sensor is a technical converter, which converts a physical value, e.g. temperature, distance or pressure into another more easily evaluated variable. This is usually an electrical signal, e.g. voltage, current, resistance or frequency of oscillation. Alternative descriptions for sensors are encoders, detectors, or transducers.

Sensor

The word sensor is derived from the latin 'sensus', in English feeling or sensation. The efficiency of many sensors is based on technical developments in semiconductor technology. They are used predominantly for the acquisition of measured data.

Sensors can be broadly compared to the receptors of human sensory organs, which also bring about the conversion of physical values, e.g. light, heat or sound pressure into a neuro-physiological sensation.

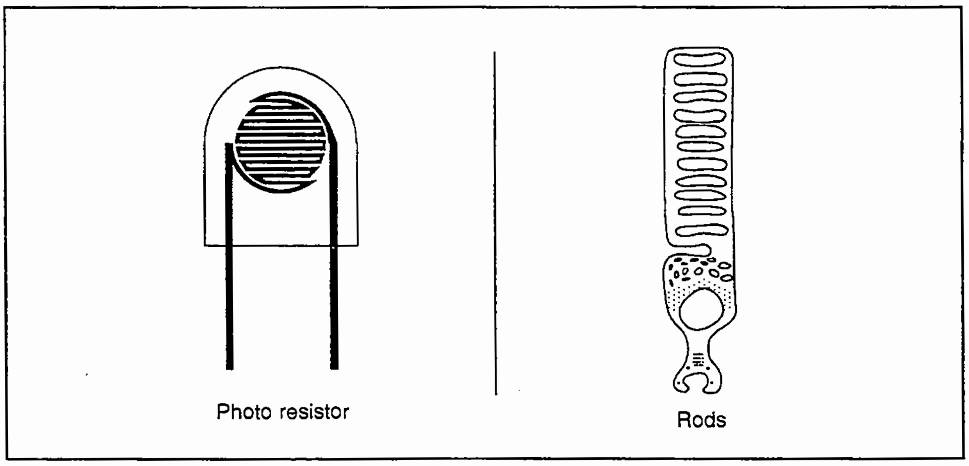


Fig. 1: Comparing sensors and receptors

Rods are receptors in the retina of the eye which convey black-and-white perception

The efficiency of sensors or receptors for comparable measuring tasks or sensory perception varies considerably. As such, our sensory organs perceive most values only approximately, and are therefore not suitable for the measurement of absolute values.

Sensory organs

The operation of sensory organs consists primarily of the coordination of signals from several receptors, as well as the partial processing and evaluation of the signal. The human eye, for example, consists of the lense system, the iris diaphragm, the retina and approximately 120 million light-sensitive rods plus approximately 6 million colour-sensitive cones as well as various muscles for the focussing of light beams and movement of the iris diaphram. As such, preliminary image processing already takes place in the nerve cells of the retina, e.g. the analysis of contours or movements. The brain then processes the image on a higher level, which includes the automatic focussing and control of the diaphragm, the perception of depth by means of superimposing the images from both eyes, compensating auto-movement of the eye and all other body movements. All this takes place prior to the actual conscious process of seeing.

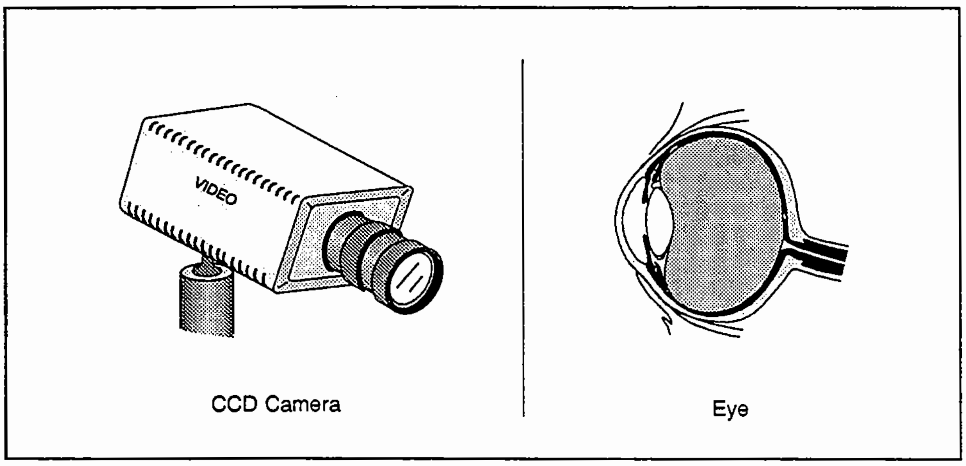


Fig. 2: Comparison of sensor system and sensory organ

Sensor systems

Here too, technology has adopted the line of copying the ingenuity of nature. Line or matrix-type configurations of several sensors of the same type, similar to CCD chips, are described as sensor systems. *CCD* is the abbreviation for *Charge Coupled Device* and describes a CCD Chip constructed from charge coupled semiconductors. The operational principle of a CCD chip is based on the premises that the electrical charge created by the photoelectric effect in the semiconductor is transmitted to a coupled memory, which is interrogated at a certain clock frequency.
Similarly, sensors where both sensor and sensor signal processing are on the same semiconductor chip, are known as sensor systems. However, these sensor systems are still a long way off from achieving the complexity and capability of sensory organs.

Smart Sensor

In addition to the integration of amplifiers, attempts are being made to incorporate computing power into the sensor. This trend towards decentralised data processing results in improved data throughput. This type of sensor system, described as a smart sensor both in English and in German, could be more easily compared to a sensory organ.

Micromechanics

With more recent micromechanical developments, the mechanical elements of a sensor are also integrated into the silicon chip. Primarily, these consist of membranes, spring or oscillatory parts which are etched from silicon. Research laboratories have already succeeded in producing rotary and sliding connections, thereby paving the way for the construction of miniaturised mechanical devices. Micromechanics combine the excellent mechanical properties of silicon, in particular its high elasticity, with the special electrical properties.

Biological sensors

A further interesting trend is the development of so-called biological sensors. These consist of a biologically active part, e.g. enzymes or bacteria, and a microelectronic part, which registers and processes the biological reactions. The first of these biological sensors are available specifically for the purpose of organic substances, e.g. determining blood sugar value. However, the future development of biological sensors cannot be predicted at this stage.

2. Use of sensors

Sensors are used in many areas of science and technology. In research, highly sensitive and specialised sensors are employed for the purpose of conducting experiments. In automation technology, both standard as well as specially developed sensors are in use. In the case of equipment in everyday use, mainly standard sensors are used, though these need to function reliably and maintenance free.

This workbook deals mainly with the use of sensors in automation with regard to achieving important criteria such as:

- Cost reduction
- Rationalisation
- Automation
- Flexibility
- Environmental protection.

The use of sensors is however also due to the inherent developments in technology such as:

- Increased sensitivity, precision, response rate and reliability
- adapting to further developments in design and technology
- new technologies.

Sensors are therefore used in automation because they:

- provide early and reliable signalling of error functions in automated systems, e.g. broken tools or congestion
- contain or localise the source of error as part of an intelligent error diagnosis function
- detecting wearing tools
- provide the measured values, which are required for continuous optimisation of the production process by means of adaptive control and adjustment
- are used in automated quality control
- monitor materials management and assist in automating material flow
- perform product identification, which is essential in flexible automation
- signal danger in the workplace, e.g. excessive concentration of pollutants
- provide a more humane work environment, e.g. in the case of tiring or monotonous visual inspection, monitoring and measuring tasks in a hazardous environment.

Sensors are an integral part of complex equipment. In particular, the further development of robots will be based on the use of sensors. After all, even the CIM concept with all its technical, organisational and social structures would not be feasible without the use of sensor modules.

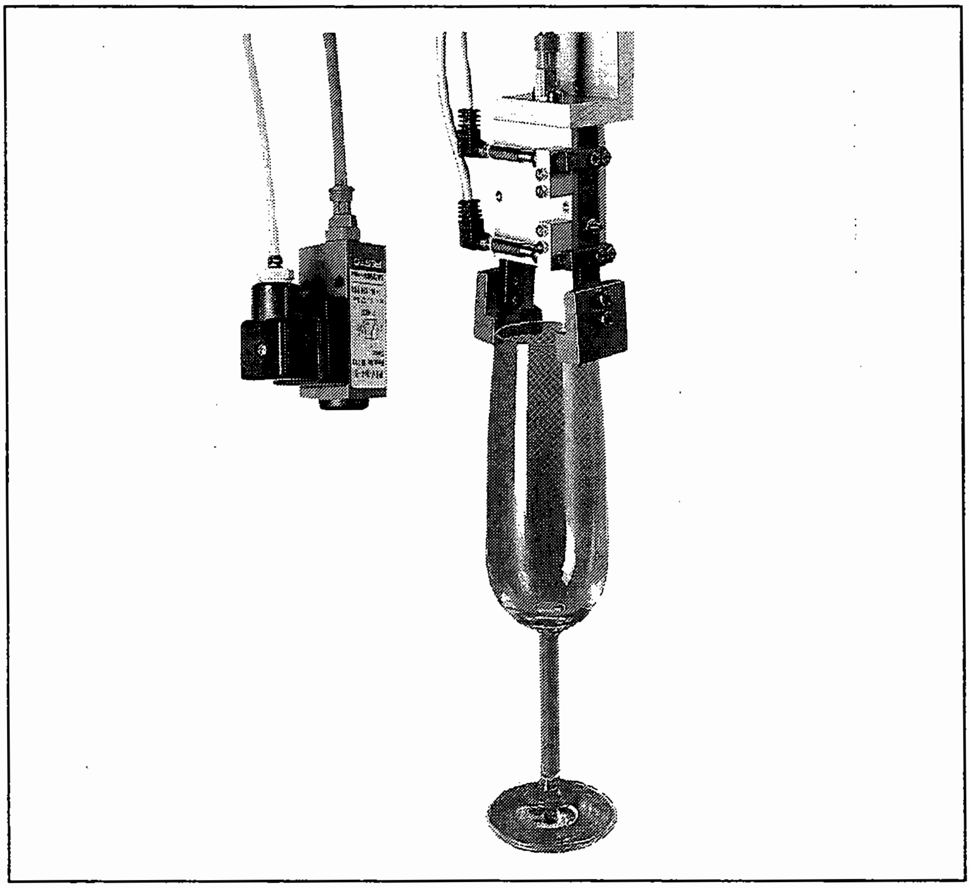


Fig. 3: A sensor monitors the closing force of a gripper

A pressure switch monitors pressure in the supply line of a pneumatic cylinder. When the actuating pressure is reached, this is signalled to the processor and the cylinder advance movement is stopped.

3. Classification of sensors

The wide range of sensors is first of all classified on the basis of the physical value to be detected and secondly according to the operational principle or type of application.

- *Sensors for geometrical values*
  position, distance, length, travel, strain, gradient, speed, acceleration, angle of rotation, rotation as well as surface characteristics of workpieces.
- *Sensors for force-related values*
  force, weight, pressure, torque and mechanical power.
- *Sensors for material quantity values*
  flow rates and filling level of gaseous, liquid or solid materials.
- *Sensors for temperature and heat quantity*
- *Sensors for quantities of optical radiation*
  radiant flux, radiant energy, radiant intensity, radiance and luminous quantities such as luminous flux, luminous energy, luminous intensity, luminance, illuminance. Moreover, this category should include all systems for image processing insofar as these are for the purpose of measuring tasks.
- *Sensors for characteristics of acoustic waves*
  sound pressure, sound energy, sound level and audio frequency.
- *Sensors for electromagnetic values*
  generally recognised elementary electrical values such as voltage, current, electrical energy and power. Also included amongst these are electrical and magnetic field force and electromagnetic emission. The latter is limited by the above mentioned optical emission due to the wavelength condition $\lambda > 10^{-3}$ m.
- *Sensors for high-energy radiation*
  X-ray radiation, gamma radiation. The high-energy radiation is limited by the optical emission due to the wavelength condition $\lambda < 10^{-10}$ m. Sensors for particle radiation such as electrons, alpha particles, elementary particles and nuclear fragments.
- *Sensors for chemical substances* (gases, Ions), and in particular water in the form of humidity, dew-point and icing sensors.
- *Sensors for physical material properties*
  mechanical, electrical, optical, thermal and acoustic properties.
- *Sensors for identification of objects and pattern recognition*
  This caterogy generally includes sensor systems such as optical character readers, bar code readers, magnetic strip readers and image processing systems.

4. Sensor signals

Sensors convert a physical value, usually into an electrical signal. Sensors can be divided, according to the type of output signal, into binary sensors, also called switches, and analogue sensors.

Binary sensors

Binary sensors generate just two output signals, i.e. the switching statuses "On" and "Off". The changeover from one switching status to another takes place at a very specific value of the physical variable; this switching point can often be set. In many instances, the switching point on the characteristic curve for an approaching object differs to that of a withdrawing object. The difference between the two switching points or threshold value is known as hysteresis. In many applications, hysteresis can be quite favourable in that it reduces the switching frequency in the case of closed loop control and leads to improved stability of the system.

Analogue sensors

Analogue sensors create an electrical signal which changes continually according to the constant change in physical values. This correlation need not necessarily be linear, but in contrast with binary sensors always indicates the actual size of the physical value. Analogue sensors offer more information than binary sensors, though the processing of signals is costly.

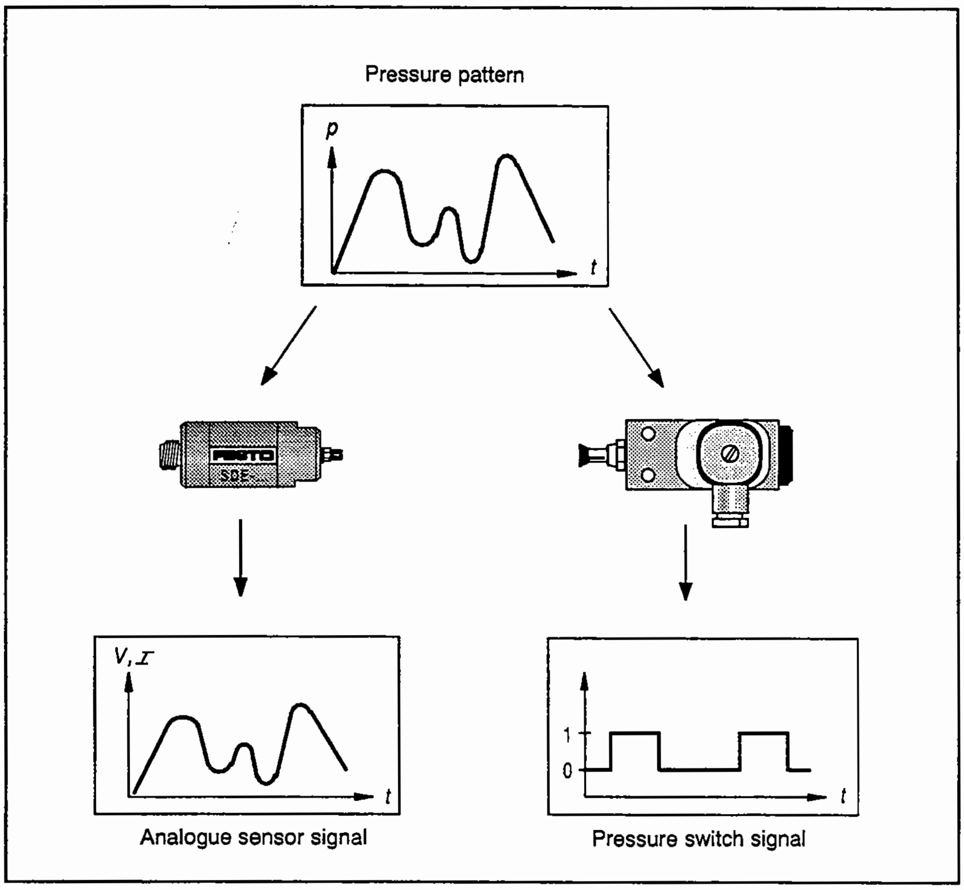


Fig. 4: Analogue and binary signals

This diagram illustrates the correlation between pressure variation and resulting binary and analogue signals. In automation, analogue sensors are used, if a gradual change of the value is important. Binary sensors are however often used as limit switches or alarm contacts.

5. Information flow in automation

In research laboratories, quality assurance and process monitoring alike, sensors provide information on a technical sequence or a physical or chemical reaction. These functions are known as a process. The information is indicated to the operator by means of a display instrument or fed into a data recording device, e.g. a computer. In this context, both the operator as well as the data recording device should be regarded as information processing systems. The term 'processors' is used to describe these systems.

Process measurement

In process measurement, information flows from the process via the sensors to the processor.

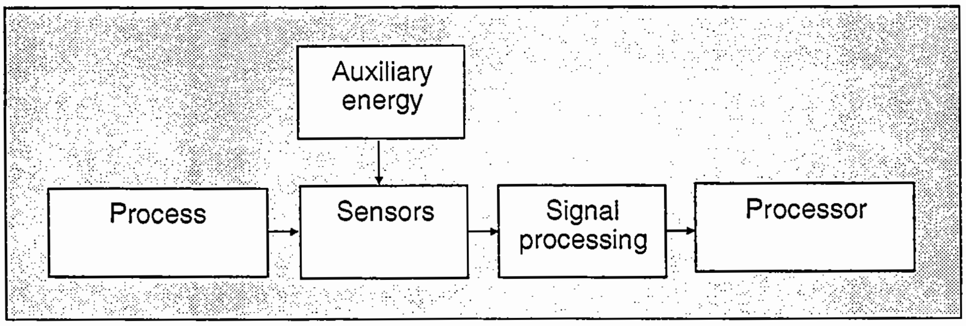


Fig. 5: Information flow in process measurement

Process control

In process control the information flow is the reverse. The operator or a processor intervenes in the process with the help of actuators. The information flows from the processor to the process via the actuators.

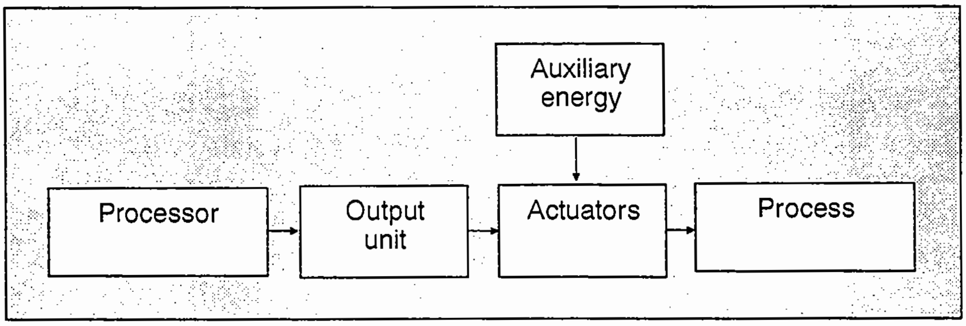


Fig. 6: Information flow in process control

Automation technology

In automation technology, both types of information flow occur. The closed circuit of information ressembles closed loop control technology, i.e. processor to process and back again to the processor, but places the emphasis on the methods of transmitting and processing information. Control loops can be part of an automation system.

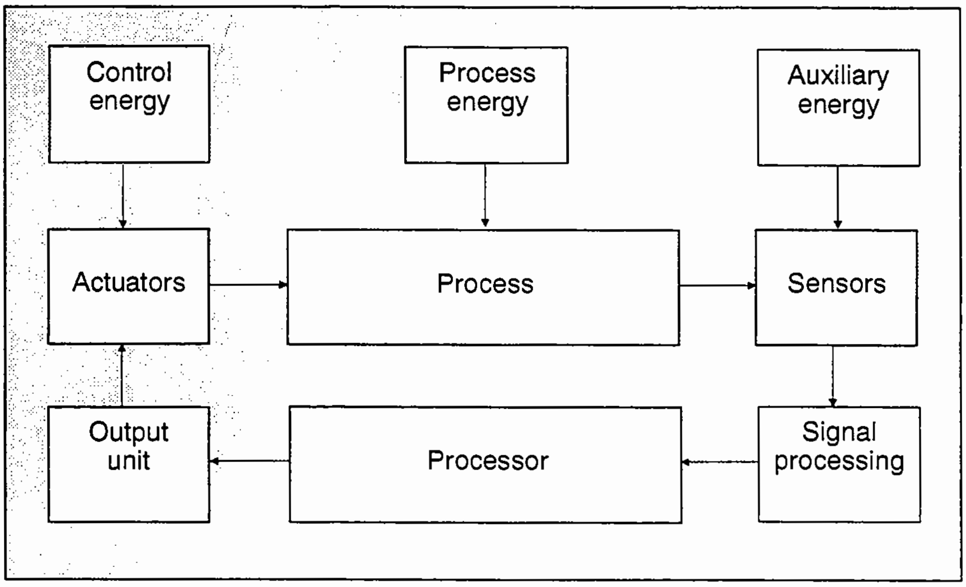


Fig. 7: Information flow in automation technology

User notes

Apart from the general notes on safety, the following operating notes should be observed:

Setting the equipment for the measurements:

- Switch off voltage supply
- Complete the electrical circuit and note the polarity of the voltages to be connected
- Check the circuit by means of the circuit diagram
- Switch on the power supply at a regulated voltage of 24 V D.C. / 5 A.

Having completed the measurements:

- Switch off power supply
- Disconnect measuring lines

Comments regarding the exercises in the course section

When using electrical equipment, the colour codings for the connecting lines and plugs must be observed. The following table of colour abbreviations and the relevant data sheets in appendix D will enable you to establish the correct electrical connections.

Colour	Abbreviation
black	BK
brown	BN
blue	BU
white	WH
red	RD
green	GN
yellow	YE

Table 1: Colour abbreviation to DIN IEC 757

Graphic symbols

The graphic symbols shown in respect of pressure switches and analogue pressure sensors in the pneumatic circuit diagrams are based on the ISO/DIS standard 1219-1:

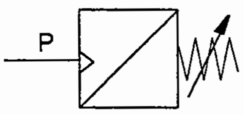


Fig. 8: Symbols in pneumatic circuit diagrams

Assembly

The equipment set includes two kinds of equipment with different types of mounting. The equipment using a knurled screw and T-head nut can be screwed directly on to the profile plate. The equipment using locating pins can also be mounted on to a plug-in board and requires the use of plug-in adapters from the set of adapters D.MP-B-ME-AS (Order No. 035651), in order to mount it on to the profile plate. In course A, the plug-in adapters are listed in the component list as and when they are required.

A number of procedures or simplifications are required or defined in the exercises, which will not be individually described in each exercise. You should therefore observe the following notes. Please refer also to the relevant data sheets in the appendix.

Measuring bridge amplifier

The electronic amplifier components of the measuring bridge amplifier are subject to temperature drift until they reach their operating temperature. Due to this, the zero-point of a sensor cannot be accurately set on the amplifier during the warming-up period. The amplifier must therefore be switched on approximately 5 minutes before the exercise is carried out. After this period, temperature drift will no longer occur. The connections Out- and 0V are electrically isolated. When carrying out measurements, these two connections must not be linked or mixed up.

Force sensor

The force sensor contains the calibrating device D.AS-SGA. With the help of this device, a force can be applied to the sensor by means of a weighted disc from the set of weights D.AS-S-GWS-FP1130.
The colours of the connecting cables and the plugs do not always correspond. The plugs for the voltage supply and the signal lines, however, are the same colour for each pair.
In order to avoid damage, forces in excess of 200 N must not be applied to the force sensor. As far as the introduction of force with cylinder D.AS-DSN-PPV is concerned, air pressure must not exceed 4 bar on the piston side.

Connection plate

The connection plate D.ER-AE-101AF is a unit with which the analogue signals are switched to the programmable logic controller FPC 101AF. The FPC 101AF controller is used in the function package FP1131. In the function package FP1130, the connection plate D.ER-AE-101AF is used as a distributor unit for analogue signals in conjunction with the signal changeover switch D.AS-SUAE-101.
On the lefthand side of the connection plate, there is a 9-pin socket for the connection of signals to the counter input of FPC 101AF. Because the counter input is not used for carrying out the exercises with the equipment set of FP1130, it has not been illustrated in any of the electrical connection diagrams. Care should be taken that the load connections of the analogue section (GND) and the voltage supply (0 V) are not connected together internally. For the measuring tasks using the multimeter, the two load connections must always be connected to one another.

Signal switching unit

The voltage signals are switched to output 0 via the signal switching unit, and the current signals are switched to output 1. The unit switches the signals of both input sockets to the appropriate output socket for each switching position.

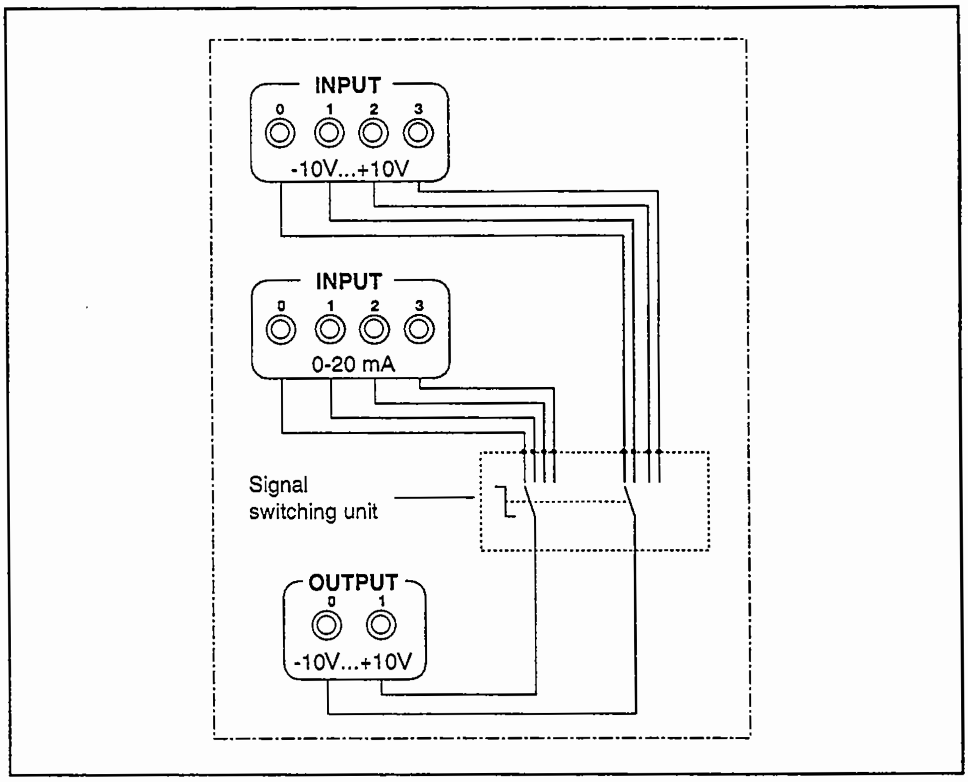


Fig. 9: Principle of interconnecting the signal switching unit and the connection unit 101 AF
Please note: In combination with the signal switching unit, output 1 of the connection unit is used as a current output.

Sets of weights

In the exercises using the set of weights, the following simplification applies with regard to determining force:
A mass of 100 g corresponds approximately to a force of 1 N.

Electrical connection diagrams

The distributor and connection plates are shown without the 24 V voltage supply.

Electrical circuit diagrams

In each case, only the signal changeover switch is shown, but not the distributor and connection units.

Deflecting arm force sensor and back pressure switch

The deflecting arm force sensor and the back pressure switch must be assembled above the profile plate. The following illustration shows the position of the two components on the profile supports. It should be noted that the deflecting arm force sensor must be mounted directly above the vertical profile rail. The deformation movement of the deflecting arm in the mechanical stop is approximately 0.5 mm upwards and 1.5 mm downwards.
An additional connection cable, a piece of tubing and a transparent plastic beaker form part of the back pressure sensor unit. The lugs of the connection cable are plugged into the electrical contacts of the back pressure switch. The allocation of cable lugs and plug contacts is unimportant. The tubing is connected to the pressure input (lower connection) of the back pressure switch. The upper connection remains vacant. The beaker is secured underneath the back pressure switch which is mounted on the profile, whereby the tubing is inserted in the beaker.

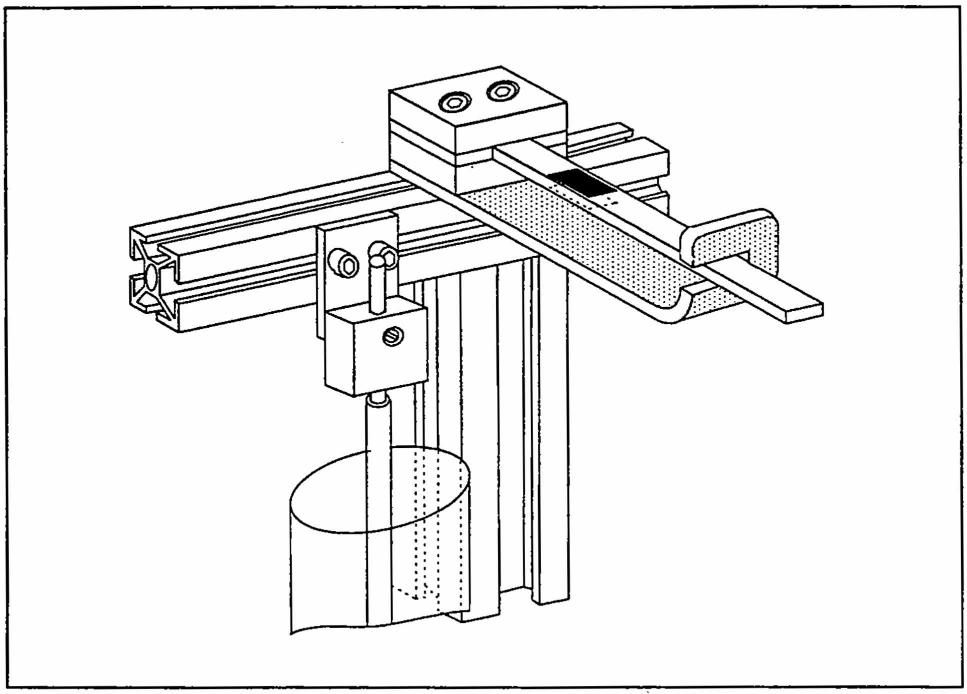


Fig. 10: Assembly of back pressure switch and deflecting arm force sensor

Description Equipment set FP1130

Designation D.CP-FP-1130

Order No. 150531

Quant.	Order No.	Description	Designation
1	150554	Pressure switch	D.ER-PEV-1/4-B
1	150556	Analogue pressure sensor	D.ER-SDE-10-10V/20mA
1	150558	Analogue pressure sensor	D.ER-SDE-10-5V/20mA
2	150555	Pressure manifold	D.ER.FR-4-1/8-B
1	150557	Compressed air reservoir	D.ER-VZS-0,4
1	150565	Back pressure switch, including beaker, D.AS-RK	D.ER-SDS
1	150542	Deflecting arm	D.ER-BB-KS-FP1130
1	150541	Force sensor, including weight support D.AS-SGA	D.ER-KS-FP1130
1	034080	Distribution plate *	D.ER-VERT-SENSOR
1	014595	Connection plate *	D.ER-AE-101AF
1	150538	Signal switching unit	D.AS-SUAE-101
1	034009	Set of weights	D.AS-GWS
1	150543	Set of round weights	D.AS-S-GWS-FP1130
1	150563	Measuring bridge amplifier *	D.ER-BV-FP1130
1	032188	Pneum.-elect. switch *	D.ER-PEN-M5
1	011700	One-way flow control valve *	D.ER-GR-1/8 B
1	011422	Panel mounted valve *	D.ER-SV-3-M5
1	011758	Service unit *	D.ER-FRC-1/8-S
1	115608	Profile 32x32x168 C/C	
1	107635	Profile 32x32x170 B/B	
1	035651	Set of adapters	D.MP-B-ME-AS
1	150578	Cylinder *	D.AS-DSN-PPV

* Two or four plug-in adapters from the set of adapters D.MP-B-ME-AS are required to assemble the designated units on the profile plate. One set of adapters contains 27 adapters.

Components-exercises table

Components, Description, Designation	Exercises													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Pressure switch D.ER-PEV-1/4-B										1			1	
Analogue pressure sensor D.ER-SDE-10-10V/20m							1	1	1	1	1	1	1	
Analogue pressure sensor D.ER-SDE-10-5V/20mA									1					
Pressure manifold D.ER-FR-4-1/8-B							1	1	1	1	1	2	1	
Compressed air reservoir D.ER-VZS-0,4												1	1	
Back-pressure switch D.ER-SDS with beaker														1
Force sensor D.ER-KS-FP1130 with weight support						1	1							
Distribution plate D.ER-VERT-SENSOR										1	1	1	1	1
Connection plate D.ER-AE-101AF							1	1	1	1	1	1	1	

Component, Description, Designation	Exercises													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Signal switching unit D.AS-SUAE-101							1	1	1	1	1	1	1	
Set of weights D.AS-GWS				1	1									
Set of round weights D.AS-S-GWS-FP1130						1								
Measuring bridge amplifier D.ER-BV-FP1130			1	1	1	1	1							
Pneum.-elect. switch D.ER-PEN-M5											1	1		
Deflecting arm force sensor D.ER-BB-KS-FP1130	1	1	1	1	1									
One-way flow control valve D.ER-GR-1/8B												1	1	
Panel mounted valve D.ER-SV-3-M5												1	1	
Service unit D.ER-FRC-1/8-S							1	1	1	1	1	1	1	
Cylinder D.AS-DSN-PPV							1							
Digital multimeter D.AS-DMM *	1	1	1	1	1	1	2	1	1	1	1	1	1	1

* *not included in equipment set (separate accessory, Order No. 035 681)*

Course

Exercises

Force measurement

Pressure measurement

Subject

Sensors for force and pressure

Title

Electrical behaviour of mechanically loaded strain gauges

Learning content

B 3.2

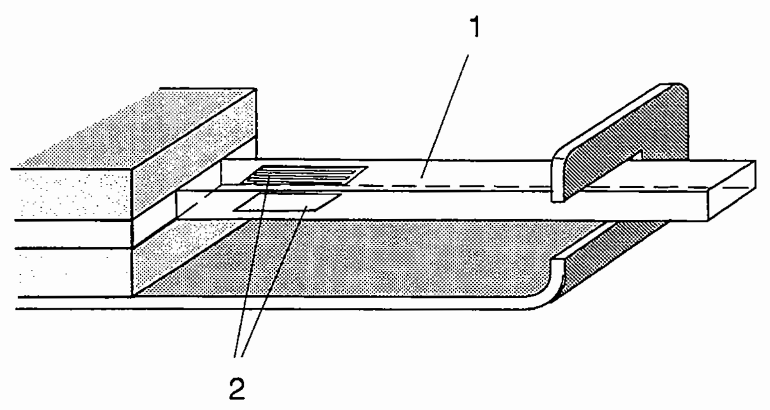
To learn about the electrical behaviour of strain gauges (SG) under tension and compression.

Technical knowledge

Strain gauges (SG) consist of a resistance layer. The resistance value increases, if the strain gauge is tensioned in the direction of the resistance paths. It decreases if the strain gauge is compressed. The resistance change is based on the change in length, cross section and specific resistance as a result of the tension or the compression.

Problem definition

A deflecting arm with two opposing strain gauges is used for force measurement. In order to examine the electrical behaviour of the strain gauges in principle, a load is to be applied lightly to the deflecting arm by hand while the resulting electrical behaviour of the strain gauges is observed.



1) Deflecting arm
2) Strain gauge

Fig. 1/1: Deflecting arm

Exercise

a) Connect the upper strain gauge to the multimeter for a resistance measurement.

b) Lightly press down the deflecting arm and determine the qualitative resistance change of the strain gauge.

c) Lightly press the deflecting arm upwards and establish the qualitative resistance change of the strain gauge.

d) Calculate the percentage resistance change of the measurement in exercise part b).

Please observe the user notes in the introduction section when carrying out the exercises. Appropriate information regarding connection method and additional technical data can be found in the corresponding data sheets in the appendix.

Practical implementation
Part exercise a)

The connection cables of the upper strain gauge are connected directly to the multimeter.

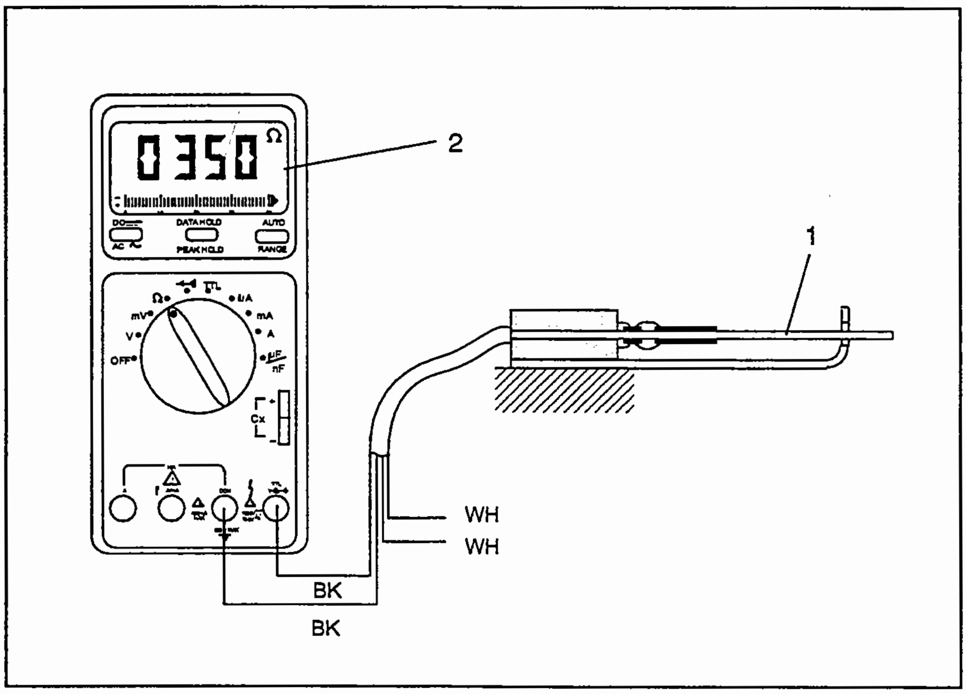


Fig. 1/2: Electrical connection

Comp. Ref. No.	Qty.	Description	Designation
1	1	Deflecting arm force sensor	D.ER-BB-KS-FP1130
2	1	Digital multimeter	D.AS-DMM

Table 1/1: Component list

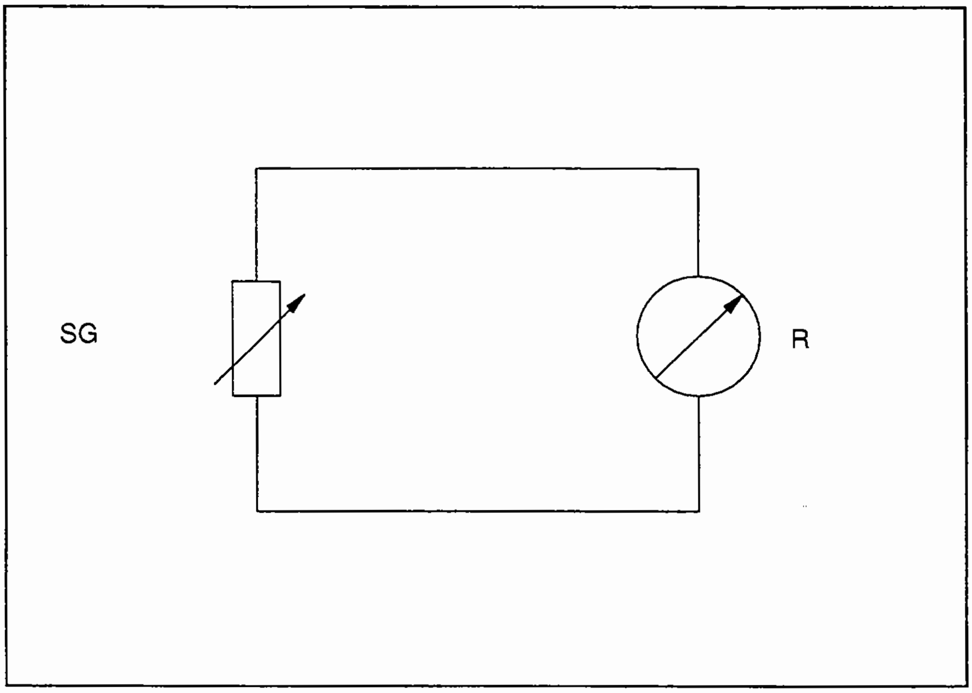


Fig. 1/3: Electrical circuit diagram

Note

The resistance of the strain gauge is approximately 350 Ohm. The nearest larger measuring range is to be set on the multimeter.

Part exercise b)

If you press down the deflecting arm slightly with your finger, the multimeter registers a signal change. The force applied should not be excessive, because deformation of the deflecting arm should only occur within its range of elasticity.

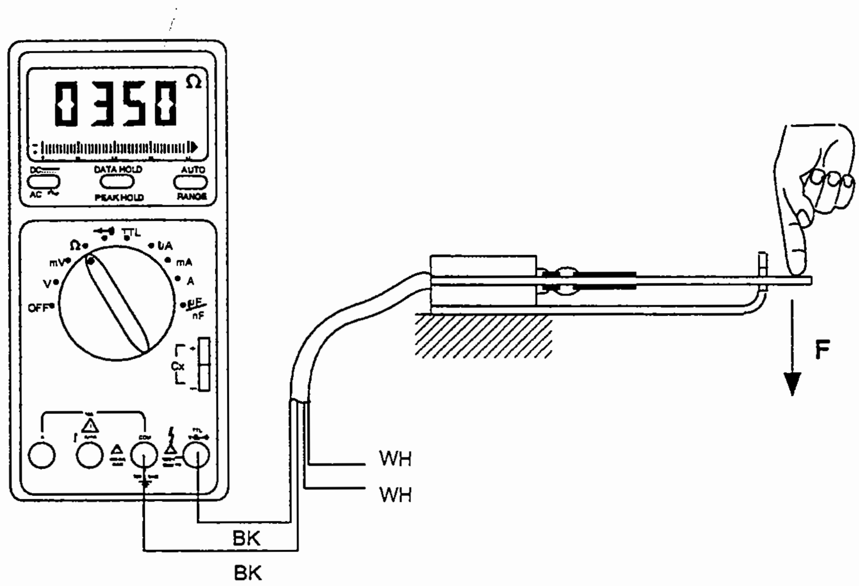


Fig. 1/4: Test procedure

- Record the qualitative signal change in table 1/2 on the worksheet.

Part exercise c)

- Press the deflecting arm upwards with roughly the same amount of force as that used in part exercise b).

Note

It may be necessary to remove the mechanical stop in order to carry out the exercise. If so, please note that there must not be any plastic deformation of the deflecting arm.

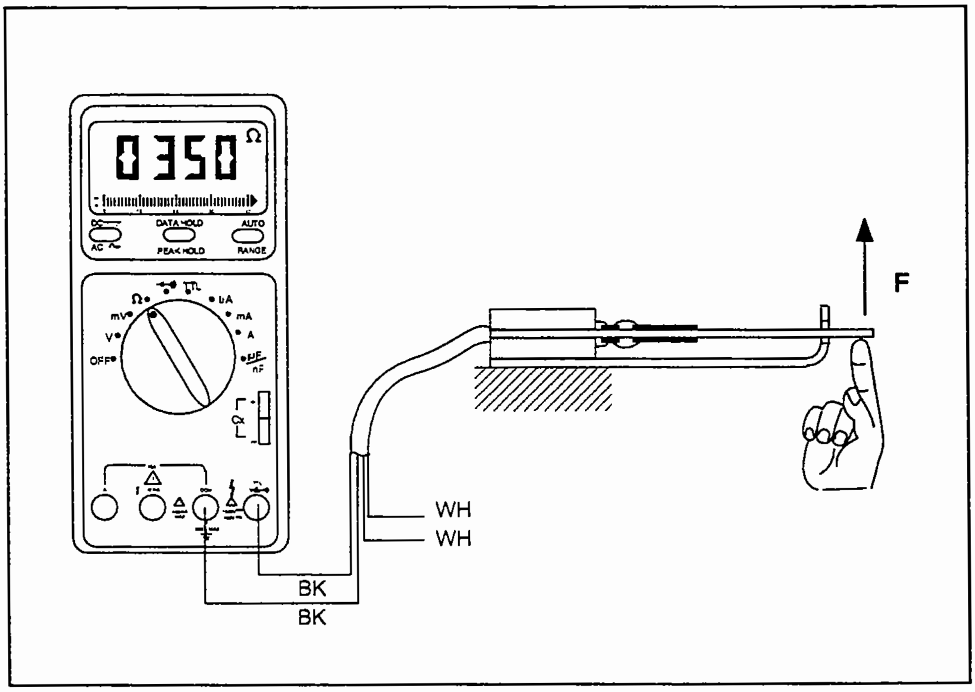


Fig. 1/5: Test procedure

- Record the qualitative signal change in table 1/3 of the worksheet.

Part exercise d)

The percentage resistance change ΔR% is calculated as follows:

$$\Delta R_{\%} = \frac{\Delta R_{SG}}{R_{SG}} \cdot 100$$

- Calculate the percentage resistance change for the measurement in part exercise b).
- Enter the value in table 1/4 of the worksheet.

Question

Estimate the resistance behaviour of the strain gauge in the unloaded state after plastic deformation of the deflecting arm has occurred.

Resistance of unloaded SG:____________ Ohm
Change of resistance ΔR_{SG} = ____________ Ohm
The resistance of the loaded SG is:
☐ increasing ☐ decreasing ☐ the same

Table 1/2: Qualitative signal change of a strain gauge with tensile stress

Resistance of unloaded SG:____________ Ohm
Change of resistance ΔR_{SG} = ____________ Ohm
The resistance of the loaded SG is:
☐ increasing ☐ decreasing ☐ the same

Table 1/3: Qualitative signal change of a strain gauge with compressive stress

Percentage resistance change $\Delta R_{\%}$ = ____________ %

Table 1/4: Percentage resistance change

Answer

____

____

____

____

____

____

____

____

____

____

Notes

Subject

Sensors for force and pressure

Title

Strain gauges connected in series

Learning content

To learn about the electrical behaviour of strain gauges connected in series.

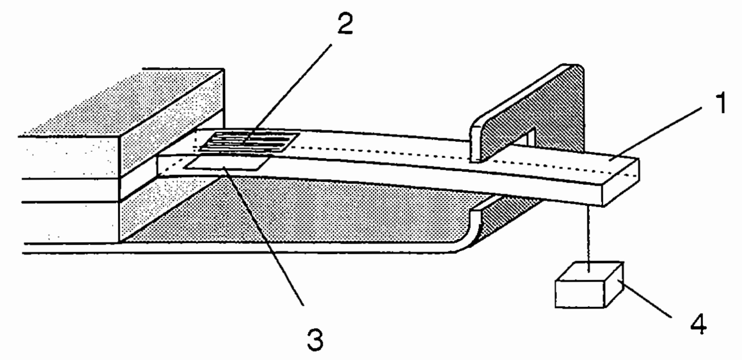
Technical knowledge

B 2.3

If a load is applied to a deflecting arm, a mechanical stress is created, which leads to strain of the material. Depending on the amount of stress, this is greatest on the upper and lower surface of the deflecting arm at the point of clamping. If force is applied downwards strain is positive on the upper side and negative on the lower side. Positive strain is known as tension. Negative strain is also known as compression. For simplicity, we can assume that both strains are of equal magnitude.

Problem definition

The principle of the electrical behaviour of loaded strain gauges, which are interconnected, is to be investigated.



1) Deflecting arm
2) Upper strain gauge strip
3) Lower strain gauge strip
4) Load

Fig. 2/1: Loaded deflecting arm

Exercise

a) Connect the two strain gauges in series to the multimeter for resistance measurement.

b) Lightly press the deflecting arm downwards and determine the qualitative resistance change of the two strain gauges.

c) Lightly press the deflecting arm upwards and determine the qualitative resistance change of the two strain gauges.

Please observe the user notes in the introduction section when carrying out the exercises. Appropriate information regarding connection method and additional technical data can be found in the corresponding data sheets in the appendix.

Practical implementation
Part exercise a)

The two strain gauges are connected in series to the multimeter. Because the strain gauges in question are resistors, order and polarity are unimportant.

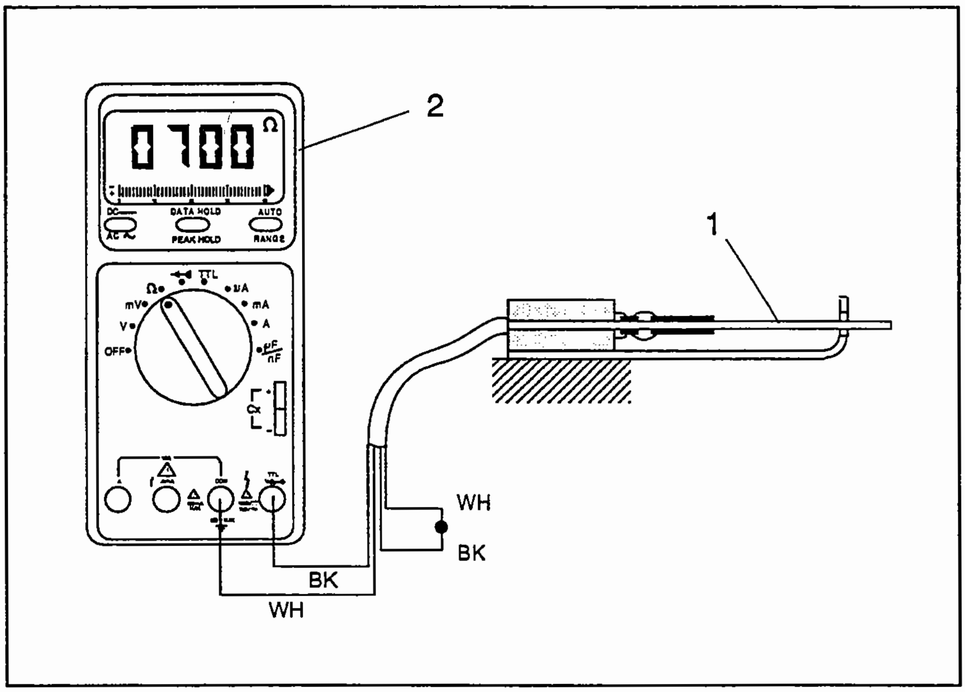


Fig. 2/2: Electrical connection

- Connect one black plug (BK) of the upper strain gauge to a white plug (WH) of the lower strain gauge. Plug in the two free connectors to the multimeter for resistance measurement.

Comp. Ref. No.	Qty.	Description	Designation
1	1	Deflecting arm force sensor	D.ER-BB-KS-FP1130
2	1	Digital multimeter	D.AS-DMM

Table 2/1: Component list

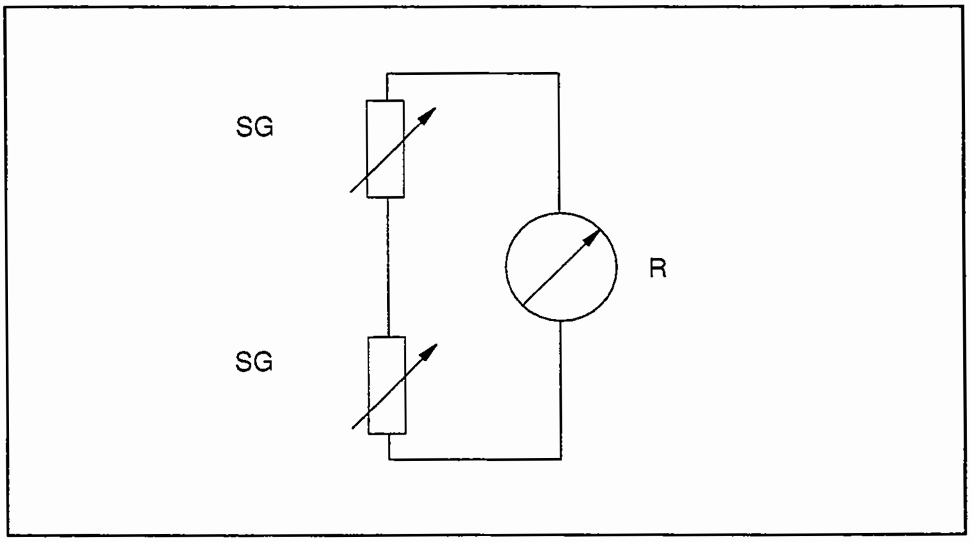


Fig. 2/3: Electrical circuit diagram

Part exercise b)

- Lightly press down the deflecting arm using your finger. Ensure that the force applied is not excessive. The deflecting arm must be deformed only within its elastic range.

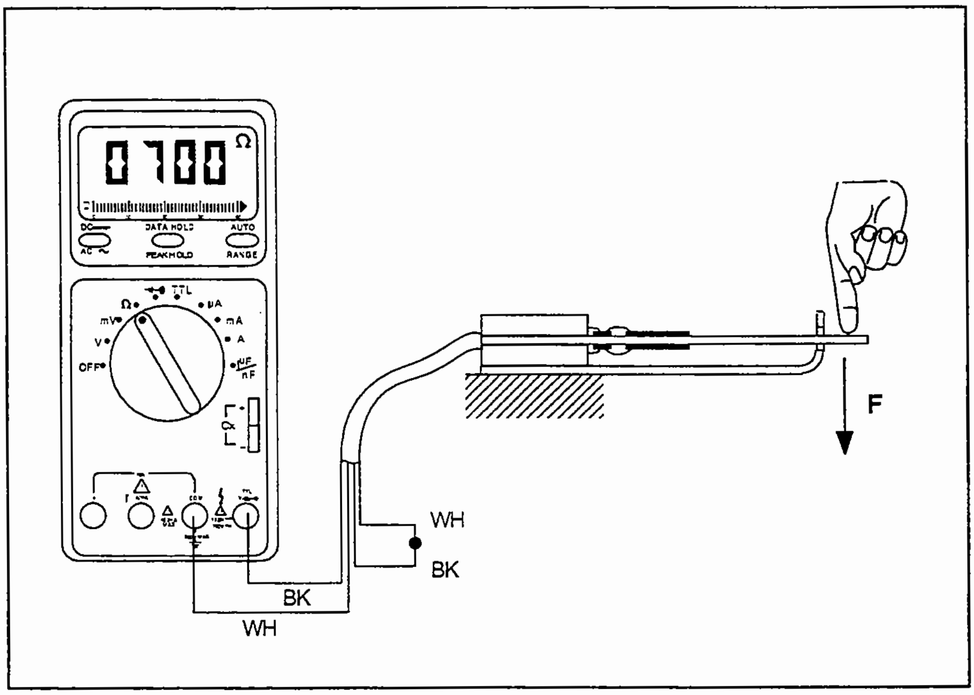


Fig. 2/4: Test procedure

- Record the qualitative signal change in table 2/2 of the worksheet.

Part exercise c)

- Press the deflecting arm upwards with roughly the same amount of force as that used in part exercise b).

Note

It may be necessary to remove the mechanical stop in order to carry out this part exercise. If so, please note that there must not be any plastic deformation on the deflecting arm.

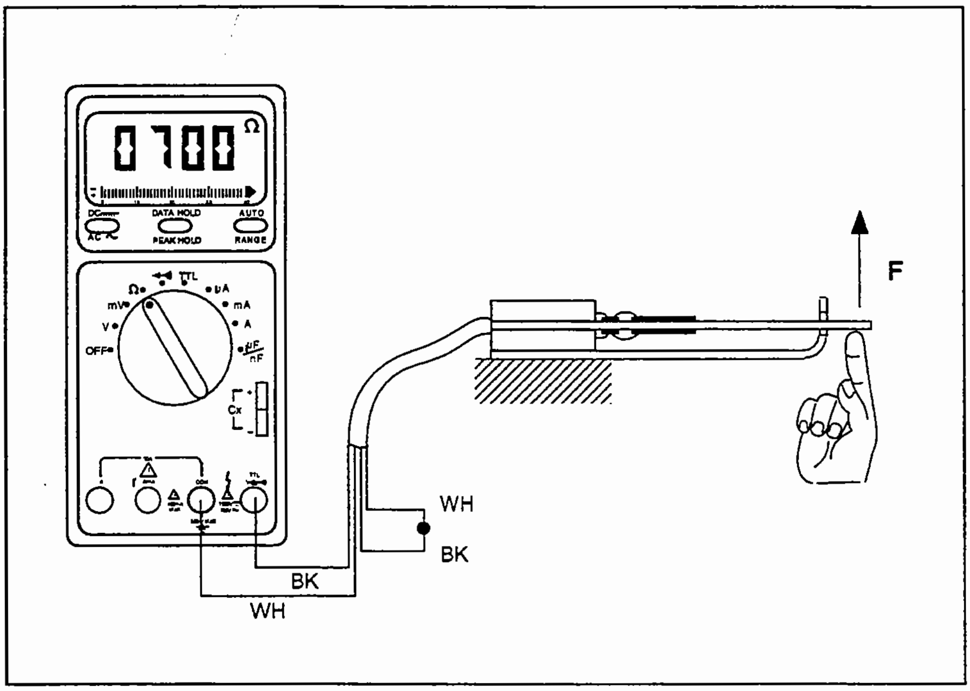


Fig. 2/5: Test procedure

- Record the qualitative signal change in table 2/3 on the worksheet.

Question

Assess the resistance behaviour of the two strain gauges connected in series in the unloaded state, after plastic deformation of the deflecting arm.

Resistance of unloaded SG:________________Ohm
The resistance of the loaded SG is:
☐ increasing ☐ decreasing ☐ the same

Table 2/2: Qualitative signal change when pressed down

Resistance of unloaded SG:________________Ohm
The resistance of the loaded SG is:
☐ increasing ☐ decreasing ☐ the same

Table 2/3: Qualitative signal change when pressed upwards

Answer

Notes

Subject

Sensors for force and pressure

Title

Connection of a measuring bridge amplifier

Learning content

Tests for signal evaluation of strain gauges using a bridge circuit and a measuring amplifier.

Technical knowledge

B 4.2
B 4.6

A relative strain ε produces a relative change in the strain gauge resistance of $\Delta R/R = k \cdot \varepsilon$ with k approx. 2. This resistance change causes a change in the output signal of the quarter-bridge $V_A/V_E = 1/4 \cdot \Delta R/R = 0.5\ \varepsilon$. Because a bridge is not normally balanced, the zero compensator of the measuring amplifier adjusts the inherent error signal of the measuring bridge, therefore enabling the meter to display 0 V in the unloaded state. The amplification of the bridge signal thus permits trouble-free measurement and display of the signal.

Problem definition

In order to obtain meaningful measured values, the force sensor of the deflecting arm is to be connected to the measuring bridge amplifier and the amplifier adjusted to this sensor.

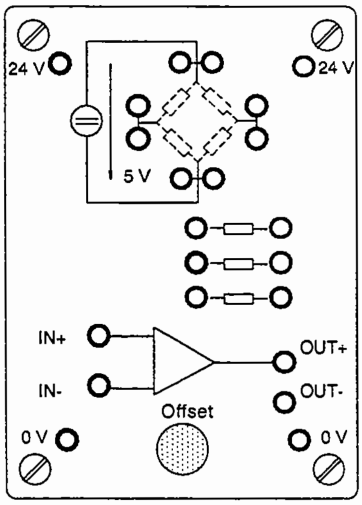


Fig. 3/1: Measuring bridge amplifier

Exercise

a) Construct a quarter-bridge using the upper strain gauge of the deflecting arm force sensor.

b) Carry out a zero-balance of the bridge amplifier.

c) Press down the deflecting arm lightly and measure the qualitative signal change at the output of the amplifier.

d) Calculate the amplifier output voltage V_O of a quarter-bridge circuit with a resistance change ΔR_{SG} of approx. 0.2 Ohm. The bridge voltage V_E is 5 V.

Please observe the user notes in the introduction section when carrying out the exercises. Appropriate information regarding connection method and additional technical data can be found in the corresponding data sheets in the appendix.

Practical implementation
Part exercise a)

The upper strain gauge of the deflecting arm is connected as resistor R1 to the lefthand branch of the bridge. The remaining resistors of the Wheatstone bridge circuit are connected as fixed resistors

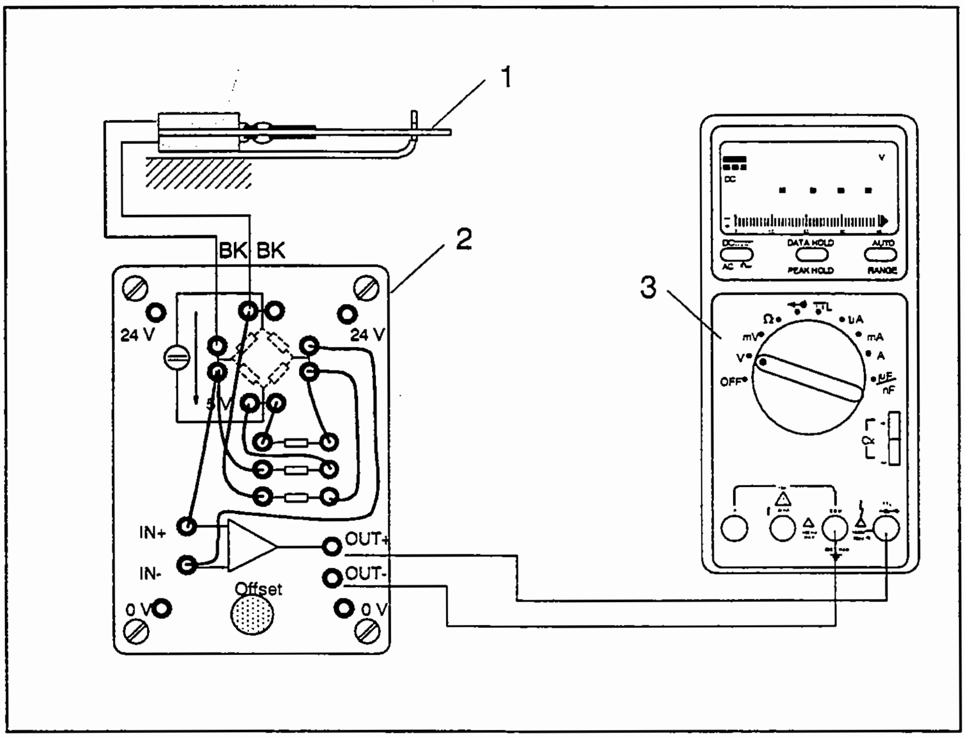


Fig. 3/2: Electrical connection

Comp. Ref. No.	Qty.	Description	Designation
1	1	Deflecting arm force sensor	D.ER-BB-KS-FP1130
2	1	Measuring bridge amplifier	D.ER-BV-FP1130
3	1	Digital multimeter	D.AS-DMM
	4	Plug-in adapter	D.MP-B-ME-AS

Table 3/1: Component list

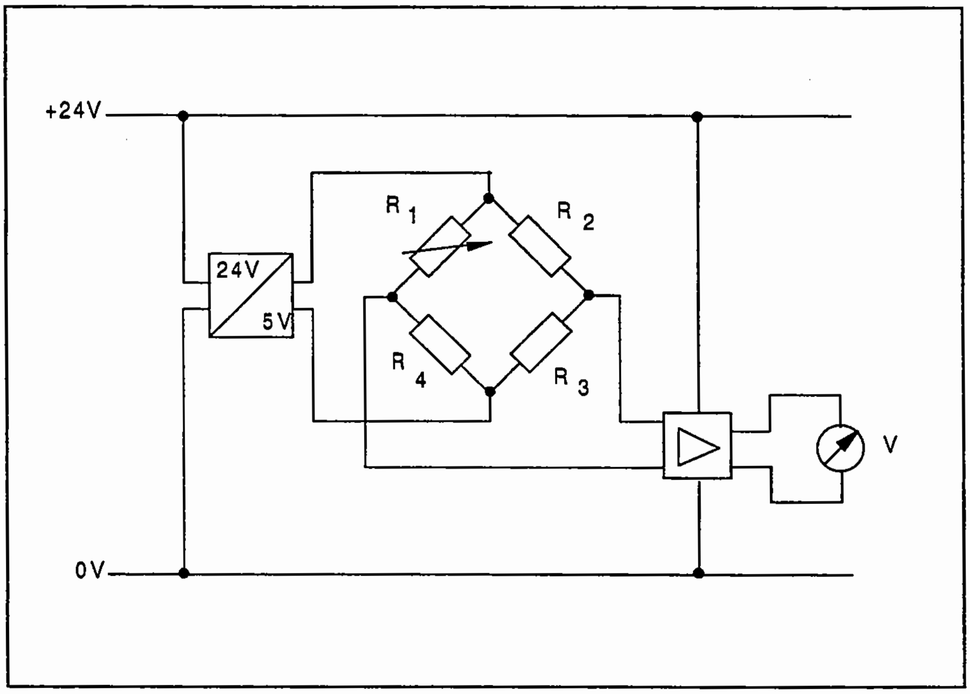


Fig. 3/3: Electrical circuit diagram

Note

The Wheatstone bridge is supplied with 5 V D.C. This voltage is created via the measuring bridge amplifier from an operating voltage of 24 V D.C.

Part exercise b)

If, in the no-load condition, the bridge is not showing 0 Volts, a zero-balance must be carried out. In order to do this, the deflecting arm is to remain unloaded. The amplifier output voltage is set at 0 Volts with the help of the adjustment potentiometer.
Because of the sensitivity of the strain gauge and the bridge amplifier a zero-balance to within an accuracy of 10 millivolt is sufficient at the amplifier output.

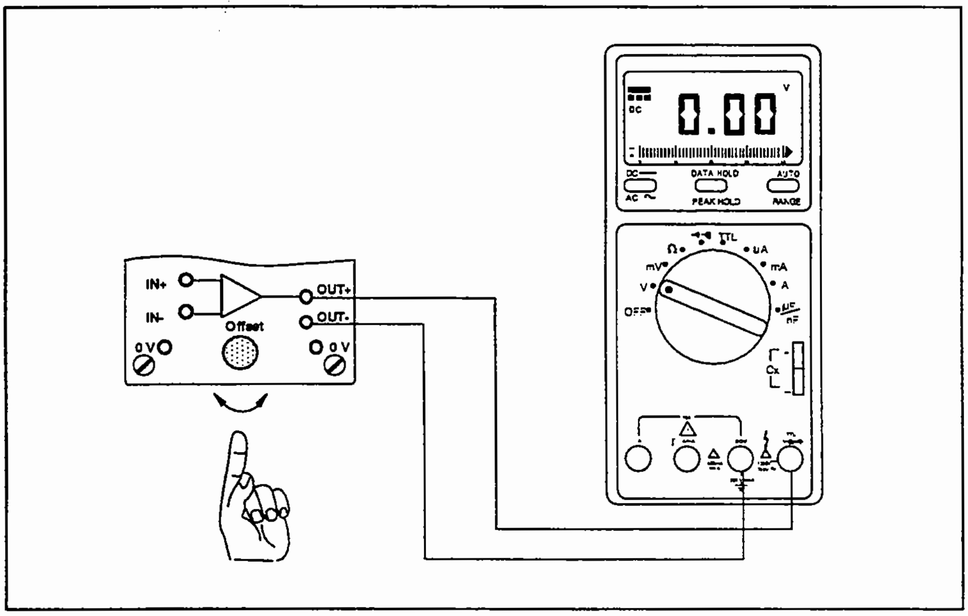


Fig. 3/4: Zero balance

Note

The reason for the bridge signal voltage deviating from 0 V is the minor deviations of the individual bridge rèsistors (strain gauge and fixed resistors) from the nominal resistance value.
Even in the case of very accurately manufactured resistors, there is a fluctuation of a few tenths of a percent. The signal voltage resulting from this in the bridge circuit is also very minor. Due to the large signal amplification, this deviation from the zero point can be clearly seen.

Part exercise c)

- Press down lightly on the deflecting arm using your finger. Make sure that the force applied is not excessive, as deformation of the deflecting arm must only occur within its elastic range.

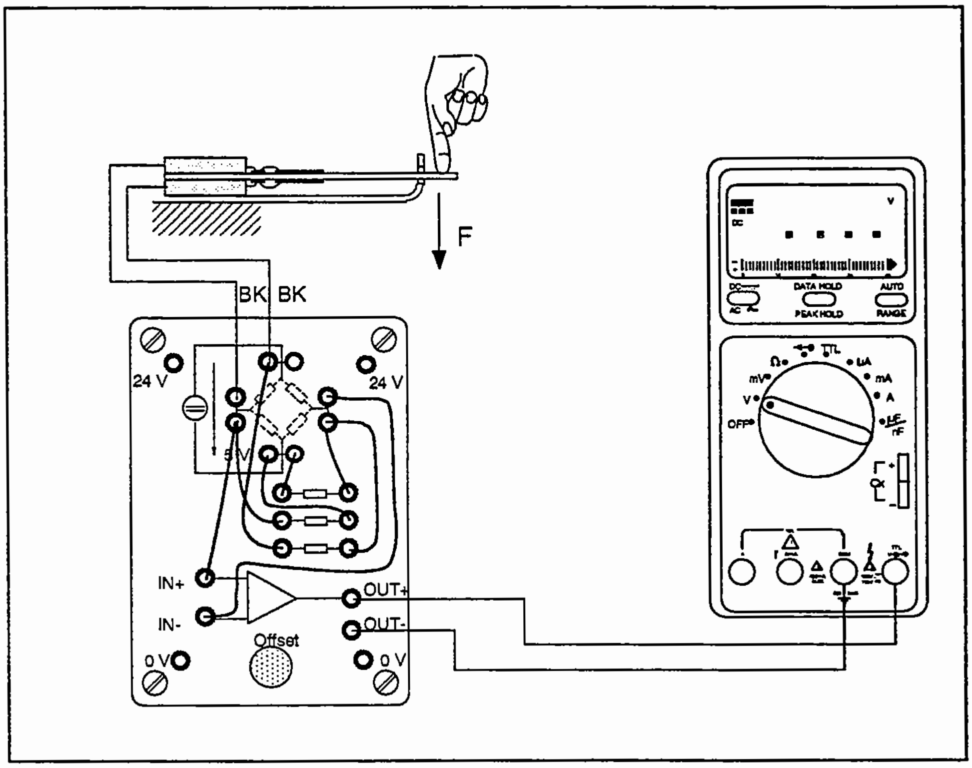


Fig. 3/5: Test procedure

- Record the qualitative signal change at the output of the amplifier in table 3/2 of the worksheet.

Part exercise d)

- Calculate the amplifier output voltage V_O. Enter the value in table 3/3 of the worksheet.

The amplifier output voltage V_O is calculated as follows:

$$V_O = a \cdot V_E \cdot 0.25 \cdot \frac{\Delta R_{SG}}{R_{SG}} \text{ in Volt}$$

a = Amplification factor of the measuring bridge amplifier

V_E = Bridge voltage (5 V)

ΔR_{SG} = Resistance change of the strain gauge (hypothetical value 0.2 Ohm)

R_{SG} = Resistance of the unloaded strain gauge (350 Ohm)

- Use the amplification factor a of the measuring bridge amplifier from the corresponding data sheet in Section D. Enter the value in table 3/3 of the worksheet.

The signal change on the amplifier output occurs in the:
☐ Millivolt range ☐ Volt range

Table 3/2: Qualitative signal change

Notes

Amplification factor	a =	________________
Amplifier output voltage	Vo =	________________ Volt

Table 3/3: Amplifier output voltage

Subject

Sensors for force and pressure

Title

Calibration of a force sensor using a quarter-bridge circuit

Learning content

To learn about a force sensor using a quarter-bridge as an evaluation circuit. Calibration and commissioning of the unit. Calibration is carried out by means of various weights.

Technical knowledge

B 4.10

If the dimensions of the deflecting arm, the modulus of elasticity of the deflecting arm material, the k-factor of the strain gauge and the amplification of the measuring amplifier are known, these may be applied in a formula for conversion between weight and voltage signal. However, it is easier to calibrate the measuring unit using known weights. Because of the linear correlation between weight and voltage signal, the points determined from the calibration may be jointed by a straight line. Unknown weights can be determined from the voltage signal with the help of the calibration line.

Problem definition

B 4.2

Unknown forces (due to weight) are to be determined using a deflecting arm force sensor with a signal evaluation constructed by means of a quarter-bridge circuit. In order to determine the characteristic curve, the force sensor must be calibrated beforehand.

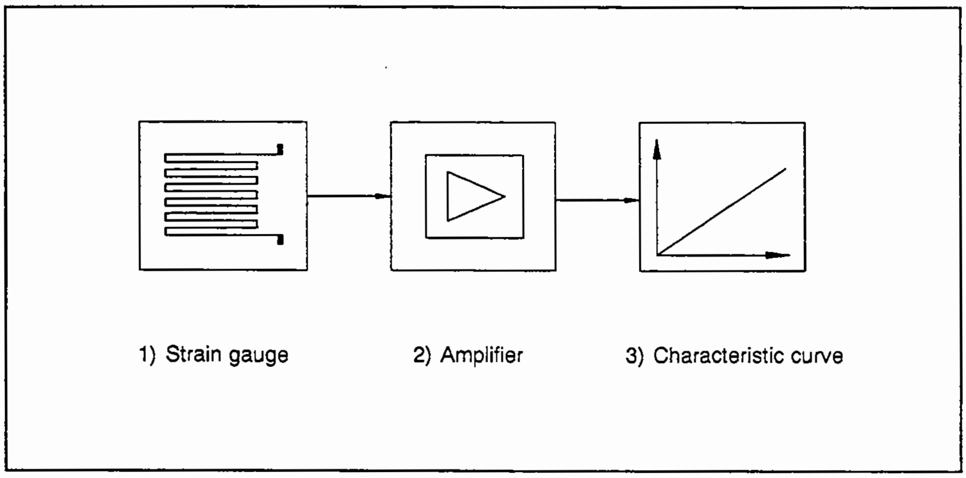


Fig. 4/1: Signal generation and evaluation

Exercise

a) Carry out the calibration of the deflecting arm force sensor D.ER-BB-KS-FP1130 using the set of weights D.AS-GWS. The evaluation circuit is constructed in the form of a quarter-bridge with the upper strain gauge.
Draw the characteristic curve of the deflecting arm force sensor.

b) Use the characteristic curve to determine an unknown force due to a given mass.

Please observe the user notes in the introduction section. Appropriate information regarding connection method and additional technical data can be found in the corresponding data sheets in the appendix.

Practical implementation
Part exercise a)

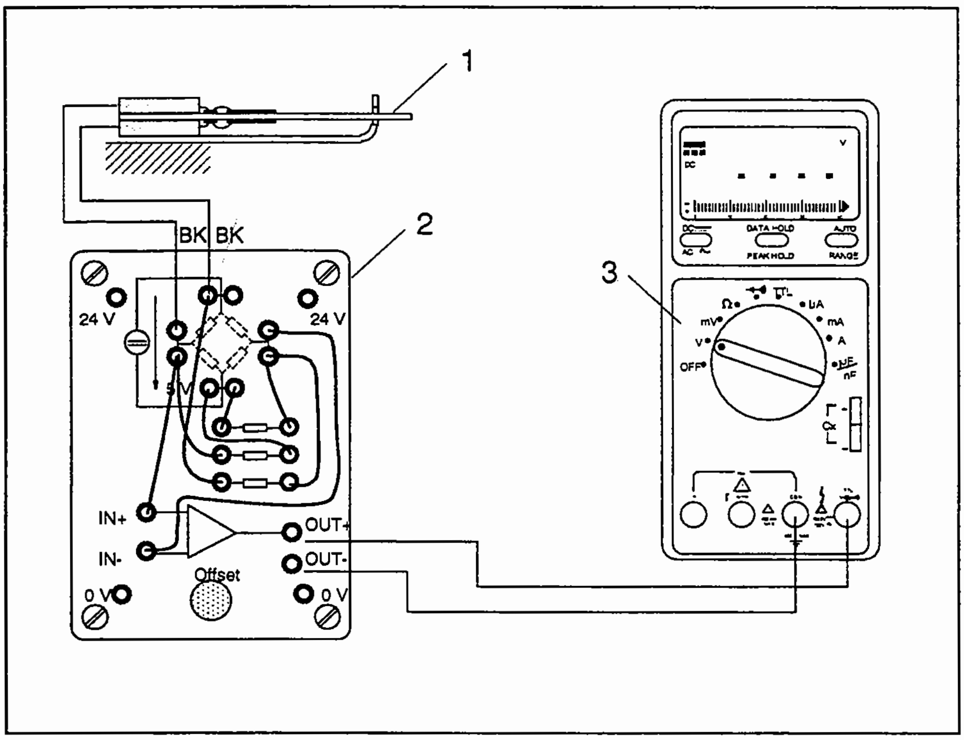


Fig. 4/2: Electrical connection

Comp. Ref. No.	Qty.	Description	Designation
1	1	Deflecting arm force sensor	D.ER-BB-KS-FP1130
2	1	Measuring bridge amplifier	D.ER-BV-FP1130
3	1	Digital multimeter	D.AS-DMM
	4	Plug-in adapter	D.MP-B-ME-AS

Table 4/1: Component list

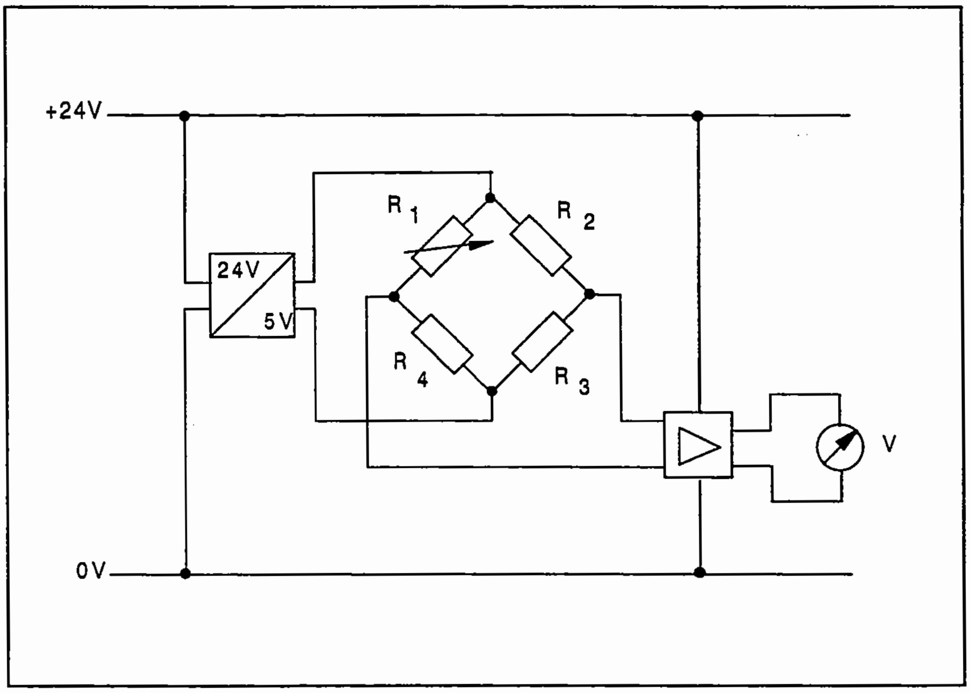


Fig. 4/3: Electrical circuit diagram

Zero-balance

B 4.6

On completion of the quarter-bridge circuit the deflecting arm force sensor remains unloaded. The amplifier output voltage is set by turning the alignment potentiometer to zero Volts.
Because of the sensitivity of the strain gauges and the bridge amplifier a zero-balance to within an accuracy of 10 millivolt is sufficient at the amplifier output.

Procedure in respect of calibration

The deflecting arm is loaded with weights from the set of weights D.AS-GWS ranging between 0 to 500 grammes (approx. 0..5 N) in stages of 20, 50, ..., grammes.

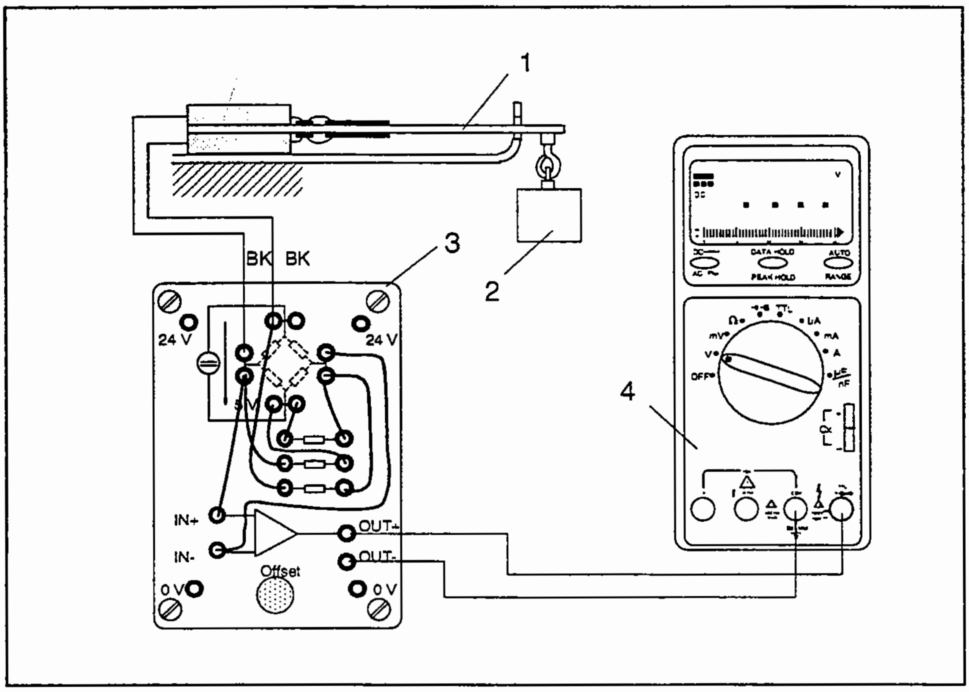


Fig. 4/4: Test procedure

Comp. Ref. No.	Qty.	Description	Designation
1	1	Deflecting arm force sensor	D.ER-BB-KS-FP1130
2	1	Set of weights	D.ER-GWS
3	1	Measuring bridge amplifier	D.ER-BV-FP1130
4	1	Digital multimeter	D.AS-DMM

Table 4/2: Component list

- Attach the weights separately to the deflecting arm. Enter the amplifier output voltage for each weight in table 4/3 of the worksheet.
- Transfer the measured values from table 4/3 to the diagram (fig. 4/5) on the worksheet and draw the characteristic curve of the force sensor for the quarter-bridge.

Part exercise b)

- Attach a mass (≤ 500 grammes) to the deflecting arm.
- Enter the voltage signal in table 4/4 on the worksheet.
- Determine the force on the basis of the characteristic curve (fig. 4/5).

Load (g)	Weight force (N)	Voltage (V)
0	0.0	
20	0.2	
50	0.5	
100	1.0	
200	2.0	
500	5.0	

Table 4/3: Truth table for characteristic curve of sensor

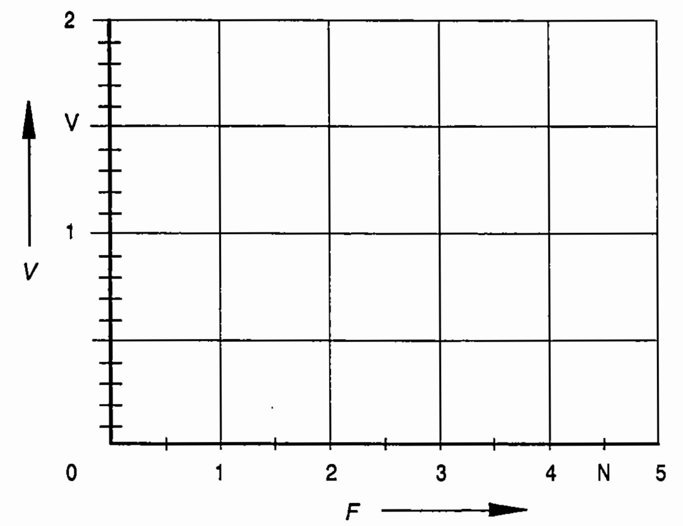


Fig. 4/5: Diagram for characteristic curve of deflecting arm force sensor in Quarter-bridge circuit

Voltage (V)	Weight force (N)	Load (g)

Table 4/4: Determining the force of a load

Notes

Subject

Sensors for force and pressure

Titel

Calibration of a force sensor using a half-bridge circuit

Learning content

To learn about a force sensor using a half-bridge as an evaluation circuit. Calibrating and commissioning of the configuration. Determining the forces.

Technical knowledge

B 4.3

In the half-bridge circuit the resistance changes of the two strain gauges are subtracted in the adjacent branches of the bridge. Both strain gauges, however, emit opposing signals so that total amounts are added and the signal is amplified in comparison to that of the quarter-bridge circuit. Signals in the same direction from the two strain gauges, e.g. derived from the interference effects of temperature changes, cancel each other out.

Problem definition

B 4.2

Unknown forces are to be determined using a deflecting arm force sensor, with signal evaluation by means of a half-bridge circuit. In order to determine the characteristic curve, a calibration of the force sensor must be carried out beforehand.

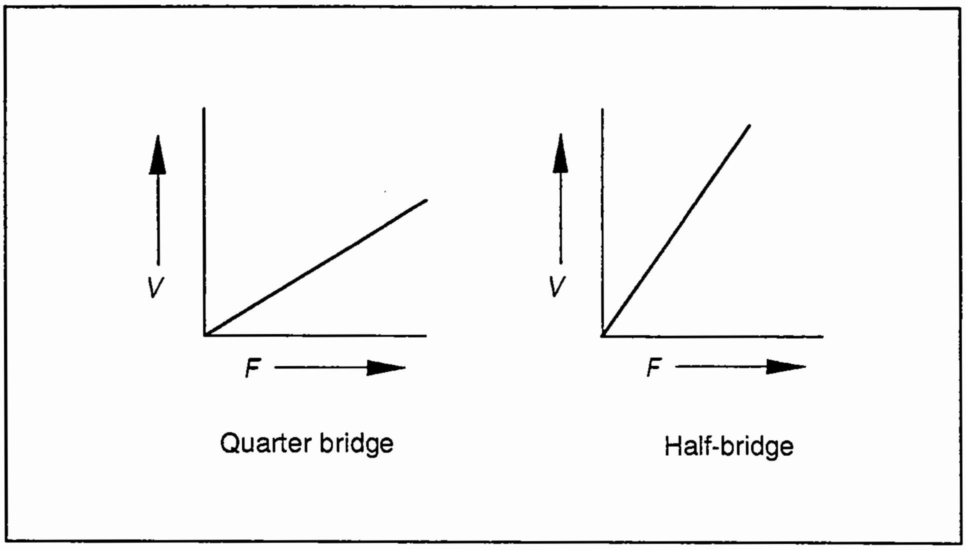


Fig. 5/1: Characteristic curve difference

Exercise

a) Construct the evaluation circuit of the deflecting arm force sensor in the form of a half-bridge.
Carry out a zero-balance.

b) Calibrate the deflecting arm force sensor D.ER-BB-KS-FP1130 using the set of weights D.AS-GWS.
Draw the characteristic curve of the deflecting arm force sensor.

c) Use the characteristic curve to determine the unknown force of a given mass.

Please observe the user notes in the introduction section when carrying out the exercises. Appropriate information regarding connection method and additional technical data can be found in the corresponding data sheets in the appendix.

Practical implementation
Part exercise a)

The two strain gauges of the deflecting arm force sensor are connected to the lefthand branch of the bridge as R1 and R4. The remaining resistors R2 and R3 of the Wheatstone bridge circuit are fixed resistors.

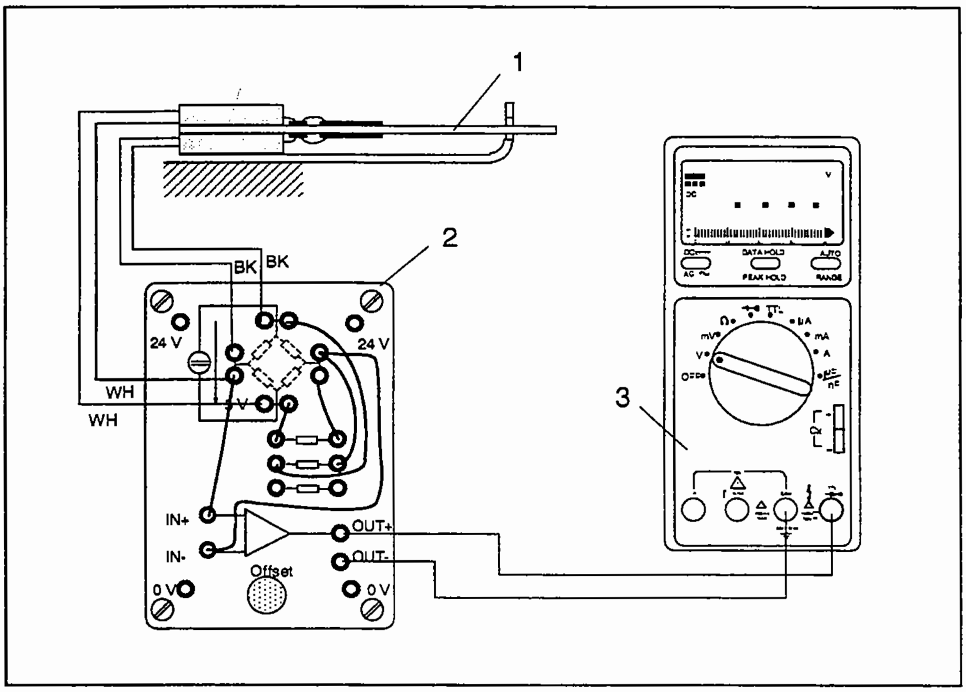


Fig. 5/2: Electrical connection

Comp. Ref. No.	Qty.	Description	Designation
1	1	Deflecting arm force sensor	D.ER-BB-KS-FP1130
2	1	Measuring bridge amplifier	D.ER-BV-FP1130
3	1	Digital multimeter	D.AS-DMM
	4	Plug-in adapter	D.MP-B-ME-AS

Table 5/1: Component list

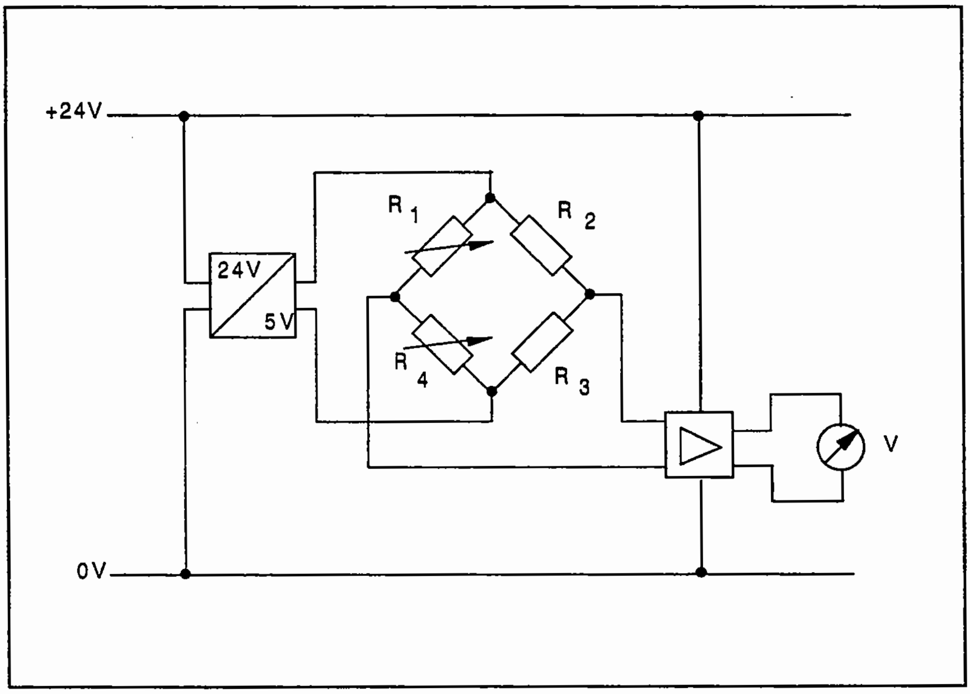


Fig. 5/3: Electrical circuit diagram

Zero-balance

On completion of the half-bridge circuit, the deflecting arm force sensor remains unloaded. The amplifier output voltage is set by turning the alignment potentiometer to zero Volts.
Because of the sensitivity of the strain gauges and the bridge amplifier, a zero-balance to within an accuracy of 10 millivolt is sufficient at the amplifier output.

Part exercise b)

The deflecting arm is loaded with weights from the set of weights D.AS-GWS ranging from 0 to 500 grammes (0..5 N) in steps of 20, 50, ..., grammes.

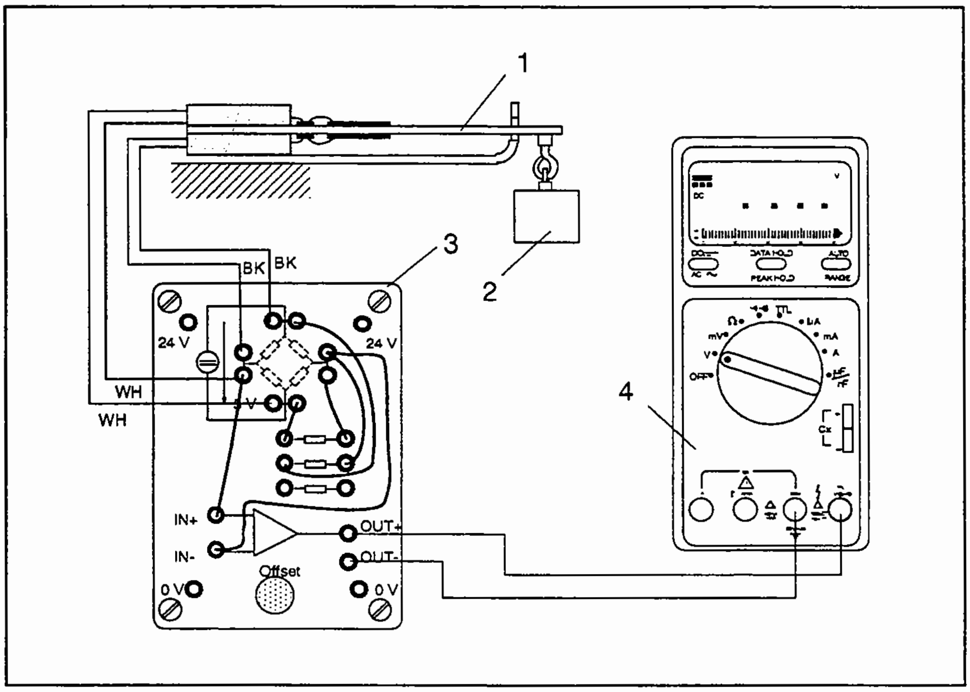


Fig. 5/4: Test procedure

Comp. Ref. No.	Qty.	Description	Designation
1	1	Deflecting arm force sensor	D.ER-BB-KS-FP1130
2	1	Set of weights	D.ER-GWS
3	1	Measuring bridge amplifier	D.ER-BV-FP1130
4	1	Digital multimeter	D.AS-DMM
	4	Plug-in adapter	D.MP-B-ME-AS

Table 5/2: Component list

- Attach the weights individually to the deflecting arm. Enter the amplifier output voltage for each weight in table 5/3 of the worksheet.
- Transfer the measured value from table 5/3 to diagram Fig. 5/5 on the worksheet and draw the characteristic curve of the force sensor for the half-bridge.

Question

Compare the characteristic curve of the half-bridge circuit with the quarter-bridge circuit from exercise 4 and describe the difference. What is their effect on the signal resolution?

Part exercise c)

- Without prior knowledge of the resulting force, attach a mass (≤ 500 gram), to the deflecting arm. In order to be able to make a direct comparison with exercise 4, the use of the same part is recommended for the weight measurement.
- Enter the signal voltage in table 5/4 of the worksheet.
- Determine the force from the characteristic curve (Fig. 5/5).

Question

How large is the signal difference, when using the same mass in exercise 4 and 5 ?

Load (g)	Weight force (N)	Voltage (V)
0	0.0	
20	0.2	
50	0.5	
100	1.0	
200	2.0	
500	5.0	

Table 5/3: Truth table for characteristic curve of sensor

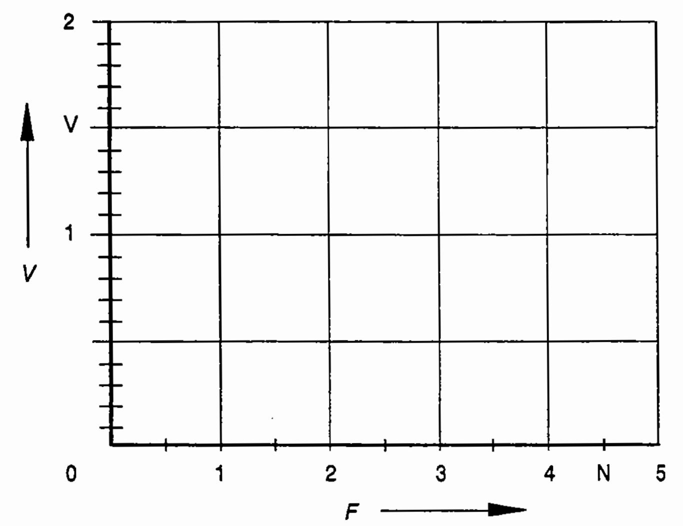


Fig. 5/5: Diagram for characteristic curve of deflecting arm force sensor in Half-bridge circuit

Voltage (V)	Weight force (N)	Load (g)

Table 5/4: Determining the force of a load

Answer
Part exercise b)

Answer
Part exercise c)

Subject

Sensors for force and pressure

Title

Calibration of an industrial force sensor

Learning content B 5.1

Construction, connection and calibration of an industrial force sensor for the direct measurement of larger forces.

Technical knowledge B 4.5

Industrial force sensors contain a full-bridge circuit. With this design, the auxiliary circuit in the form of fixed resistors is not required. The internal full-bridge circuit is complemented by means of temperature-dependent resistors and trimmed fixed resistors. With this type of circuit, which is largely independent of temperature, a good linear characteristic is achieved.

Problem definition

An industrial force sensor is used for the measurement of larger forces. The characteristic curve of this force sensor is to be determined by means of calibration.

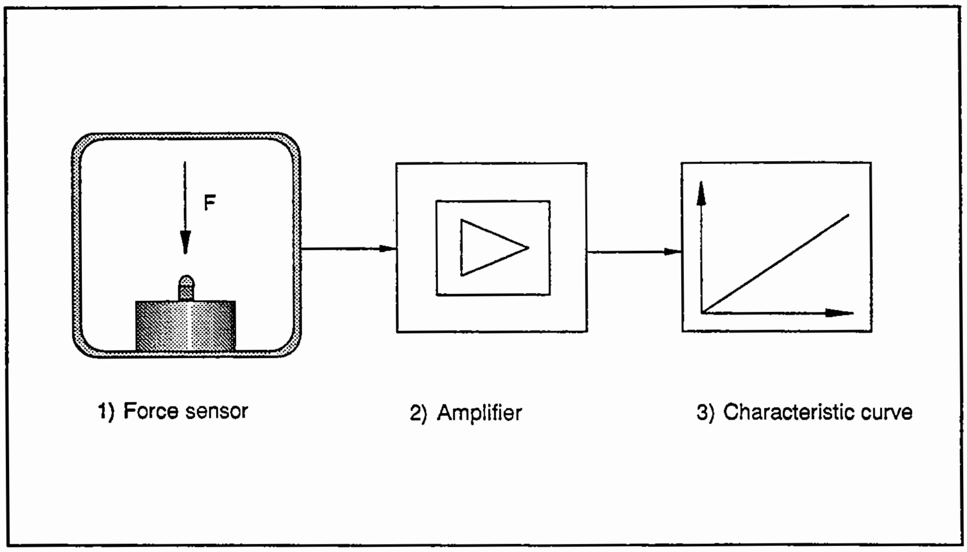


Fig. 6/1: Force sensor

Exercise

a) Connect the force sensor D.ER-KS-FP1130 to the measuring bridge amplifier D.ER-BV-FP1130.
Place the weight support D.AS-SGA on to the force sensor through the upper hole of the hollow profile.
Carry out a zero-balance.

b) Carry out a calibration of the force sensor using the set of round weights D.AS-S-GWS.
Draw the characteristic curve of the force sensor.

Please observe the user notes in the introduction section when carrying out the exercises. Appropriate information regarding connection method and additional technical data can be found in the corresponding data sheets in the appendix.

Practical implementation
Part exercise a)

The force sensor D.ER-KS-FP1130 contains a full Wheatstone bridge circuit for signal generation. Connection is established with the help of a measuring bridge amplifier D.ER-BV-FP1130 to the bridge supply voltage and the amplifier input. Additional fixed resistors for the bridge are not required.

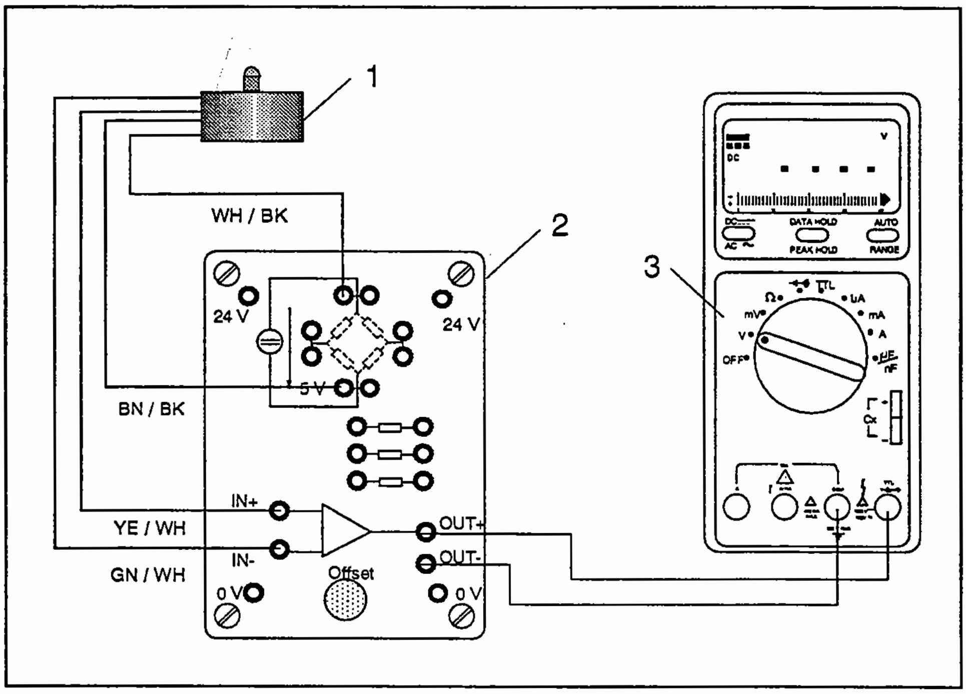


Fig. 6/2: Electrical connection

Comp. Ref. No.	Qty.	Description	Designation
1	1	Force sensor	D.ER-KS-FP1130
2	1	Measuring bridge amplifier	D.ER-BV-FP1130
3	1	Digital multimeter	D.AS-DMM
	4	Plug-in adapter	D.MP-B-ME-AS

Table 6/1: Component list

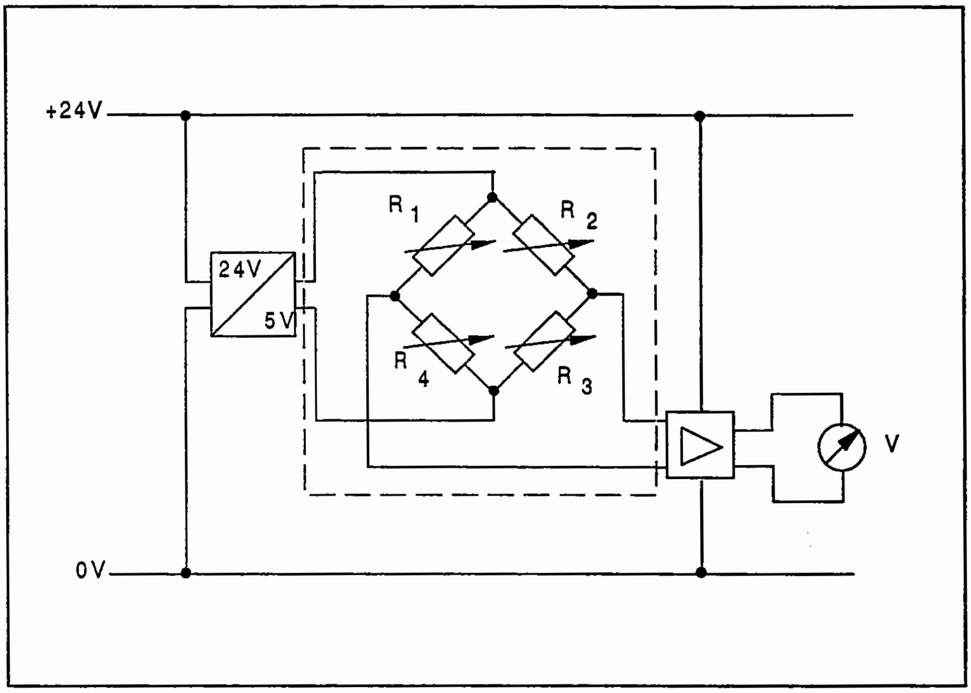


Fig. 6/3: Electrical circuit diagram

The unit enclosed by a broken line in the electrical circuit diagram denotes the full bridge in the force sensor.

Zero-balance

- Place the weight support D.AS-SGA on to the force sensor through the upper hole of the hollow profile. The amplifier output voltage is set by turning the alignment potentiometer to zero Volt.
  Because of the sensitivity of the strain gauges and the bridge amplifier, a zero-balance to within a 10 millivolt accuracy is sufficent at the amplifier output.

Part exercise b)

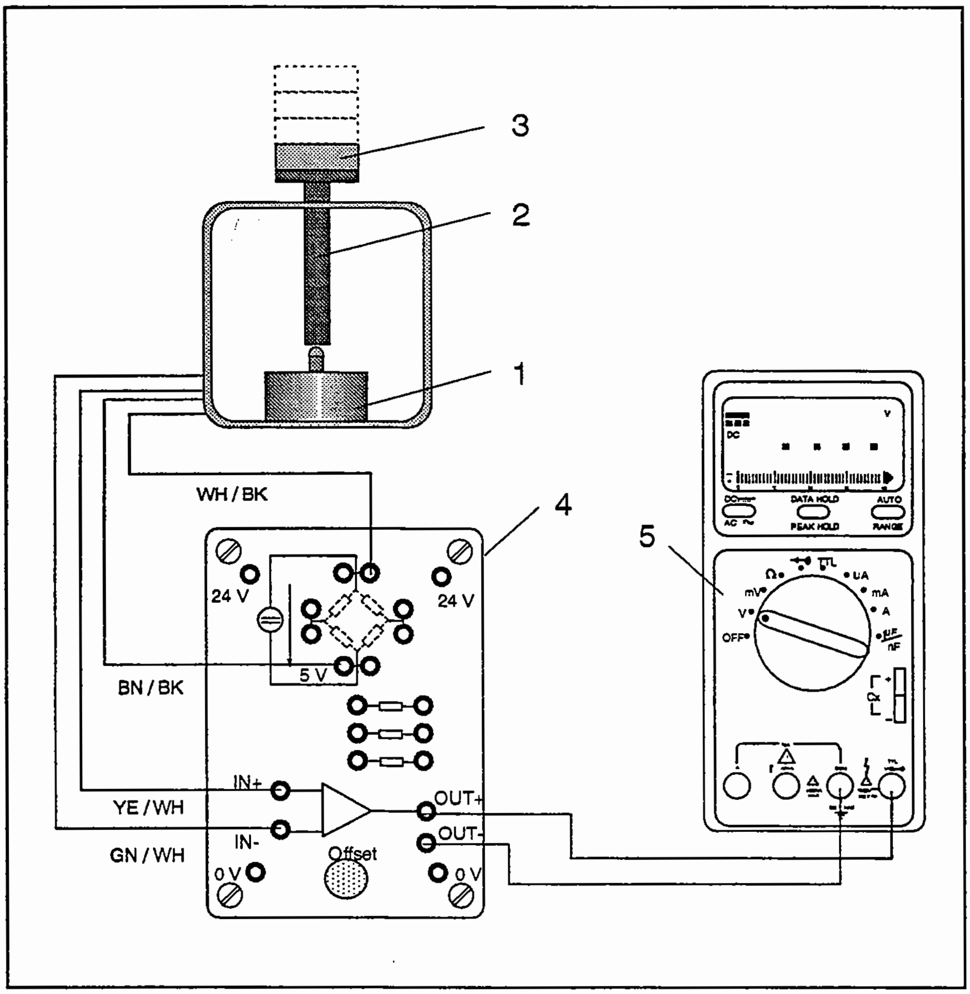


Fig. 6/4: Test procedure

Comp. Ref. No.	Qty.	Description	Designation
1	1	Force sensor	D.ER-KS-FP1130
2	1	Weight support	D.AS-SGA
3	1	Set of round weights	D.AS-S-GWS-FP1130
4	1	Measuring bridge amplifier	D.ER-BV-FP1130
5	1	Digital multimeter	D.AS-DMM
	4	Plug-in adapter	D.MP-B-ME-AS

Table 6/2: Component list

- Arrange the circular weights D.AS-S-GWS (1 kg each) in a stack on the weight support D.AS-SGA.

Note

Make sure that the force sensor is mounted firmly on the profile plate and that the stack of disc weights rests securely on the force sensor. Injury can be caused by dropping disc weights.

- Determine the signal at the amplifier output for each additional weight placed on the support.
- Enter the individual measured values in table 6/3 of the worksheet.
- *Transfer the values from table 6/3 to the diagram (fig. 6/5) of the worksheet and draw the characteristic curve of the force sensor.*

Note

Only the lower range of the characteristic curve is established (up to 100 N) by means of the 100 N weight set. The characteristic curve can be extended to the upper range (up to 200 N) on the basis of the linearity.
When determining the characteristic curve of the force sensor, the inherent weight of the weight support D.AS-SGA is not taken into account, as the zero-balance was carried out with the weight support attached.

Notes

Load (kg)	Weight force (N)	Voltage (V)
0	0	
1	10	
2	20	
3	30	
4	40	
5	50	
6	60	
7	70	
8	80	
9	90	
10	100	

Table 6/3: Truth table for characteristic curve of sensor

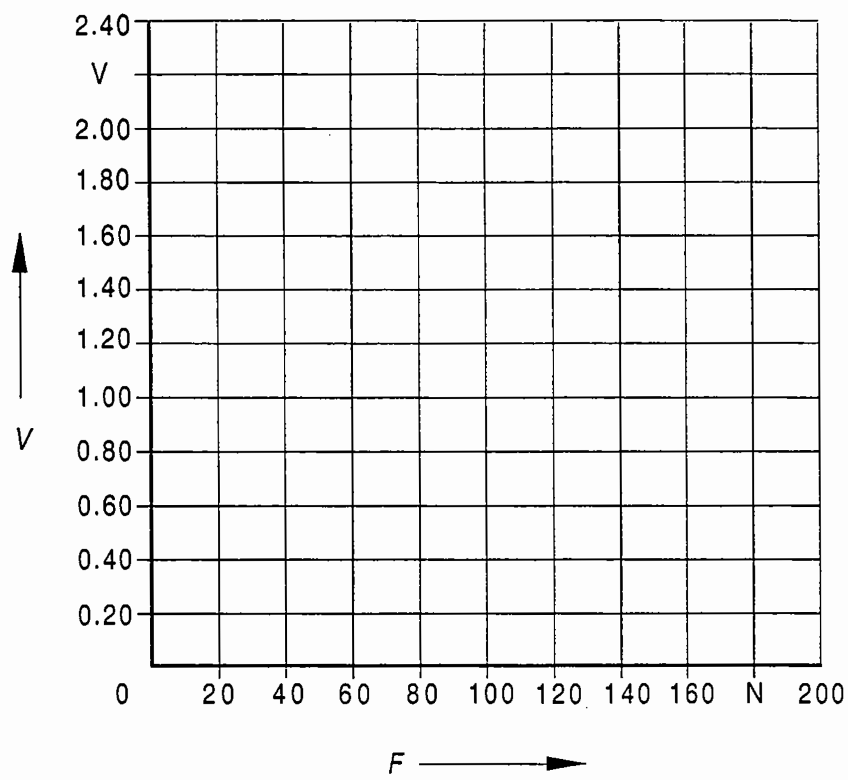


Fig. 6/5: Diagram for characteristic curve of force sensor

Subject

Sensors for force and pressure

Title

Force measurement on pneumatic cylinders using an industrial force sensor

Learning content

Detecting the force of a piston rod and the friction forces of a pneumatic cylinder using a force sensor.

Technical knowledge

B 4.5

The effect of force on the piston surface of a pneumatic cylinder can be calculated from the pneumatic pressure and the area of the piston surface. The force on the piston rod is reduced by the friction force of the piston.

Problem definition

In order to determine the piston rod and friction forces of a pneumatic cylinder a configuration is used whereby, inside a hollow profile, the piston rod of the cylinder presses directly on to a force sensor. These forces are to be determined by means of the force sensor.

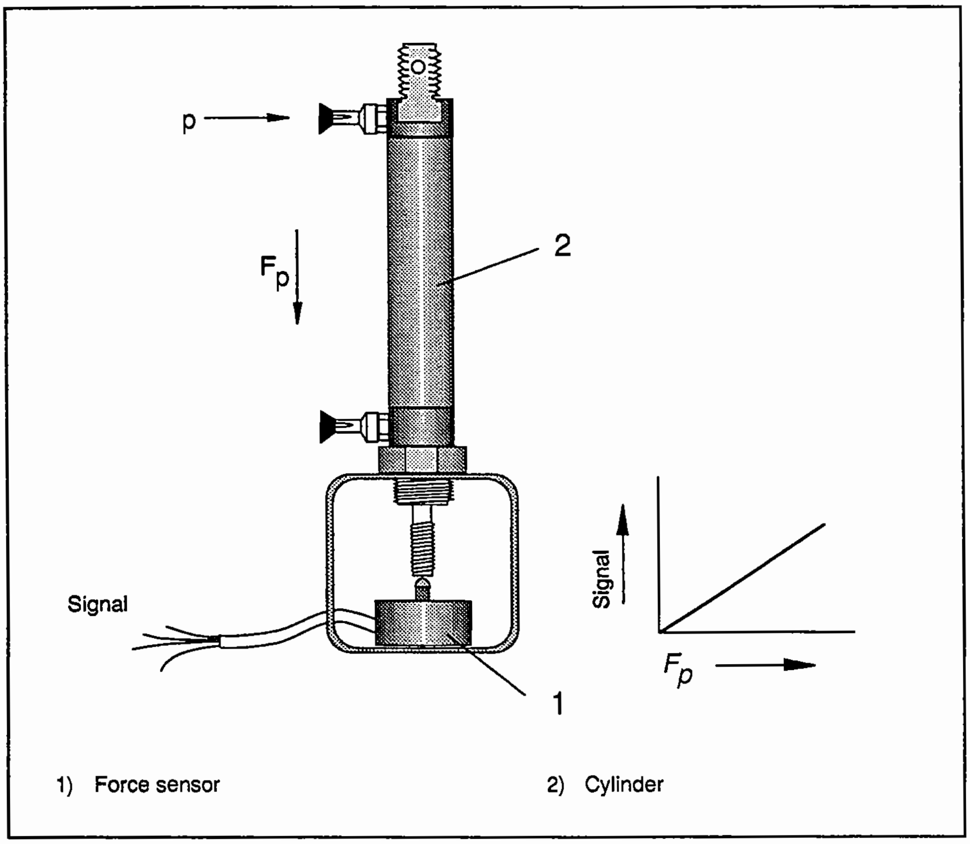


Fig. 7/1: Force measurement using a pneumatic cylinder

Note

Prior knowledge of handling and connection technology regarding analogue pressure sensors is essential to carry out this exercise. This can be obtained from the corresponding data sheets in the appendiix as well as from exercises A 8 and A 9.

Exercise

a) Connect the sensor unit D.ER-KS-FP1130 to the double-acting cylinder D.AS-DSN-PPV as follows:
   - pneumatically to the service unit D.ER-FRC-1/8-S
   - electrically to the bridge amplifier D.ER-BV-FP1130
   - Use the analogue pressure sensor D.ER-SDE-10-10V/20mA in conjunction with the connection plate D.ER-AE-101AF and the digital multimeter D.AS-DMM to detect the pressure on the piston side of the cylinder.

b) Calculate the theoretical cylinder force for the advance movement at pressure values of 1 bar, 2 bar, 3 bar and 4 bar.

c) Measure the actual force of the piston rod at the pressure values used in part exercise b).

d) Calculate the friction force for each measuring point.

Please observe the user notes in the introduction section when carrying out these exercises. Appropriate information regarding connection method and additional technical data can be found in the corresponding data sheets in the appendix.

Practical implementation
Part exercise a)

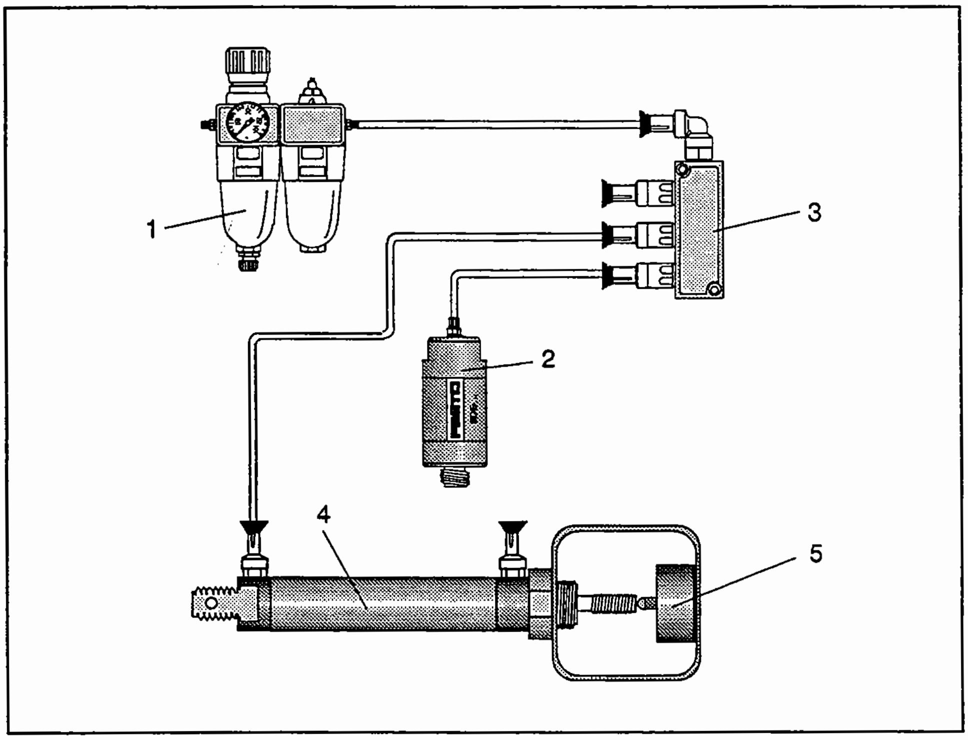


Fig. 7/2: Pneumatic connection

Comp. Ref. No.	Qty.	Description	Designation
1	1	Service unit	D.ER-FRC-1/8-S
2	1	Analogue pressure sensor	D.ER-SDE-10-10V/20mA
3	1	Pressure manifold	D.ER-FR-4-1/8-B
4	1	Cylinder	D.AS-DSN-PPV
5	1	Force sensor	D.ER-KS-FP1130
	8	Plug-in adapter	D.MP-B-ME-AS

Table 7/1: Component list

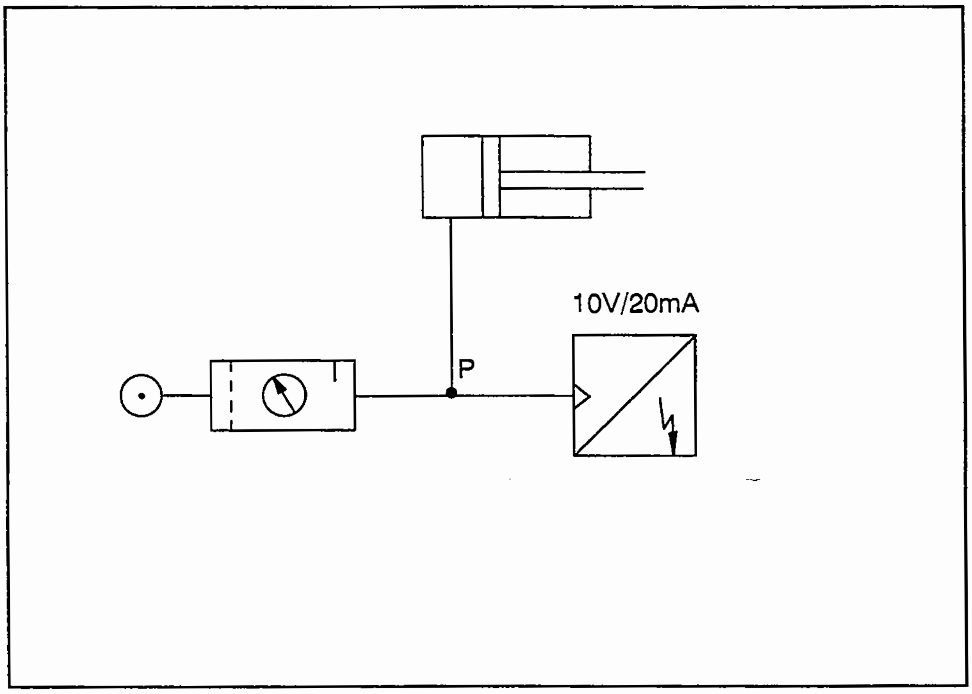


Fig. 7/3: Pneumatic circuit diagram

A certain air pressure is set at the service unit and acts on the piston side of the cylinder chamber. This pressure is measured by the analogue pressure sensor connected in parallel and can be read on the multimeter.

B 2.5

The signal is created in the force sensor by means of strain gauges, which are connected in the form of a full bridge. The use of fixed resistors on the bridge amplifier is therefore not required. The pressure on the piston side of the cylinder chamber is detected by means of the analogue pressure sensor D.ER-SDE-10-10V/20mA and the multimeter.

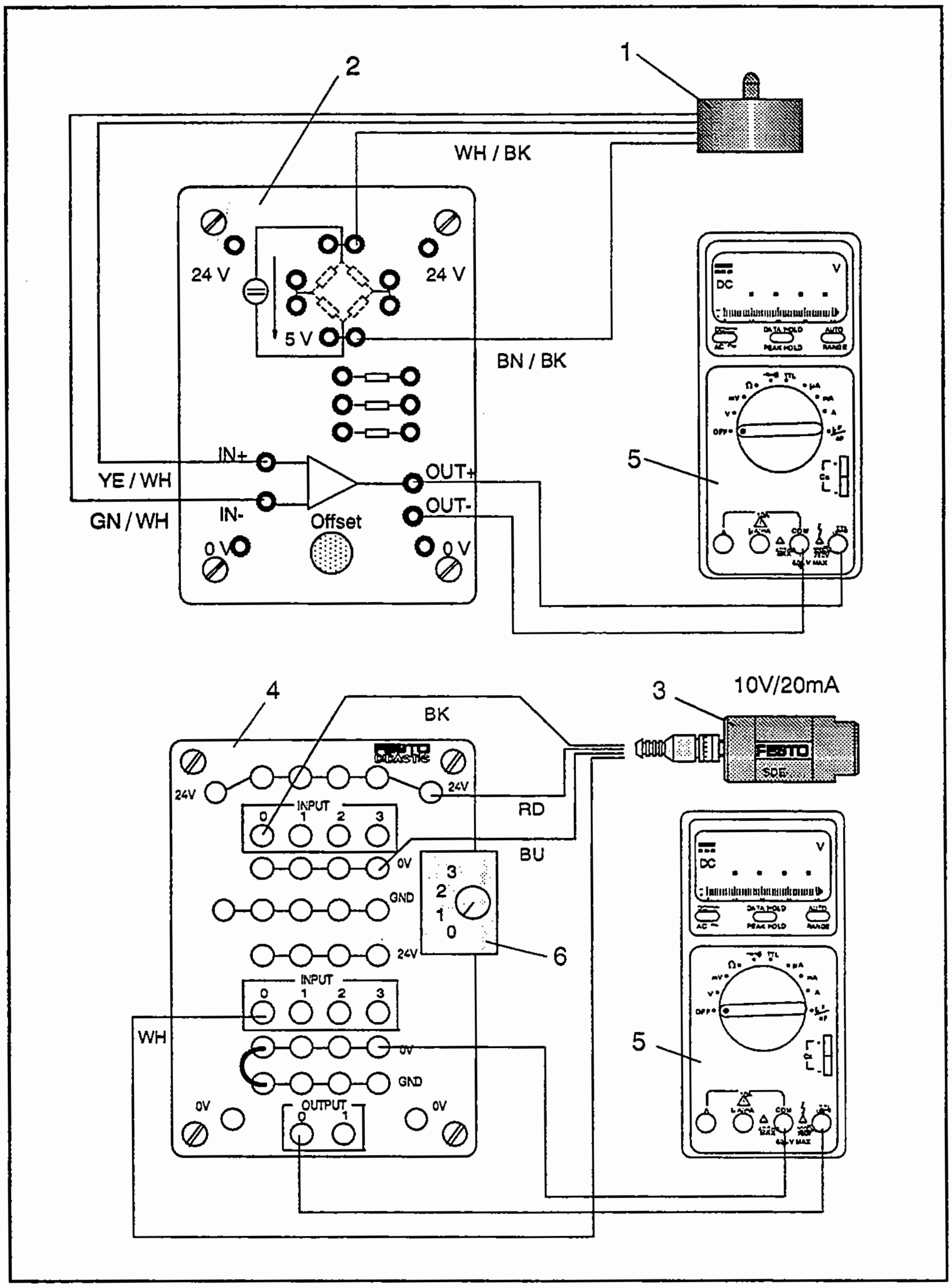


Fig. 7/4: Electrical connection

- Connect the force sensor to the measuring bridge amplifier
- Connect the voltage signal of the pressure sensor to VI0 at INPUT 0 at the top and the current signal to II0 at INPUT 0 at the bottom of the connection plate D.ER-AE-101AF. Connect 0 V to GND.
  The signal switching unit is set at 0 position.
  The voltage signal is connected to the digital multimeter via OUTPUT 0.

Comp. Ref. No.	Qty.	Description	Designation
1	1	Force sensor	D.ER-KS-FP1130
2	1	Measuring bridge amplifier	D.ER-BV-FP1130
3	1	Analogue pressure sensor	D.ER-SDE-10-10V/20mA
4	1	Adapter plate	D.ER-AE-101AF
5	2	Digital multimeter	D.AS-DMM
6	1	Signal switching unit	D.AS-SUAE-101
	8	Plug-in adapter	D.MP-B-ME-AS

Table 7/2: Component list

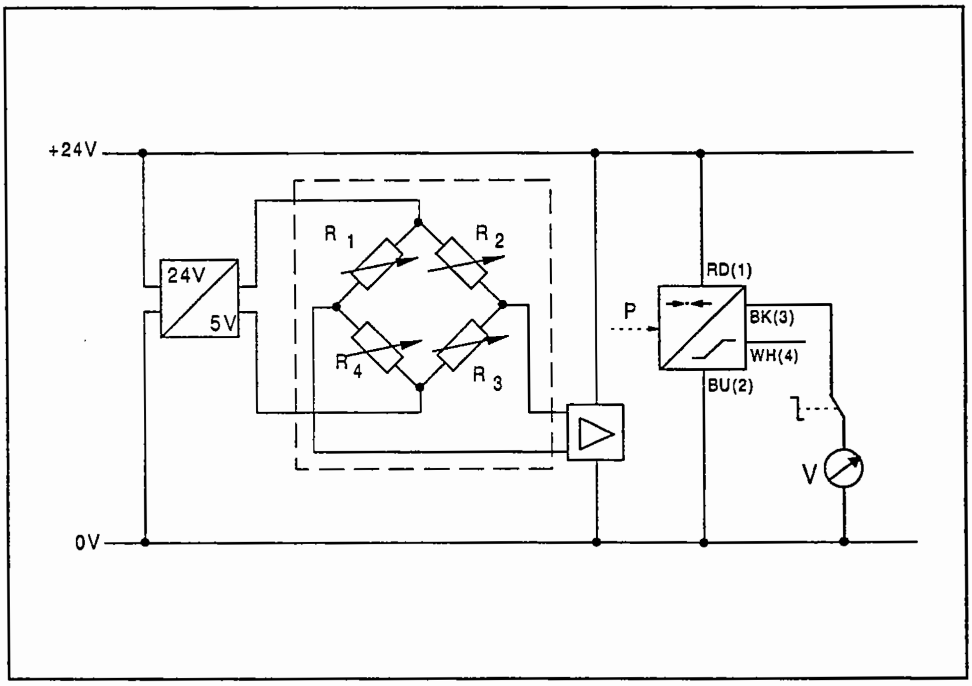


Fig. 7/5: Electrical circuit diagram

The unit enclosed by a broken line is the full bridge as constructed in the force sensor.

Zero-balance

When the electrical circuit has been constructed, the sensor remains unloaded. The amplifier output voltage is set by turning the alignment potentiometer to zero Volts.
Because of the sensitivity of the strain gauges and the bridge amplifier, a zero-balance to within an accuracy of 10 millivolt is sufficient at the amplifier output.

Part exercise b)

The theoretical force (F_{theor}) is calculated from the pressure across the piston area.

$$F_{theor} = p \cdot A$$

F_{theor} = *theoretical force in N (N = Newton)*
p = *Pressure in N/mm²*
A = *Area* $= \pi / 4 \cdot d^2$ *in* mm^2.

The piston diameter d of the cylinder is 25 mm.

1 bar = 0.1 N/mm^2

- Carry out the calculation according to the above formula. Enter the numerical values in table 7/3 of the worksheet.

B 1.7

Part exercise c)

- Set the pressure on the service unit for each measuring point. Take a reading of the precise pressure value on the multimeter.

Note

The voltage signal of the analogue pressure sensor D.ER-SDE-10-10V/20mA corresponds to the measured pressure value in bar. The voltage signal read can therefore be entered in the table without prior conversion.

- Enter the voltage signal for each measuring point in table 7/3 on the worksheet.
- Take the cylinder force (F_{act}) for each measuring point from the characteristic curve established in exercise 6. Enter the values in table 7/3 on the worksheet.

Part exercise d)

- Calculate the friction forces for each measuring point. Enter the calculated friction force also in table 7/3 of the worksheet.

Friction force

The friction force (F_F) is the difference between the theoretical force (F_{theor}) and the actual cylinder force (F_{act}).

$$F_F = F_{theor} - F_{act}$$

Pressure (bar)	F_{theor} (N)	Voltage (V)	$F_{act.}$ (N)	F_F (N)
1.0				
2.0				
3.0				
4.0				

Table 7/3: Truth table for determining cylinder force

Notes

Subject

Sensors for force and pressure

Title

Commissioning of an analogue pressure sensor

Learning content

To learn about the pneumatic and electrical connection of an analogue pressure sensor.

Technical knowledge

B 7.4

The analogue pressure sensors contained in the equipment set are piezoresistive pressure sensors. Apart from the pressure detector with built-in semiconductor strain gauges in the form of a full bridge circuit, these include a measuring amplifier which supplies both a voltage signal (0 ... 10 V) as well as a current signal (0 ... 20 mA) for the specified pressure measuring range. Both signals are available simultaneously.

Problem definition

For proper functioning, the analogue pressure sensor must be connected correctly both electrically and pneumatically and operated within the permissible pressure and voltage ranges. Its pneumatic and electrical characteristics are to be examined.

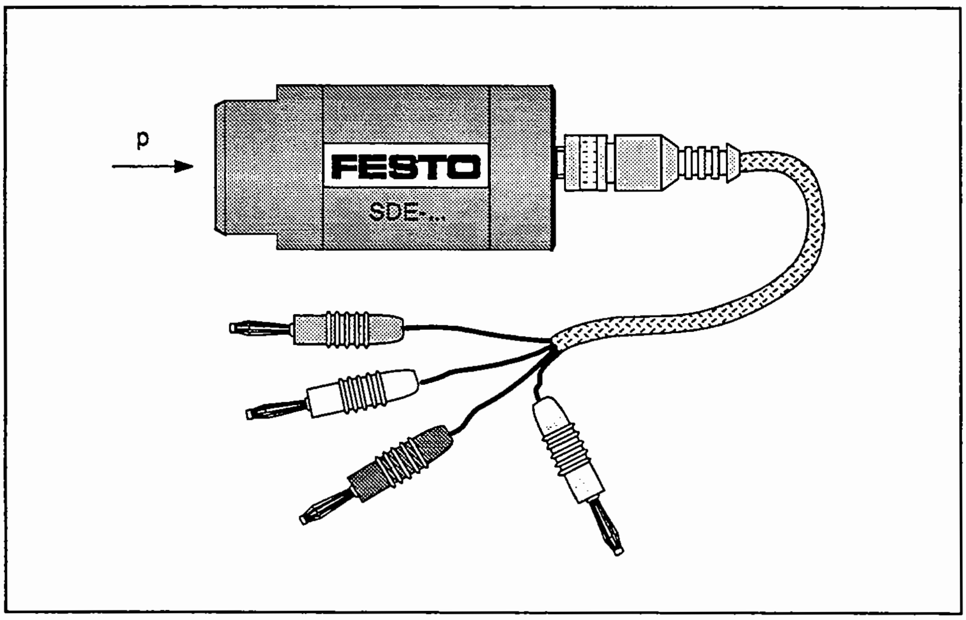


Fig. 8/1: Analogue pressure sensor

Exercise

a) Using the data sheet, identify the individual electrical connections of the SDE-... series analogue pressure sensor according to the plug colours.

b) Connect the analogue pressure sensor D.ER-SDE-10-10V/20mA as follows:
- pneumatically via the pressure manifold D.ER-FR-4-1/8-B to the service-unit D.ER-FRC-1/8-S
- electrically via the connection plate D.ER-AE-101AF to the voltage supply and the multimeter D.AS-DMM.

Please observe the user notes in the introduction section when carrying out these exercises. Appropriate information regarding connection method and additional technical data can be found in the corresponding data sheets in the appendix.

Practical implementation
Part exercise a)

Connection and plug colour can be matched up with the help of the data sheet. Please follow this information.

- Enter the data in table 8/3 on the worksheet.

Part exercise b)

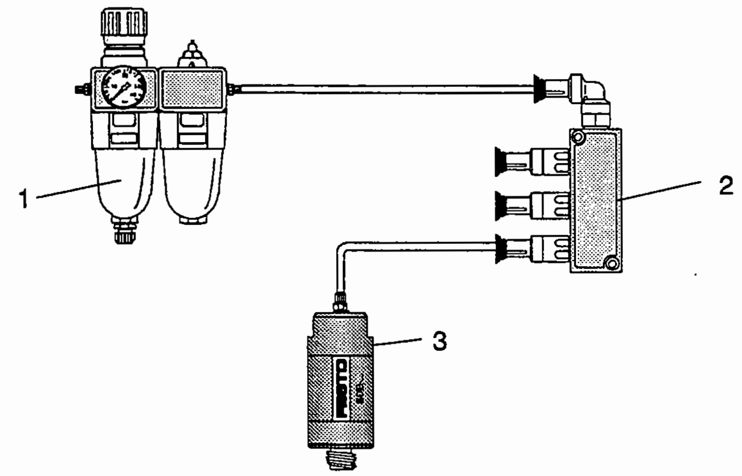


Fig. 8/2: Pneumatic connection

Comp. Ref. No.	Qty.	Description	Designation
1	1	Service unit	D.ER-FRC-1/8-S
2	1	Pressure manifold	D.ER-FR-4-1/8-B
3	1	Analogue pressure sensor	D.ER-SDE-10-10V/20mA
	4	Plug-in adapter	D.MP-B-ME-AS

Table 8/1: Component list

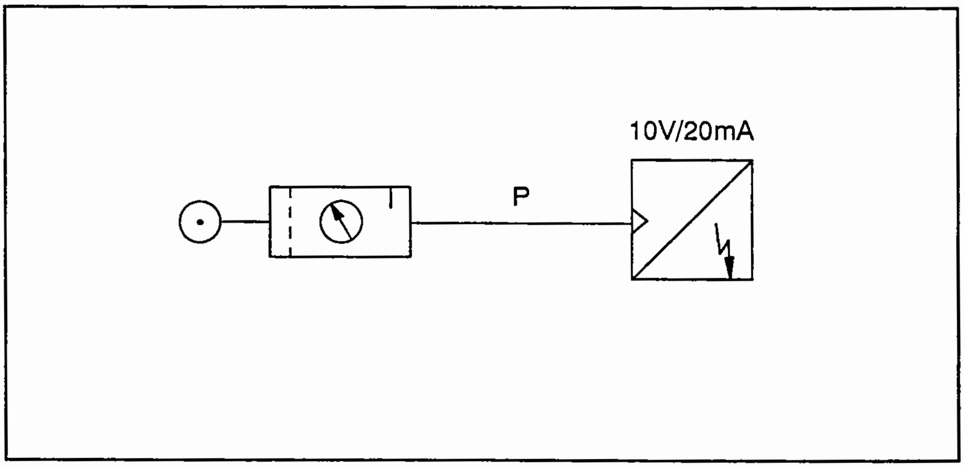


Fig. 8/3: Pneumatic circuit diagram

Note

It is important to ensure that the pneumatic supply line to the sensor is as short as possible, i.e. the sensor should be near the point in the pneumatic circuit, where the air pressure is to be measured. Due to lengthy columns of air in the lines, the measurement of pressure change is subject to a time delay.

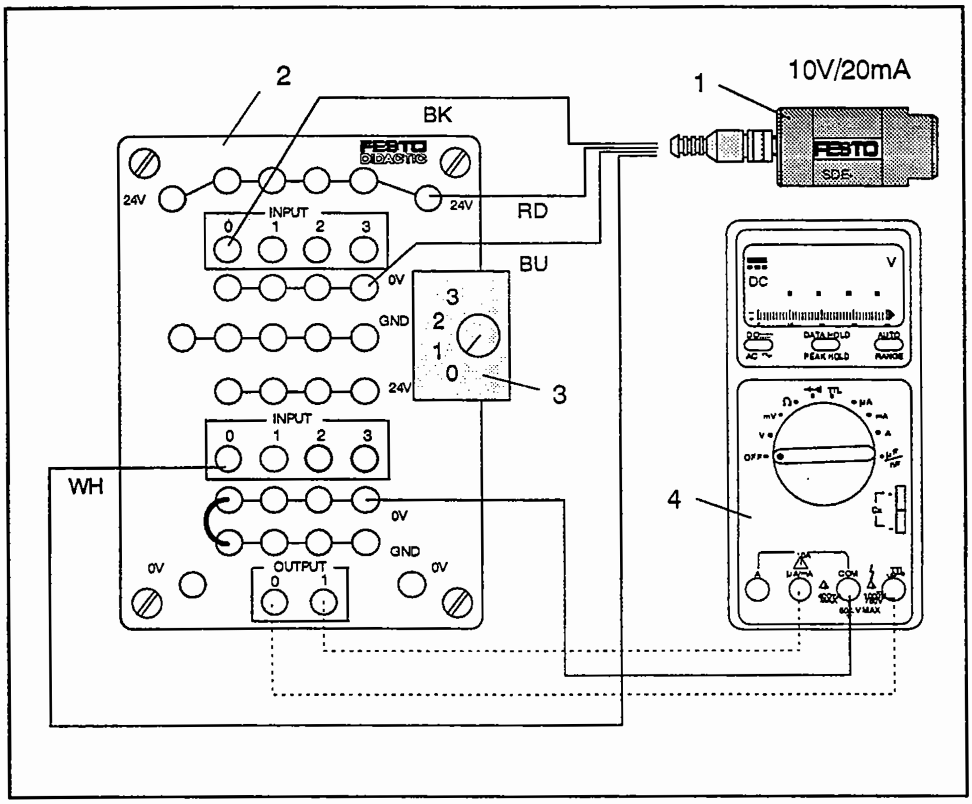


Fig. 8/4: Electrical connection

The broken lines indicate that with only one multimeter, current and voltage measurements cannot be carried out simultaneously.

Comp. Ref. No.	Qty.	Description	Designation
1	1	Analogue pressure sensor	D.ER-SDE-10-10V/20mA
2	1	Connection unit	D.ER-AE-101AF
3	1	Signal switching unit	D.AS-SUAE-101
4	1	Digital multimeter	D.AS-DMM
	4	Plug-in adapter	D.MP-B-ME-AS

Table 8/2: Component list

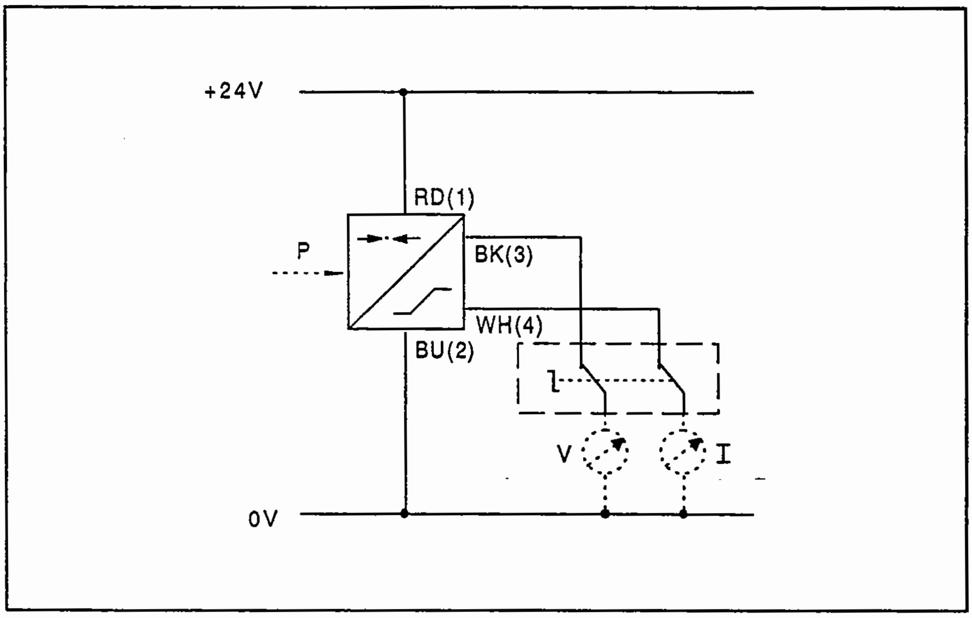


Fig. 8/5: Electrical circuit diagram

The analogue pressure sensor D.ER-SDE-10-10V/20mA is connected to the voltage supply and the multimeter via the connection unit D.ER-AE-101AF. The voltage signal is connected to input 0 of the upper row of sockets and the current signal to input 0 of the lower row of sockets. The multimeter is connected to that connection unit corresponding to the 'voltage' or 'current' measurement:

- Voltage signal to output 0
- Current signal to output 1
- The signal switching unit is set at 0

Connection	Plug colour
+ 24 V	
0 V	
Signal V	
Signal I	

Table 8/3: Plug colours

Notes

Subject

Sensors for force and pressure

Title

Characteristic curve of an analogue pressure sensor

Learning content

To learn about the behaviour of an analogue pressure sensor by means of measuring and comparing the voltage and current characteristic curves and carrying out pressure measurements.

Technical knowledge

B 4.7

There are analogue pressure sensors, which have a characteristic curve with a zero offset. The zero offset can be detected by calibrating the pressure sensor D.ER-SDE-10-5V/20mA against a reference pressure sensor D.ER-SDE-10-10V/20mA. The purpose of the zero offset, or zero signal, is to check the functionality of the sensor and the connected measuring amplifier, particularly in automated systems. An analogue pressure sensor generates an electrical signal, which is proportional to the pressure being measured. With the help of a characteristic curve pertaining to a pressure sensor, it is possible to determine unknown pressure values very accurately and at any point.

Problem definition

With the help of the known characteristic curve of an analogue pressure sensor the voltage and current characteristic curves of a second analogue pressure sensor are to be established. The newly established characteristic curves are to be used for determining air pressure.

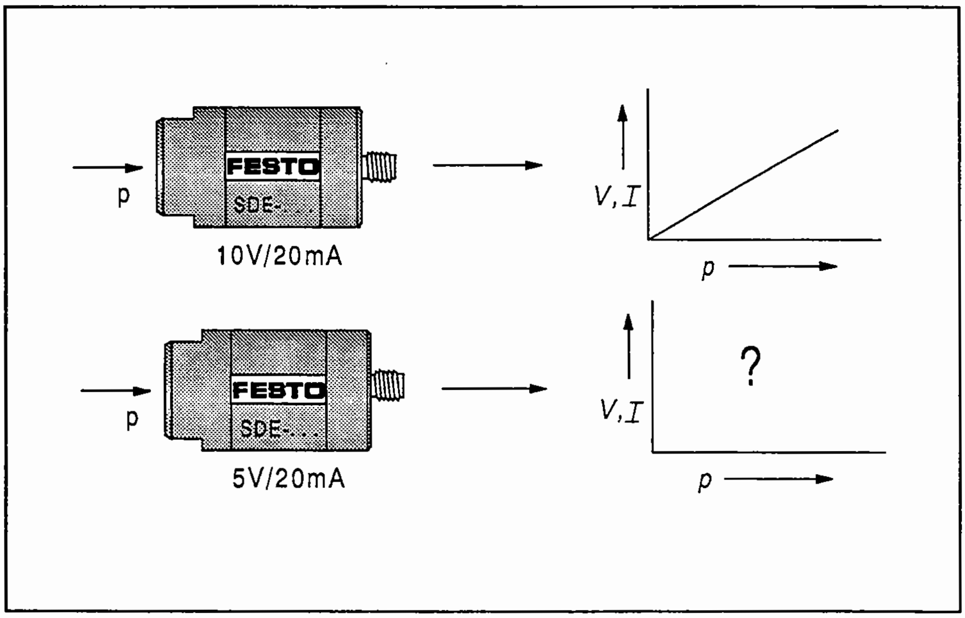


Fig. 9/1: Characteristic curves of various analogue pressure sensors

Exercise

a) Connect the pressure sensor D.ER-SDE-10-5V/20mA as follows:
   - pneumatically in parallel with the D.ER.SDE-10-10V/20mA to the compressed air supply
   - electrically to the connection plate D.ER-AE-101AF

   In part exercises b) and c), the analogue pressure sensor D.ER-SDE-10-10V/20mA is the reference pressure sensor.

b) Determine the voltage characteristic curve of the analogue pressure sensor
   D.ER-SDE-10-5V/20mA.

c) Determine the current characteristic curve of the analogue pressure sensor D.ER-SDE-10-5V/20mA.

d) Set the service unit at any pressure. Determine the exact pressure value from the characteristic curves of the analogue pressure sensor D.ER-SDE-10-5V/20mA established in b) and c).

Please observe the user notes in the introduction section when carrying out the exercises. Appropriate information regarding connection method and additional technical data can be found in the corresponding data sheets im the appendix.

Practical implementation
Part exercise a)

The two analogue pressure sensors are connected in parallel to the service unit via the pressure manifold D.ER-FR-4-1/8-B.

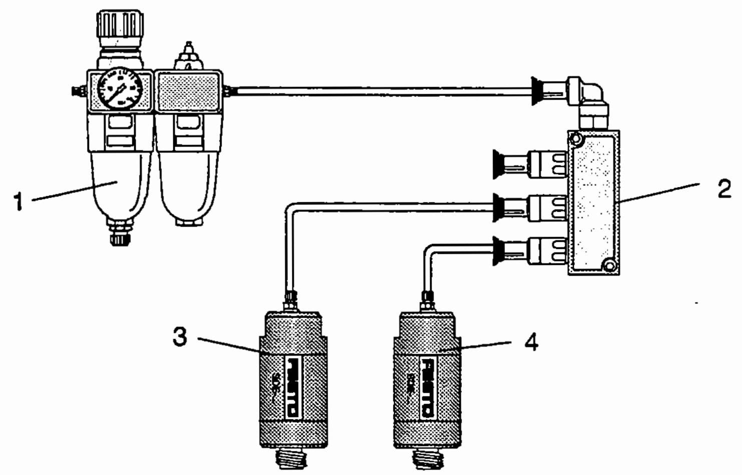


Fig. 9/2: Pneumatic connection

Comp. Ref. No.	Qty.	Description	Designation
1	1	Service unit	D.ER-FRC-1/8-S
2	1	Pressure manifold	D.ER-FR-4-1/8-B
3	1	Analogue pressure sensor	D.ER-SDE-10-10V/20mA
4	1	Analogue pressure sensor	D.ER-SDE-10-5V/20mA
	4	Plug-in adapter	D.MP-B-ME-AS

Table 9/1: Component list

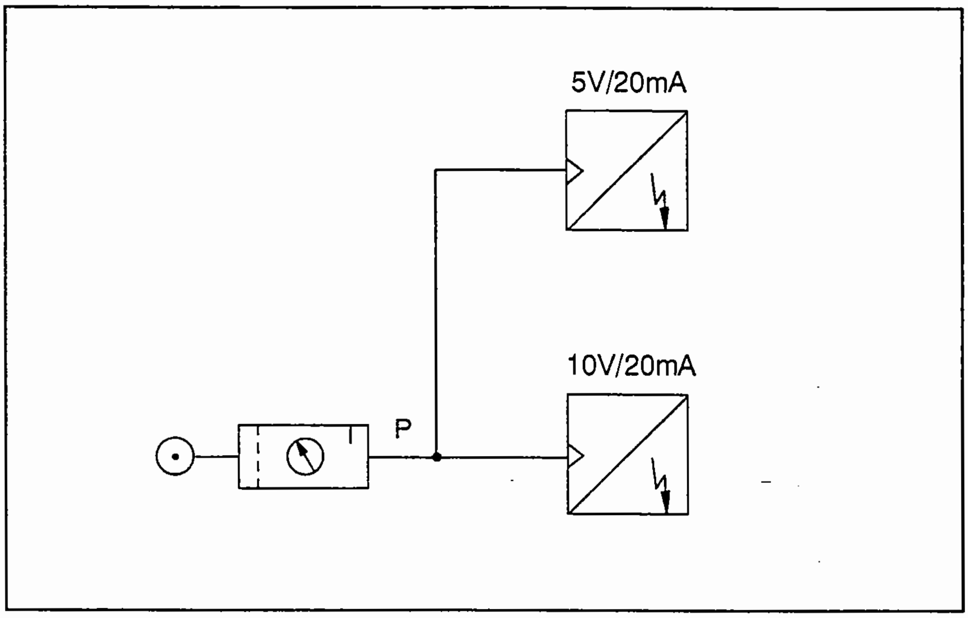


Fig. 9/3: Pneumatic circuit diagram

The analogue pressure sensor D.ER-SDE-10-5V/20mA is connected to the voltage supply and the multimeter via the connection plate D.ER-AE-101AF.

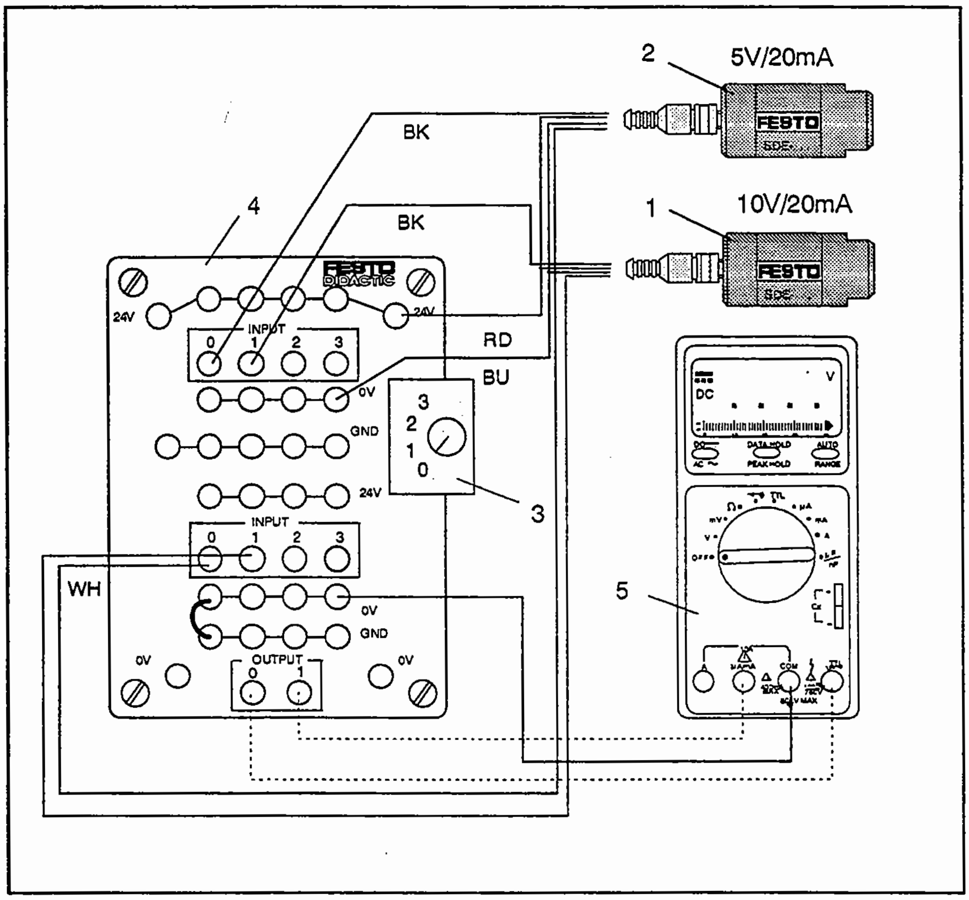


Fig. 9/4:d Electrical connection

The broken lines indicate that with one multimeter only, voltage and current measurements cannot be carried out simultaneously.

Comp. Ref. No.	Qty.	Description	Designation
1	1	Analogue pressure sensor	D.ER-SDE-10-10V/20mA
2	1	Analogue pressure sensor	D.ER-SDE-10-5V/20mA
3	1	Signal switching unit	D.AS-SUAE-101
4	1	Connection unit	D.ER-AE-101AF
5	1	Digital multimeter	D.AS-DMM
	4	Plug-in adapter	D.MP-B-ME-AS

Table 9/2: Component list

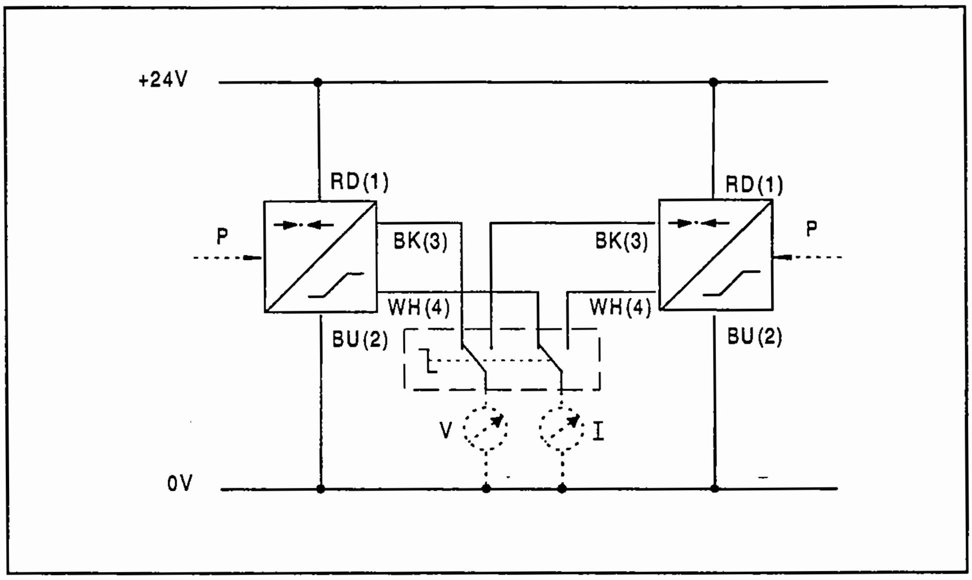


Fig. 9/5: Electrical circuit diagram

Reference sensor

B 4.10

In order to determine the sensor characteristic curve of the analogue pressure sensor D.ER-SDE-10-5V/20mA, the pressure at the individual measuring points must be known. To achieve this, the analogue pressure sensor D.ER-SDE-10-10V/20mA is used as a reference sensor. With this reference sensor, the voltage signal in Volts corresponds to the measured pressure in bar.

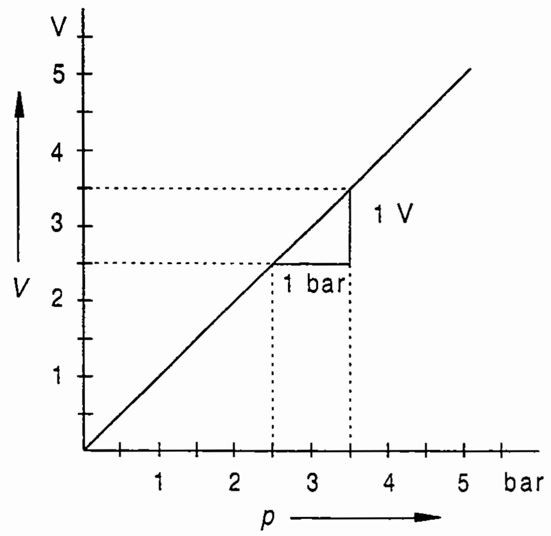


Fig. 9/6: Voltage characteristic curve of reference pressure sensor D.ER-SDE-10-10V/20mA

Example: Voltage signal 2 V ==> pressure 2 bar

Part exercise b)

The multimeter is set for 'voltage measurement' and at a measuring range which detects the anticipated voltage (in this instance: from 0 to 10 Volt). Please observe the operating instructions for the multimeter.

- Increase the pressure on the service unit from 0 bar to the system pressure in stages of 0.5 bar, whilst alternately switching the voltage signals of the two pressure sensors to the multimeter via the signal switching unit.
- Enter the voltage determined in respect of each measuring point in table 9/3 of the worksheet.
- Transfer the points to the diagram (Fig. 9/7) of the worksheet and draw the voltage characteristic curve.

Part exercise c)

The multimeter is switched to 'current measurement' and possibly (depending on the multimeter) to a measuring range, which will detect the current anticipated (in this instance: from 0 to 20 mA).

- Increase the measuring pressure on the service unit from 0 bar to the system pressure in stages of 0.5 bar, whilst alternately switching the signals of the two pressure sensors to the multimeter via the signal changeover switch.

Note

The connection cable on the multimeter between the voltage and current input must be exchanged for each measuring point. It is also possible to use two multimeters.

- Enter the established current value for each measuring point in table 9/4 of the worksheet.
- Transfer the points in the diagram (fig. 9/8) of the worksheet and draw the current characteristic curve.

Part exercise d)

- Set the service unit at any pressure observing only the pressure gauge of the service unit while doing this.
- Now determine the voltage and current signal with the help of the analogue pressure sensor D.ER-SDE-10-5V/20mA and the multimeter and enter these values in table 9/5.
- Take a reading of the pressure values in respect of each signal from the characteristic curves defined under b) and c). Enter these values in table 9/5 on the worksheet.

p (bar)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Voltage (V)											

Table 9/3: Truth table for voltage characteristic curve

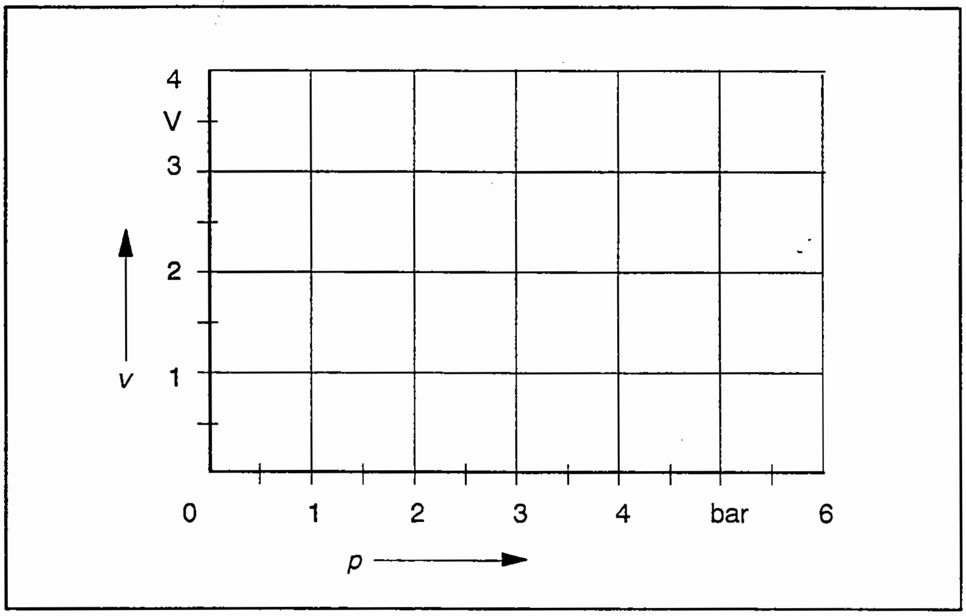


Fig. 9/7: Diagram for voltage characteristic curve

p (bar)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
I (mA)											

Table 9/4: Truth table for current characteristic curve

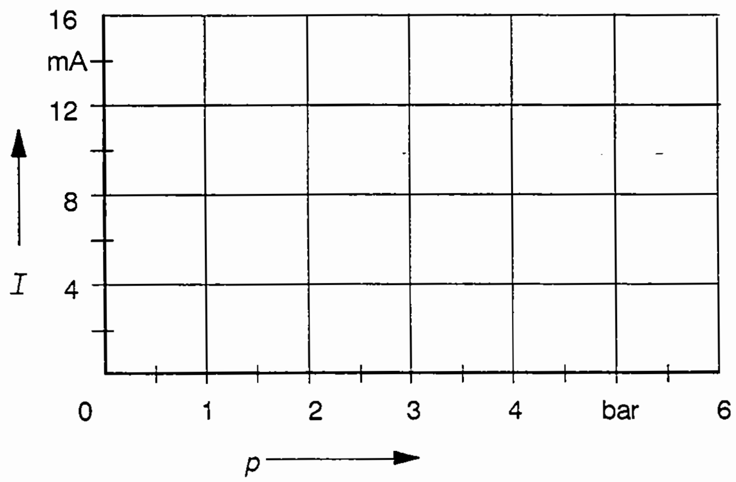


Fig. 9/8: Diagram for current characteristic curve

Measuring device	Voltage (V)	Current (mA)	Pressure (bar)
Pressure gauge	————	————	
SDE-10-10V/20mA		————	
SDE-10-5V/20mA		————	
SDE-10-5V/20mA	————		

Table 9/5: Pressure measurement

Subject

Sensors for force and pressure

Title

Setting of a mechanical pressure switch

Learning content

Knowledge regarding the setting, checking and use of mechanical pressure switches.

Technical knowledge

B 7.2

In the pressure switch D.ER-PEV-1/4-B, a mechanical microswitch is actuated by the diaphragm of the pressure sensor. This binary output signal can be processed directly via display units or controllers. The switch-on pressure during increasing pressure is higher than the reset pressure during falling pressure. The difference is described as hysteresis. Pressure switches are used mainly for the purpose of pressure monitoring in pneumatic systems. They trigger an electrical signal if a predetermined pressure value is exceeded or fails to be maintained.

Problem definition

The mechanical and electrical characteristics of a mechanical pressure switch are to be examined with the help of an analogue pressure sensor.

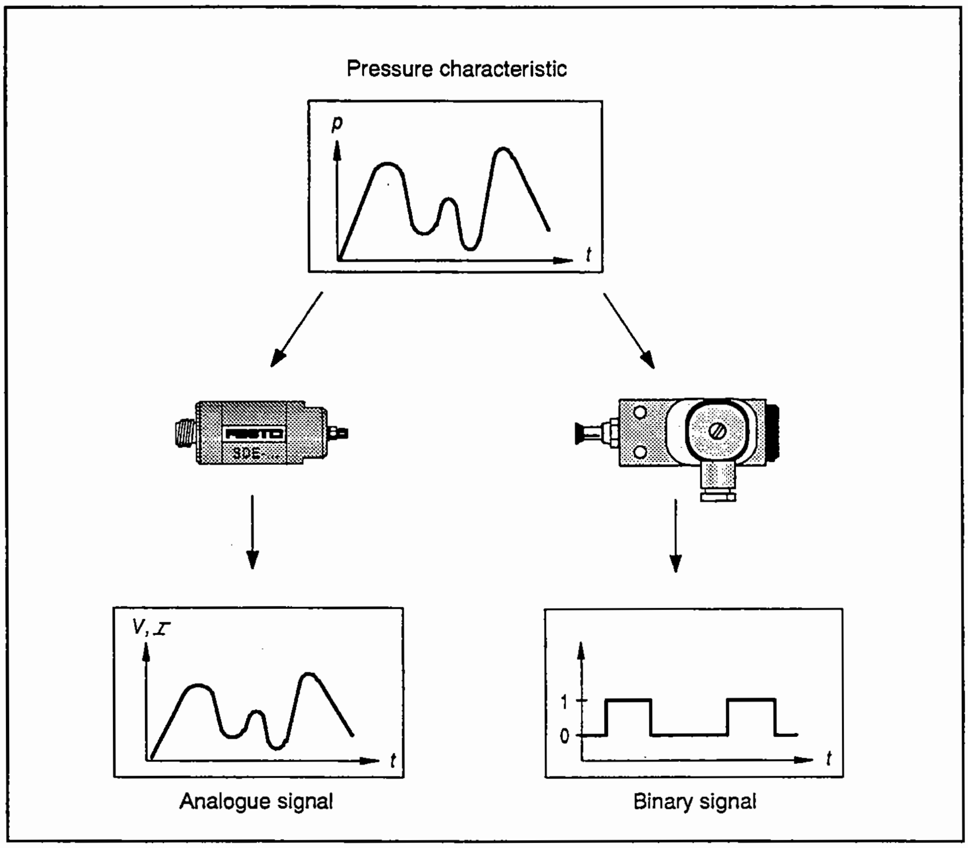


Fig. 10/1: Comparison of analogue and binary pressure switch signal

Exercise

a) Connect the mechanical pressure switch D.ER-PEV-1/4-B pneumatically and electrically so that its switching point can be determined and set with the help of the analogue pressure sensor D.ER-SDE-10-10V/20mA.

b) Determine the actual switching point set for the increasing air pressure with the help of the analogue pressure sensor D.ER-SDE-10-10V/20mA.

c) Set the pressure switch D.ER-PEV-1/4-B during increasing pressure at a value of 3 bar. Check the setting you have made.

d) Measure the hysteresis of the pressure sensor for the setting carried out under c).

e) Repeat points c) and d) for response pressures of 1 bar, 2 bar and 4 bar.

Please observe the user notes in the introduction part when carrying out the exercises. Appropriate information regarding connection method and additional technical data can be found in the corresponding data sheets in the appendix.

Practical implementation
Part exercise a)

The pressure switch D.ER-PEV-1/4-B is connected in parallel with the analogue pressure sensor D.ER-SDE-10-10V/20mA via the pressure manifold D.ER-FR-4-1/8-V/20mA.

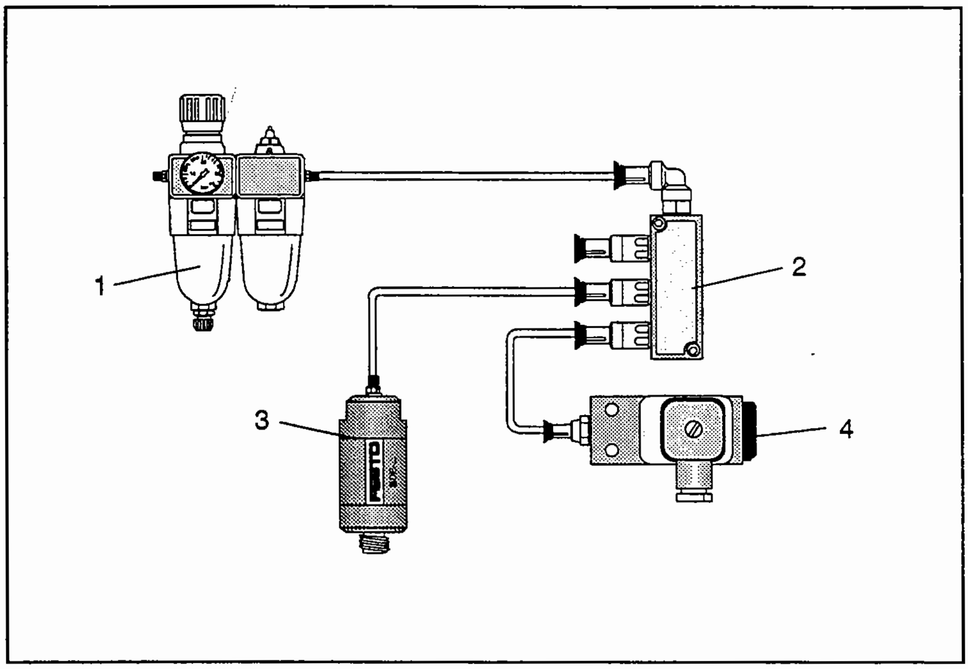


Fig. 10/2: Pneumatic connection

Comp. Ref. No.	Qty.	Description	Designation
1	1	Service unit	D.ER-FRC-1/8-S
2	1	Pressure manifold	D.ER-FR-4-1/8-B
3	1	Analogue pressure sensor	D.ER-SDE-10-10V/20mA
4	1	Pressure switch	D.ER-PEV-1/4-B
	4	Plug-in adapter	D.MP-B-ME-AS

Table 10/1: Component list

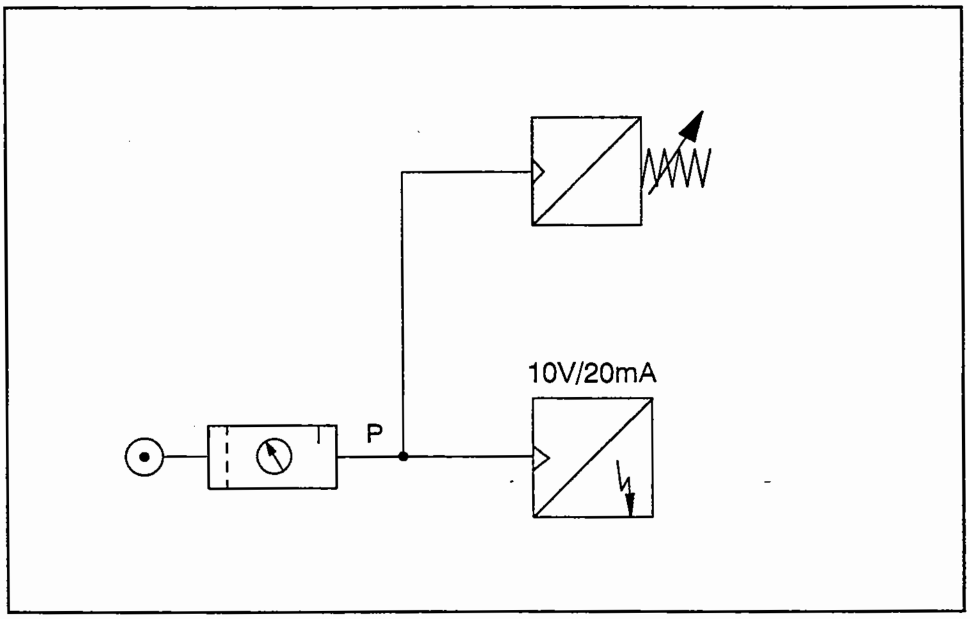


Fig. 10/3: Pneumatic circuit diagram

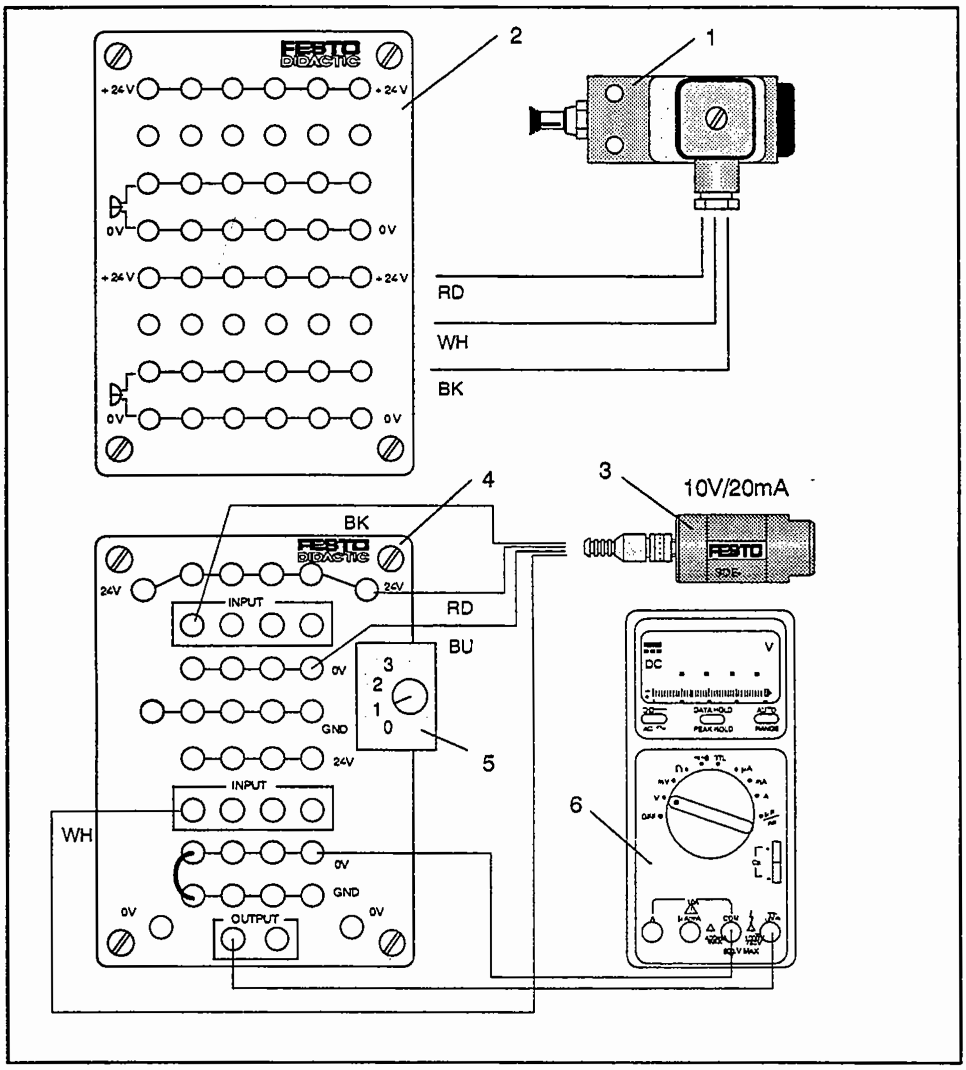


Fig. 10/4: Electrical connection

Comp. Ref. No.	Qty.	Description	Designation
1	1	Pressure switch	D.ER-PEV-1/4-B
2	1	Distribution plate	D.ER-VERT-SENSOR
3	1	Analogue pressure sensor	D.ER-SDE-10-10V/20mA
4	1	Adapter plate	D.ER-AE-101AF
5	1	Signal switching unit	D.ER-SUAE-101
6	1	Digital multimeter	D.AS-DMM
	4	Plug-in adapter	D.MP-B-ME-AS

Table 10/2: Component list

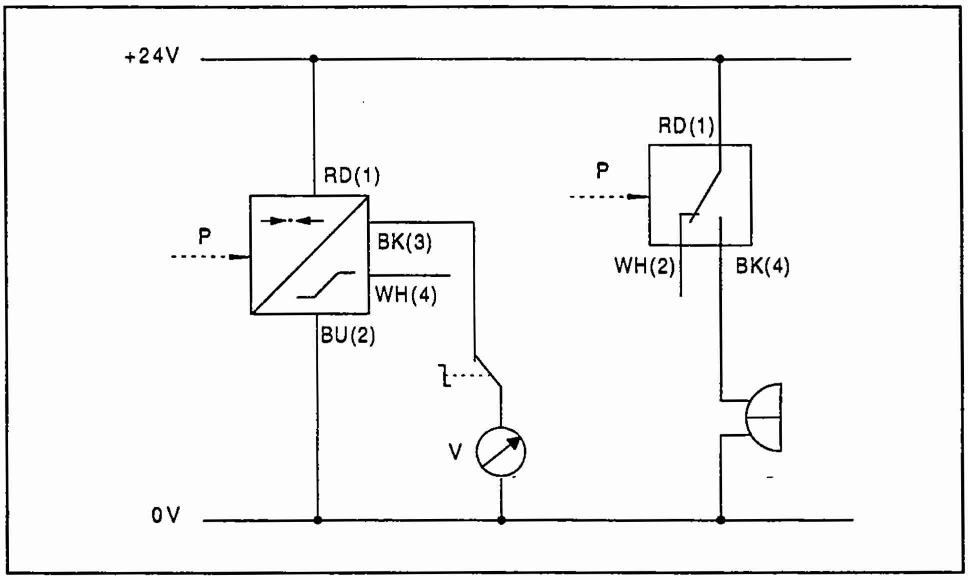


Fig. 10/5: Electrical circuit diagram

- Connect the pressure sensor to the binary distribution plate D.ER-VERT-SENSOR. This enables you to determine the switching status of the pressure switch. If a buzzer sounds, the pressure switch is in the switched status.

The pressure switch D.ER-PEV-1/4-B consists of a mechanical switch, which can be used both as a normally closed contact and a normally open contact. The signal voltage is switched direct to the buzzer of the distribution unit via this switching contact.

Part exercise b)

- By manual adjustment, slowly increase the pressure on the service unit. At the same time, the display of the multimeter must be observed. If the pressure switch is actuated, the buzzer of the distribution unit sounds. At this point (p_o) the manual pressure increase on the service unit is stopped immediately. The response pressure can be read on the multimeter.
- Enter the measured values in table 10/3 of the worksheet.
- Often, it is not possible to stop the pressure increase as soon as the response pressure has been reached. In order to avoid errors, it is recommended to repeat the measuring procedure as many times as required until a consistent value is achieved.

Note

If the setting of the pressure switch is in a high pressure range, which is not reached when the pressure on the service unit is increased (pressure switch not switching), the following rough presetting is recommended:

1) Turn the adjusting screw to the lefthand stop
2) Turn the adjusting screw three revolutions to the right.

Part exercise c)

- The system pressure is set at 3 bar on the service unit. This enables the exact pressure value to be read on the multimeter with the help of the analogue pressure sensor D.ER-SDE-10-10V/20mA.

Note

During the setting of the pressure on the service unit, it is possible for a slight reduction in pressure to occur after the lines and pressure manifold have been charged. In this case, the setting on the service unit must be adjusted until the pressure becomes stable.

- If the pressure switch has already switched, then the adjusting screw must be turned to the right by means of a screw driver until the switching contacts open.
- The setting can now begin. To do this, the adjusting screw is turned slowly to the left until the pressure switch switches. If the switching point is reached, a buzzer will sound.

Checking

The new setting of the pressure switch is checked in accordance with the method used in part exercise b).

Part exercise d)

The differential pressure is known as the hysteresis of a pressure switch, which occurs between the switch-on point for increasing pressure p_o and the switch-off point for falling pressure p_u. The extent of the hysteresis in this case is dependent on the actual setting of the pressure switch.

- The pressure of the actuated pressure switch is reduced slowly at the service unit until the pressure switch switches off. At this point, the reduction of pressure must be stopped immediately.
  Parallel to the measurement of the switch-on pressure, the switch-off pressure is determined by means of the analogue pressure sensor D.ER-SDE-10-10V/20mA and the multimeter and entered in table 10/4 of the worksheet.
  The hysteresis is calculated as follows:

Hysteresis = Switch-on pressure (p_o) - Switch-off pressure (p_u)

Part exercise e)

- Repeat the hysteresis measurements for switch-on pressures of 1 bar, 2 bar and 4 bar.
  Enter the values in table 10/5 of the worksheet.

- The hysteresis measurement is carried out as in part exercise d)

Measurement	Response pressure (bar)
1	
2	
3	
4	

Table 10/3: Truth table for determining response pressure

Measurement	p_o (bar)	p_u (bar)	Hysteresis (bar)
1			
2			
3			
4			

Table 10/4: Truth table for determining hysteresis

p_o (bar)	p_u (bar)	Hysteresis (bar)
1.00		
2.00		
3.00		
4.00		

Table 10/5: Hysteresis for various switching states

Notes

Subject

Sensors for force and pressure

Title

Setting of an electronic pressure switch

Learning content

A pneumatic-electronic switch is operated as a pressure switch.

Technical knowledge

The electronic pressure switch D.ER-PEN-M5, also known as a pneumatic-electronic switch, fulfills the function of the differential pressure switch. The position of a metal bellows varies depending on the differential pressure and is measured with the help of an inductive proximity switch. By pre-loading the bellows using an adjustable spring, it is possible to select the pressure switching point. The binary switching signal of the pressure switch D.ER-PEN-M5 is bounce-free and can be processed directly in display units or controllers.

B 7.2

Problem definition

An electronic pressure switch is to be used for pressure monitoring in a pneumatic system. For this purpose, the pressure switch is to be set at a specified switching pressure.

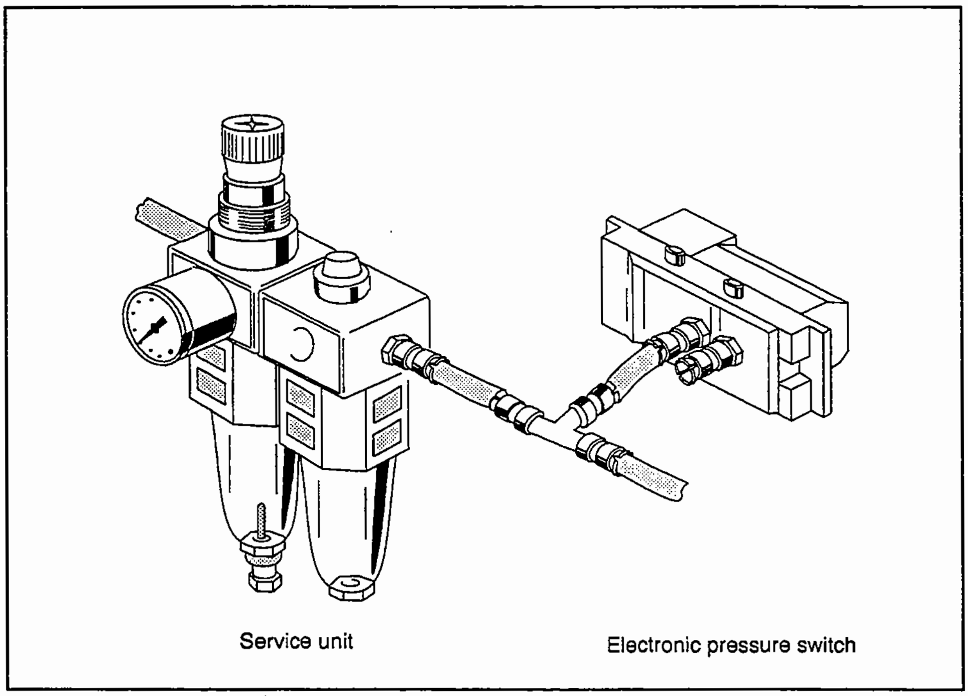


Fig. 11/1: Monitoring of pneumatic pressure using a pressure switch

Exercise

a) Connect the electronic pressure switch D.ER-PEN-M5 pneumatically and electronically so that its switching point can be determined and set by means of the analogue pressure sensor D.ER-SDE-10-10V/20mA. The differential pressure input remains unconnected.

b) Determine the actual switching point set for rising air pressure with the help of the analogue pressure sensor D.ER-SDE-10-10V/20mA.

c) Set the pressure switch D.ER-PEN-M5 for rising pressure to a switching point of 3 bar.
Check the setting you have made.

d) Measure the hysteresis of the pressure switch for the setting carried out under c).

e) Repeat points c) and d) for response pressures of 1 bar, 2 bar and 4 bar.

Please observe the user notes in the introduction section when carrying out the exercises. Appropriate information regarding connection method and additional technical data can be found in the corresponding data sheets in the appendix.

Practical implementation
Part exercise a)

When using the pneumatic-electronic switch D.ER-PEN-M5 as a pressure switch, the differential pressure in respect of ambient pressure is measured. To do this, the signal pressure is connected to port P1. Port P2 remains open, i.e. the differential pressure input is subject to ambient pressure.
In order to measure the actual pressure on the pressure switch, the analogue pressure sensor D.ER-SDE-10-10V/20mA is connected parallel to port P1 via the pressure manifold D.ER-FR-4-1/8-B.

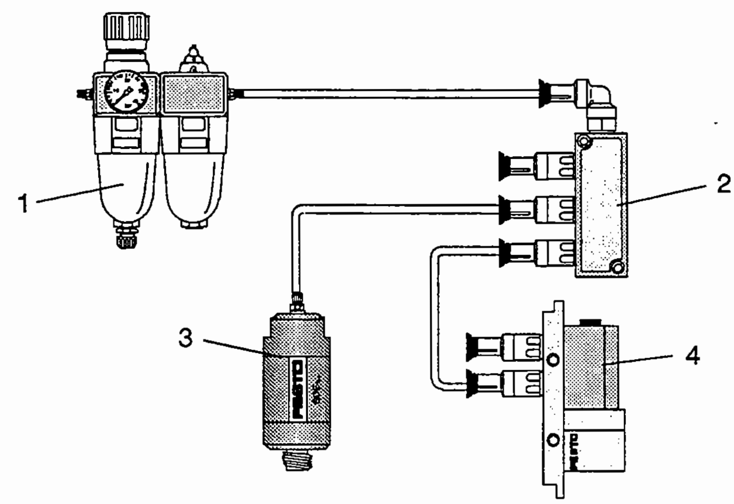


Fig. 11/2: Pneumatic connection

Comp. Ref. No.	Qty.	Description	Designation
1	1	Service unit	D.ER-FRC-1/8-S
2	1	Pressure manifold	D.ER-FR-4-1/8-B
3	1	Analogue pressure sensor	D.ER-SDE-10-10V/20mA
4	1	Pneum.-elect. switch	D.ER-PEN-M5
	4	Plug-in adapter	D.MP-B-ME-AS

Table 11/1: Component list

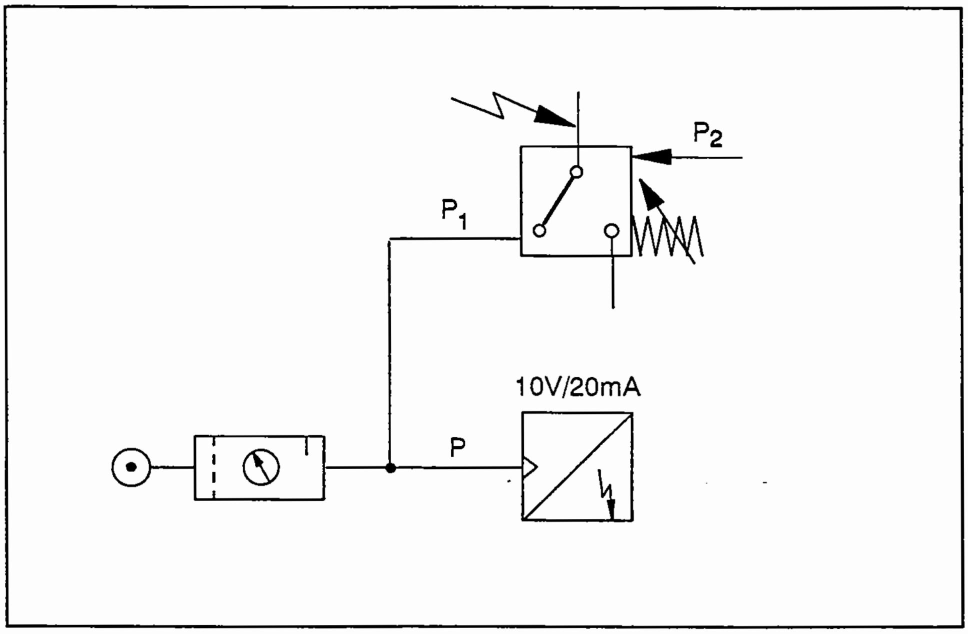


Fig. 11/3: Pneumatic circuit diagram

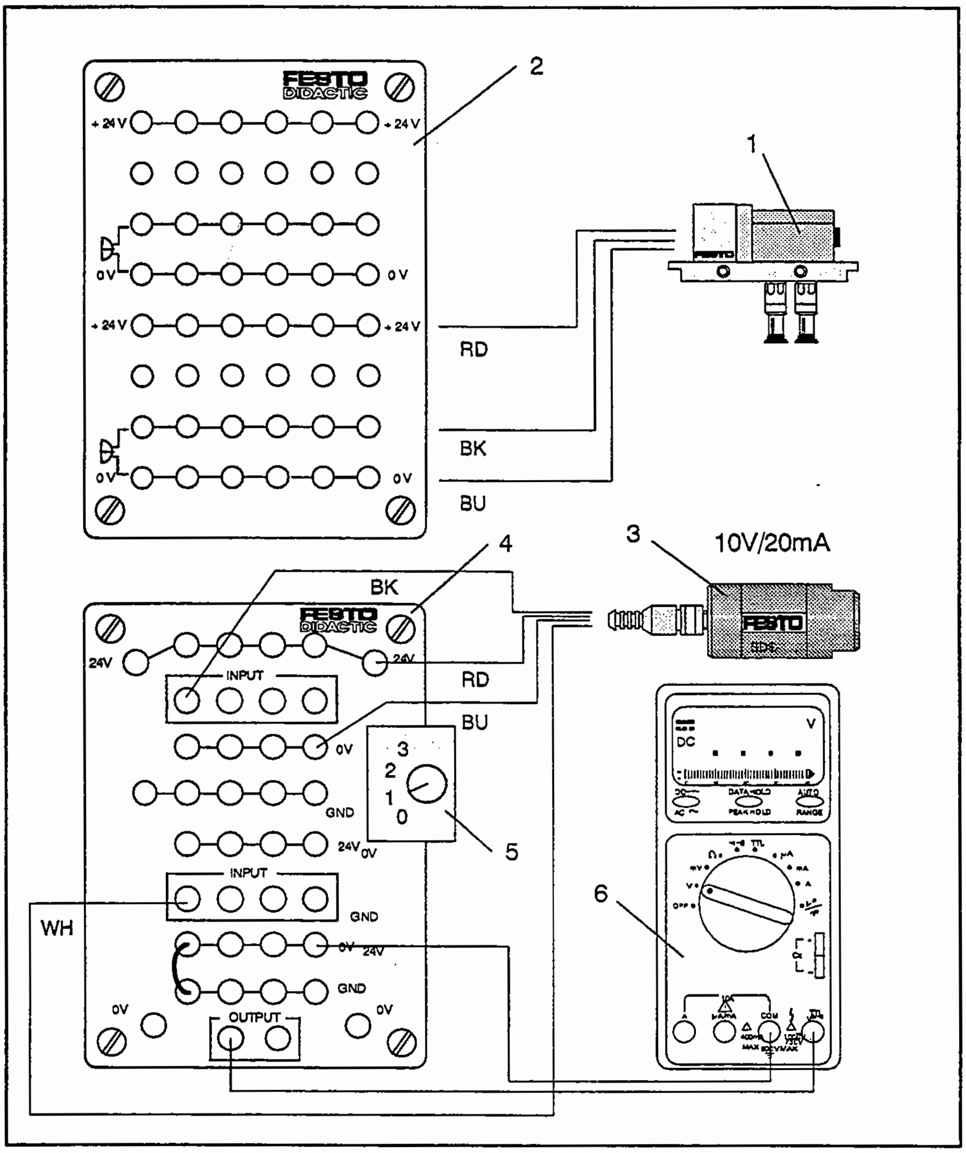


Fig. 11/4: Electrical connection

Comp. Ref. No.	Qty.	Description	Designation
1	1	Pneum.-elect. switch	D.ER-PEN-M5
2	1	Distribution plate	D.ER-VERT-SENSOR
3	1	Analogue pressure sensor	D.ER-SDE-10-10V/20mA
4	1	Adapter plate	D.ER-AE-101AF
5	1	Signal switching unit	D.ER-SUAE-101
6	1	Digital multimeter	D.AS-DMM
	12	Plug-in connector	D.MP-B-ME-AS

Table 11/2: Component list

In order to measure the switching status, the pressure switch D.ER-PEN-M5 is connected to the binary distribution plate D.ER-VERT-SENSOR. When the buzzer sounds, the pressure switch is in the switched status.

The electronic pressure switch D.ER-PEN-M5 has a signal output, to which the operating voltage is electronically switched. The pressure switch can only be used as a normally open contact.

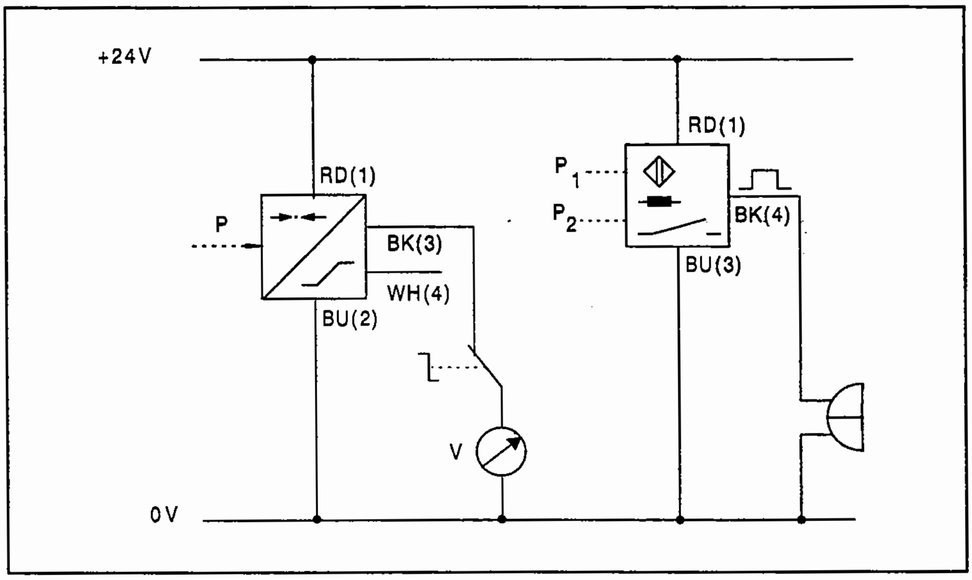


Fig. 11/5: Electrical circuit diagram

Part exercise b)

- The pressure on signal input P1 is increased slowly until the pressure switch is actuated. Switching can be observed via both the light emitting diode (LED) of the pressure switch D.ER-PEN-M5 as well as the sound of the buzzer.

- The manual pressure increase on the service unit is stopped immediately after switching. The switching point can then be read on the multimeter with the help of the analogue pressure sensor D.ER-SDE-10-10V/20mA. Carry out the measurements and enter the measured values in table 11/3 on the worksheet.

- There is a danger that the manual pressure increase will not be stopped in time when the switching point is reached. In order to avoid measuring errors, it is recommended to repeat the measuring process until several coinciding measured values are available.

Note

If the setting of the pressure switch is in a pressure range which is so high that it is not achieved by increasing the pressure on the service unit (the pressure switch does not switch), then the following rough presetting is recommended:

1) Turn the adjusting screw to the righthand stop

2) Turn the adjusting screw six revolutions to the left.

Part exercise c)

- The system pressure is set at 3 bar on the service unit whereby the exact pressure value is read on the multimeter with the help of the analogue pressure sensor D.ER-SDE-10-10V/20mA.
  If the pressure switch D.ER-PEN-M5 is already actuated, then the the adjusting screw is to be turned to the left by means of a screw driver until the switch resets.
- You can now start the setting by turning the adjusting screw very slowly towards the right until the pressure switch actuates at switching point p_o. Immediately upon switching, cease turning the adjusting screw.

Checking

Checking of the new pressure switch setting is carried out according to the procedure used in part exercise b).

If it is not sufficiently accurate, then the entire setting of the pressure switch must be repeated using the procedure described.

Part exercise d)

Hysteresis occurs with an electronic pressure sensor in the same way as it does with a mechanical pressure switch.

- The actuating pressure applied to the pressure switch is reduced at the service unit until the pressure switch resets. At the point of resetting, the reduction in pressure must be stopped immediately.
- Parallel to the measurement of the switch-on pressure, the switch-off pressure is determined by means of the analogue pressure sensor D.ER-SDE-10-10V/20mA and the multimeter and entered in table 11/4 on the worksheet.

The hysteresis is calculated as follows:

Hysteresis = Switch-on pressure (p_o) - Switch-off pressure (p_u)

Part exercise e)

- Repeat the hysteresis measurement for the differential pressures of 1 bar, 2 bar and 4 bar. Enter the measured values in table 11/5 on the worksheet.
- The hysteresis measurement is carried out in the same way as in part exercise d).

Measurement	Response pressure (bar)
1	
2	
3	
4	

Table 11/3: Truth table for determining response pressure

Measurement	p_o (bar)	p_u (bar)	Hysteresis (bar)
1			
2			
3			
4			

Table 11/4: Truth table for determining the hysteresis

p_o (bar)	p_u (bar)	Hysteresis (bar)
1.00		
2.00		
3.00		

Table 11/5: Hysteresis for various switching states

Notes

Subject

Sensors for force and pressure

Title

Using an electronic pressure switch as a differential pressure switch

Learning content

A pneumatic-electronic switch is operated as a differential pressure switch.

Technical knowledge

B 7.1

Differentiation is made between absolute pressure sensors, relative pressure sensors and differential pressure sensors. Absolute pressure sensors measure pressure against vacuum. The air pressure quoted in meteorological broadcasts is one example of this. Relative pressure sensors measure pressure relative to ambient pressure. Absolute pressure sensors and relative pressure sensors have one single pressure port. In contrast, differential pressure sensors measure the difference in pressure across two pressure ports. If one pressure port of a differential pressure sensor is left open, then the differential pressure sensor operates identically to a relative pressure sensor. Differential pressure sensors are available as analogue differential pressure sensors or differential pressure switches. Pressure sensor D.ER-PEN-M5 is an example of a differential pressure switch.

Problem definition

The pressure switch D.ER-PEN-M5 is to be used to monitor the contamination level of a filter in a pneumatic system. To do this, the pressure switch must be set to a predetermined differential pressure. The air filter function is simulated by means of two pressure circuits.

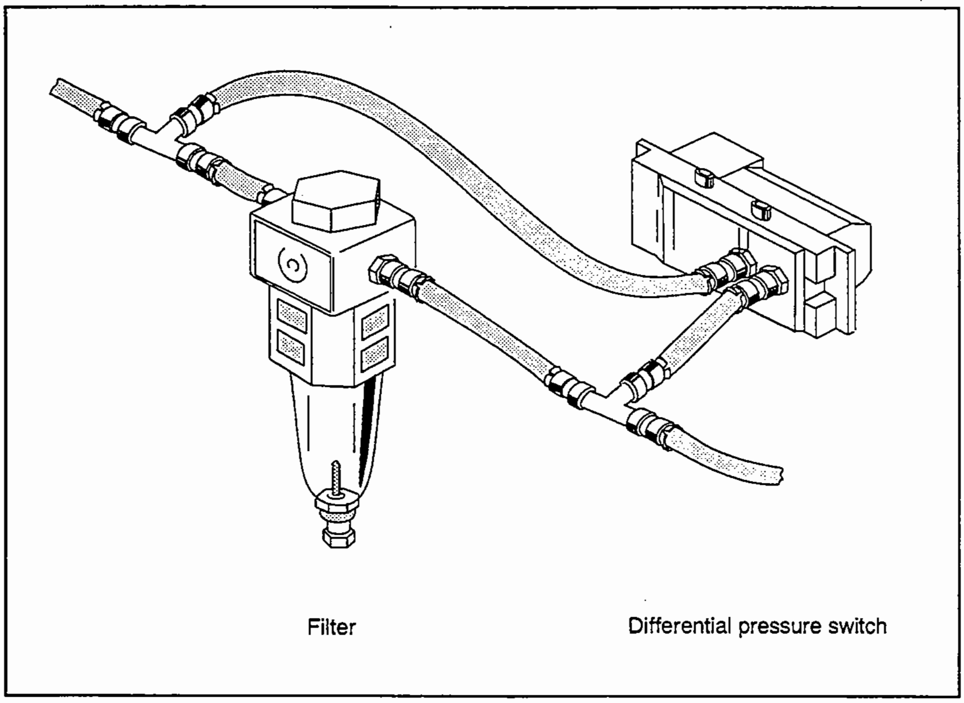


Fig. 12/1: Monitoring of filter using a differential pressure switch

Exercise

a) Carry out the pneumatic connection of pressure sensor D.ER-PEN-M5 in such a way that an adjustable, static pressure can be connected to point P_2 (see Fig. 12/3).

b) Set the pressure at point P_1 to 4 bar. A signal should be emitted from the pressure switch, when the pressure drop on the filter is 1 bar. Now set the differential pressure at point P_2 in order for this condition to be fulfilled.

c) Set the pressure switch at a differential pressure of 1 bar. Check the setting on the pressure switch.

d) Measure the hysteresis of the pressure switch for the setting carried out under c).

e) Repeat the hysteresis measurement for differential response pressures of 3 bar and 2 bar. The system pressure in each case is 4 bar.

Please observe the user notes in the introduction section when carrying out the exercises. Appropriate information regarding connection method and additional technical data can be found in the corresponding data sheets in the appendix.

Practical implementation
Part exercise a)

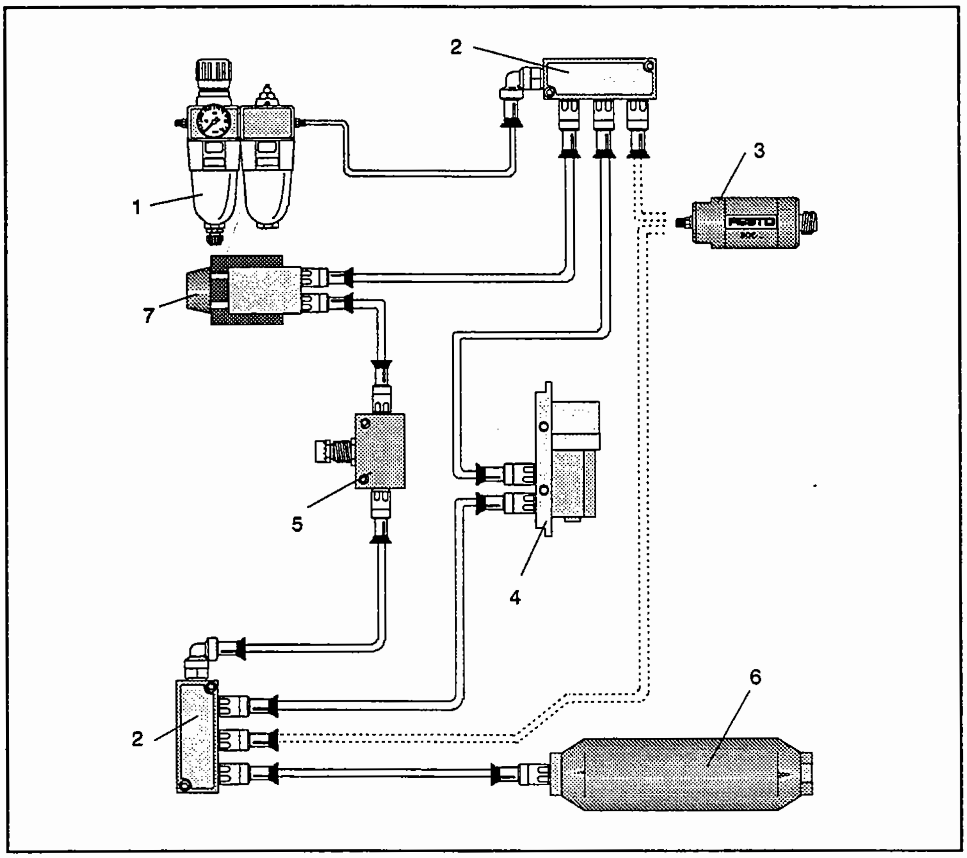


Fig. 12/2: Pneumatic connection

The pressure on differential pressure input P_2 is created statically with the help of a partly charged compressed air reservoir. The analogue pressure sensor is used for pressure measurement at several points in the pneumatic system, hence the supply lines are denoted by broken lines.

Comp. Ref. No.	Qty.	Description	Designation
1	1	Service unit	D.ER-FRC-1/8-S
2	2	Pressure manifold	D.ER-FR-4-1/8-B
3	1	Analogue pressure sensor	D.ER-SDE-10-10V/20mA
4	1	Pneum.-elect. switch	D.ER-PEN-M5
5	1	One-way flow control valve	D.ER-GR-1/8-B
6	1	Compressed air reservoir	D.ER-VZS-0,4
7	1	3/2-way panel mounted valve	D.ER-SV-3-M5
	12	Plug-in adapter	D.MP-B-ME-AS

Table 12/1: Component list

Please observe the designation in the following pneumatic circuit diagram for connecting the panel mounted valve.

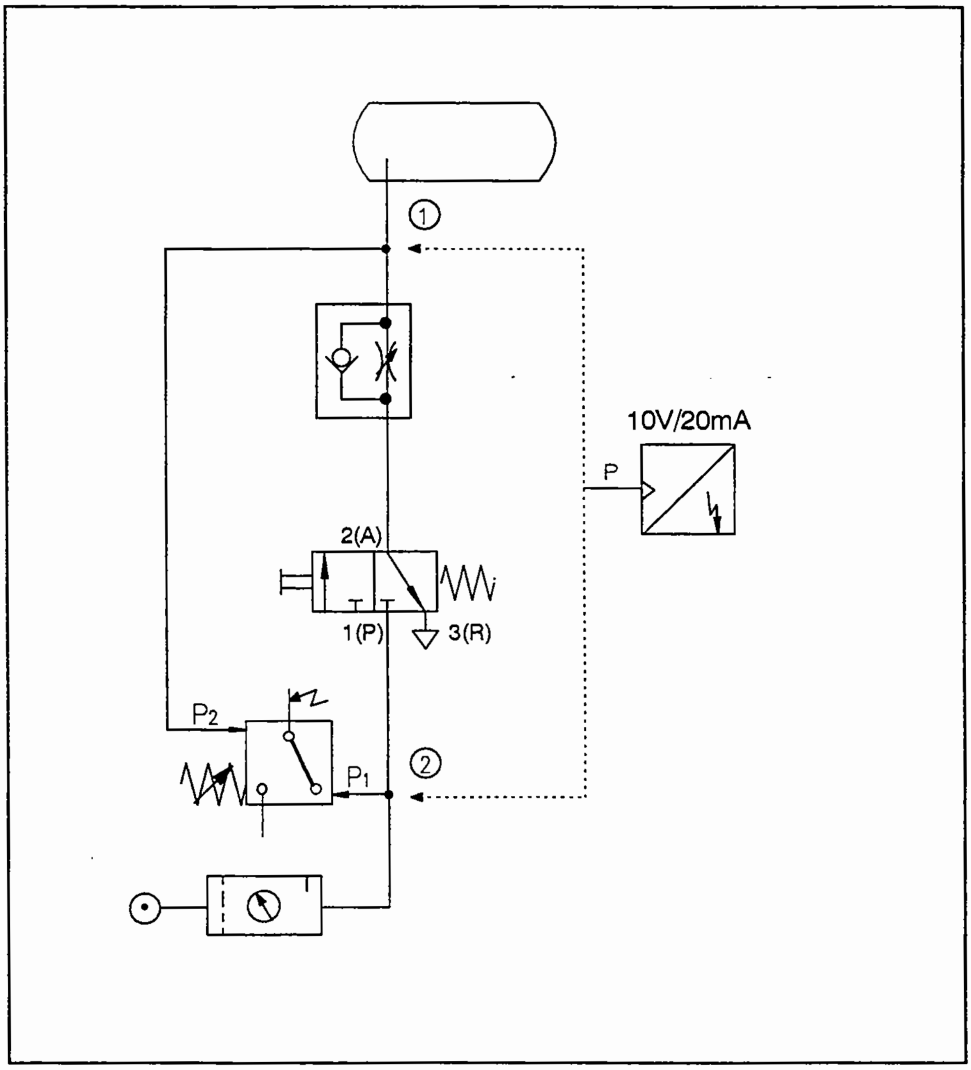


Fig. 12/3: Pneumatic circuit diagram

Operational principle

An actuated 3/2-way panel mounted valve fills the reservoir to system pressure via a one-way flow-control valve. To set the pressure, compressed air is released via the flow control from the reservoir until the required pressure is obtained.
To measure the pressure in the individual pressure circuits, the analogue pressure sensor is connected to the respective compressed air distributors; hence the supply lines to the analogue pressure sensor are denoted by broken lines.

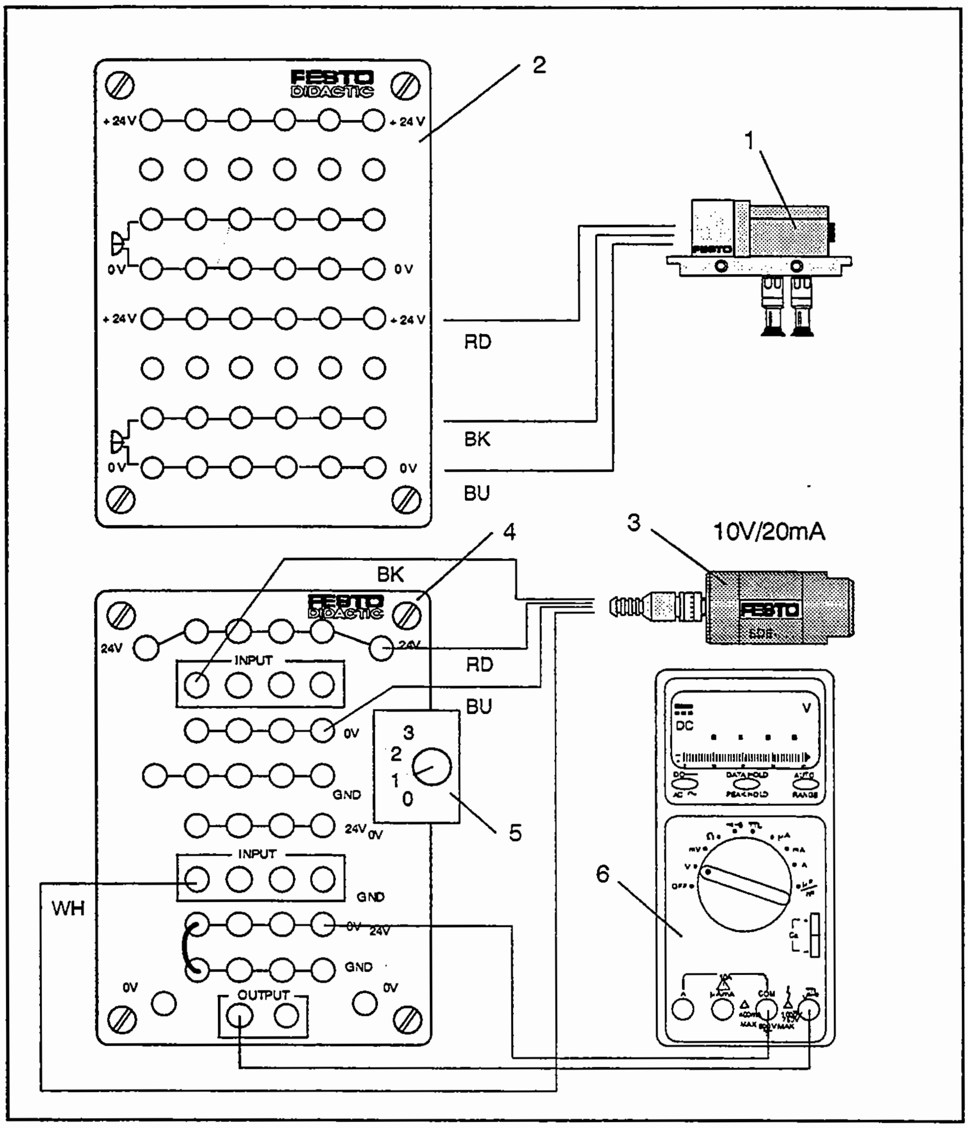


Fig. 12/4: Electrical connection

Comp. Ref. No.	Qty.	Description	Designation
1	1	Pneum.-elect. switch	D.ER-PEN-M5
2	1	Distribution plate	D.ER-VERT-SENSOR
3	1	Analogue pressure sensor	D.ER-SDE-10-10V/20mA
4	1	Adapter plate	D.ER-AE-101AF
5	1	Signal switching unit	D.ER-SUAE-101
6	1	Digital multimeter	D.AS-DMM
	12	Plug-in adapter	D.MP-B-ME-AS

Table 12/2: Component list

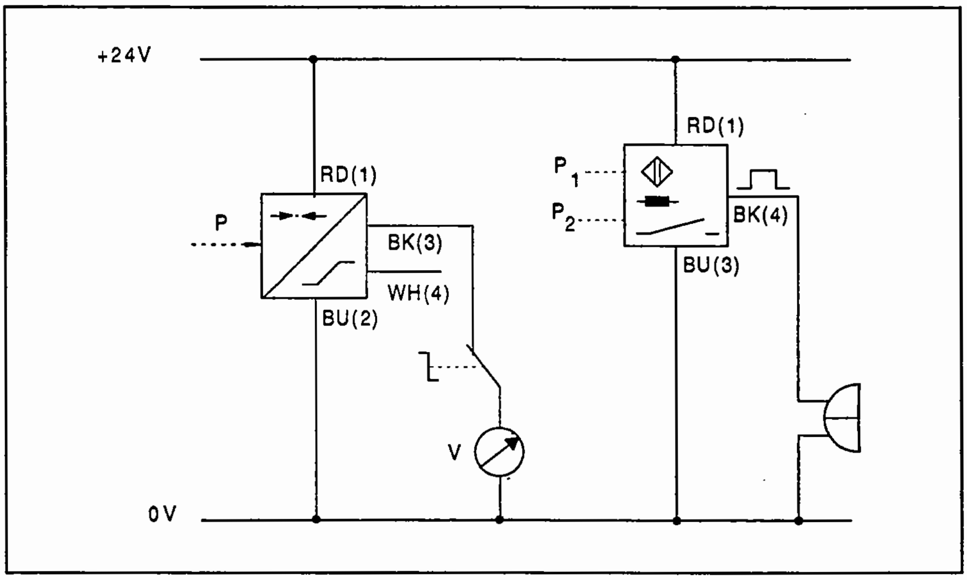


Fig. 12/5: Electrical circuit diagram

Part exercise b)

Note

The analogue pressure sensor D.ER-SDE-10-10V/20mA is used to measure the pressures at points P_1 and P_2 of the pressure switch D.ER-PEN-M5. To do this, the sensor is connected via its compressed air port to the respective pressure circuit. The connection is effected via a self-closing plug-in coupling on the respective compressed air manifold. It is possible for a slight pressure drop to result in the pressure circuit when the analogue pressure sensor is changed over. This pressure drop should be ignored.

Setting of the system pressure

- To set the system pressure of 4 bar at P_1, the compressed air tubing of the analogue pressure sensor is connected to the pressure circuit parallel to the service unit (connection 2 in the pneumatic circuit diagram).
- Set the pressure on the service unit to 4 bar and check or correct the setting by means of the multimeter reading.

Setting of the differential pressure

- To carry out this part of the exercise, the analogue pressure sensor is connected parallel to the compressed air reservoir in the differential pressure circuit (connection 1 in the pneumatic circuit diagram).

The pressure (P_2) is calculated from the difference between system and differential pressure.

Pressure (P_2) = System pressure (P_1) – Differential pressure

The pressure at point (P_2) must be 3 bar.

- The compressed air reservoir is charged to system pressure via the panel mounted valve. During this, the adjusting screw of the one-way flow control valve is turned to the right-hand stop (flow control closed).
- The adjusting screw is turned slightly to the left. Compressed air is now escaping from the compressed air reservoir and the pressure in the reservoir starts to drop. Once the required pressure value has been attained (in this instance: 3 bar) the flow control is to be closed immediately by means of the adjusting screw. Observe the pressure on the multimeter at this setting. A pressure of 3 bar is thus set at P_2.

Part exercise c)

- If the pressure switch has already been set, the adjusting screw must be turned to the left with a screwdriver until the switch resets.
- Setting can now be commenced. To do this, the adjusting screw is turned slowly to the right until the switch is actuated. Immediately upon switching, cease turning the adjusting screw. Switching will be signalled by means of the audible buzzer or the integrated LED.
- The analogue pressure sensor is connected parallel to the service unit. This is connection 2 in the pneumatic circuit diagram.

Checking

- In order to check the setting, the system pressure at signal input P1 is increased slowly until the pressure switch switches. Switching will be signalled by the light emitting diode (LED) of pressure switch D.ER-PEN-M5 as well as by the sounding of the buzzer.
- After switching, the manual pressure increase is stopped immediately. The response pressure can be read on the voltmeter with the help of the analogue pressure sensor SDE-10-10V/20mA.

If it is not sufficiently accurate, then the entire setting of the pressure switch must be repeated using the procedure described.

Part exercise d)

- The actuating pressure applied to the pressure switch is reduced at the service unit until the pressure switch D.ER-PEN-M5 resets. At the point of resetting, the reduction of pressure must be stopped immediately. Similar to the measurement of the switch-on pressure, the reset pressure is determined by means of the analogue pressure sensor D.ER-SDE-10-10V/20mA and the multimeter and entered in table 12/3 of the worksheet.

The hysteresis is calculated as follows:

$$\text{Hysteresis} = \text{Switch-on pressure } (p_o) - \text{Reset pressure } (p_u)$$

Part exercise e)

- Repeat the hysteresis measurement for the differential switching pressures of 2 bar and 3 bar. Enter the measured values in table 12/4 of the worksheet.
  The hysteresis measurement is carried out as in part exercise d).

Question

What information do you obtain regarding the level of contamination of the filter, if the differential response pressure is increased or if it is reduced?

Measurement	p_o (bar)	p_u (bar)	Hysteresis (bar)
1			
2			
3			
4			

Table 12/3: Truth table for determining the hysteresis

$p_{Difference}$ (bar)	p_o (bar)	p_u (bar)	Hysteresis (bar)
1.00	4.00		
2.00	4.00		
3.00	4.00		

Table 12/4: Truth table for determining the hysteresis

Answer

Notes

Subject

Sensors for force and pressure

Title

Leak testing of compressed air reservoirs

Training aim

Designing a test station for leak testing of compressed air reservoirs.

Technical knowledge

Leaks in pneumatic systems lead to an unwanted pressure drop, if the system pressure is greater than the ambient pressure, or to an increase in pressure if the system pressure is less than the ambient pressure. It is possible to determine the size of the leak, by observing the time for the pressure change in a closed system.

B 1.7

Problem definition

Compressed air reservoirs are to be leak tested in quality control by means of a mechanical pressure switch D.ER-PEV-1/4-B.

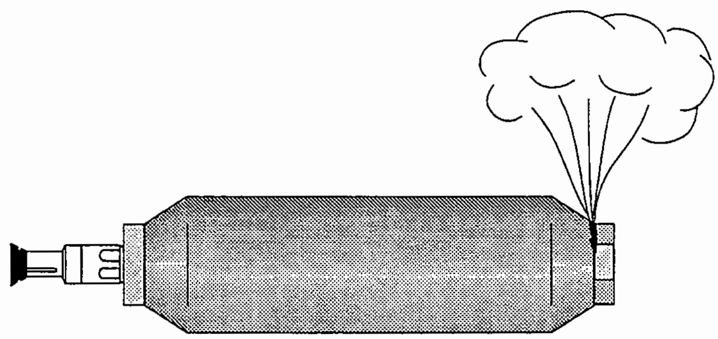


Fig. 13/1: Leaking compressed air reservoir

Exercise

a) Design a test station pneumatically and electrically in such a way that the leak testing of compressed air reservoirs can be carried out with the mechanical pressure switch D.ER-PEV-1/4-B. The pressure drop at the leakage point is to be simulated by means of a restrictor.

b) Set the testing station according to the following data:
- Charging pressure of reservoir 4 bar
- Maximum permissible pressure drop 1.5 bar

c) Measure the hysteresis of the pressure switch in respect of the setting carried out under b).

d) The criteria for a rejected part is a pressure drop within 20 seconds as referred to in part exercise b). Adjust the restrictor in such a way that it just meets this criteria.

e) Record the pressure drop curve p over time t for the setting carried out under d). The recording time is 120 seconds.

Please observe the user notes in the introduction section when carrying out the exercises. Appropriate information regarding connection method and additional technical data can be found in the corresponding data sheets in the appendix.

Practical implementation
Part exercise a)

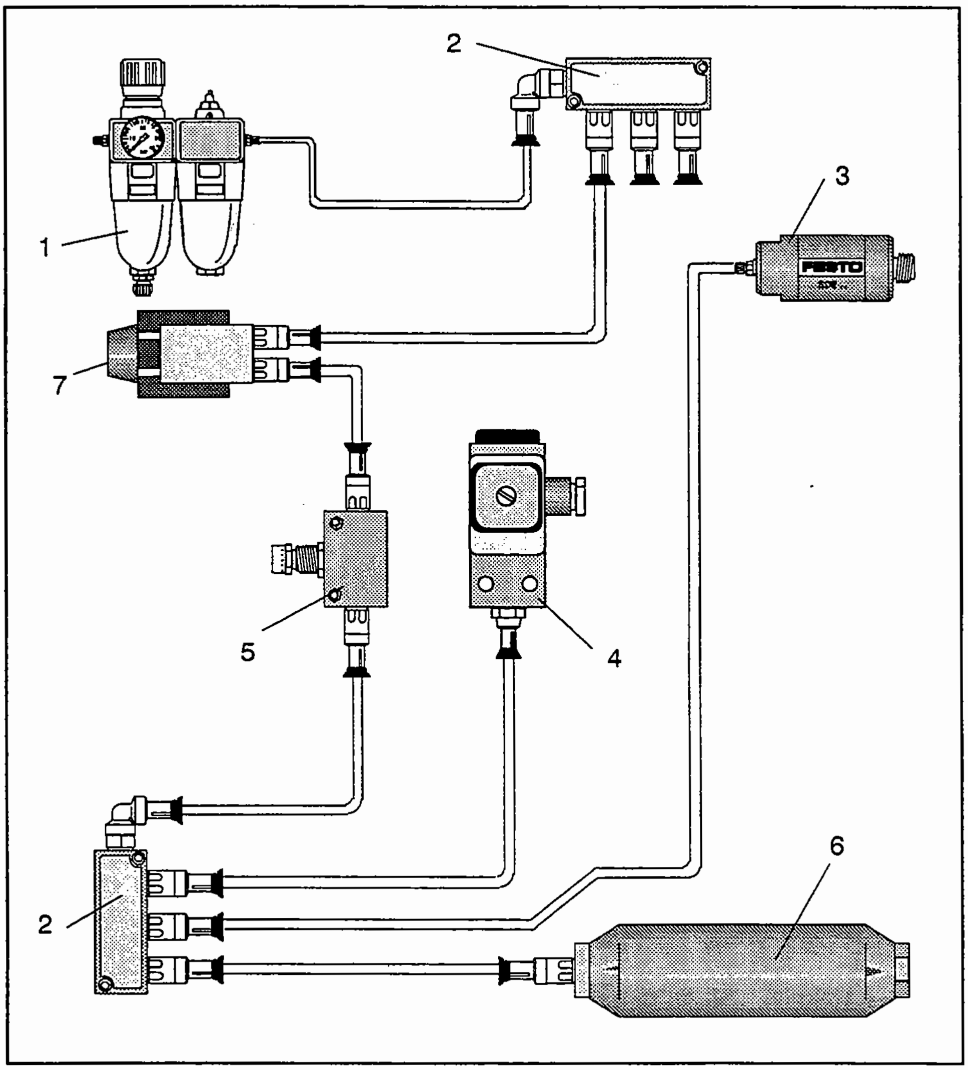


Fig. 13/2: Pneumatic connection

Comp. Ref. No.	Qty.	Description	Designation
1	1	Service unit	D.ER-FRC-1/8-S
2	2	Pressure manifold	D.ER-FR-4-1/8-B
3	1	Analogue pressure sensor	D.ER-SDE-10-10V/20mA
4	1	Pressure switch	D.ER-PEV-1/4-B
5	1	One-way flow control valve	D.ER-GR-1/8-B
6	1	Compressed air reservoir	D.ER-VZS-0.4
7	1	3/2-way panel mounted valve	D.ER-SV-3-M5
	8	Plug-in adapter	D.MP-B-ME-AS

Table 13/1: Component list

Please observe the designation in the following pneumatic circuit diagram for the connections of the panel mounted valve.

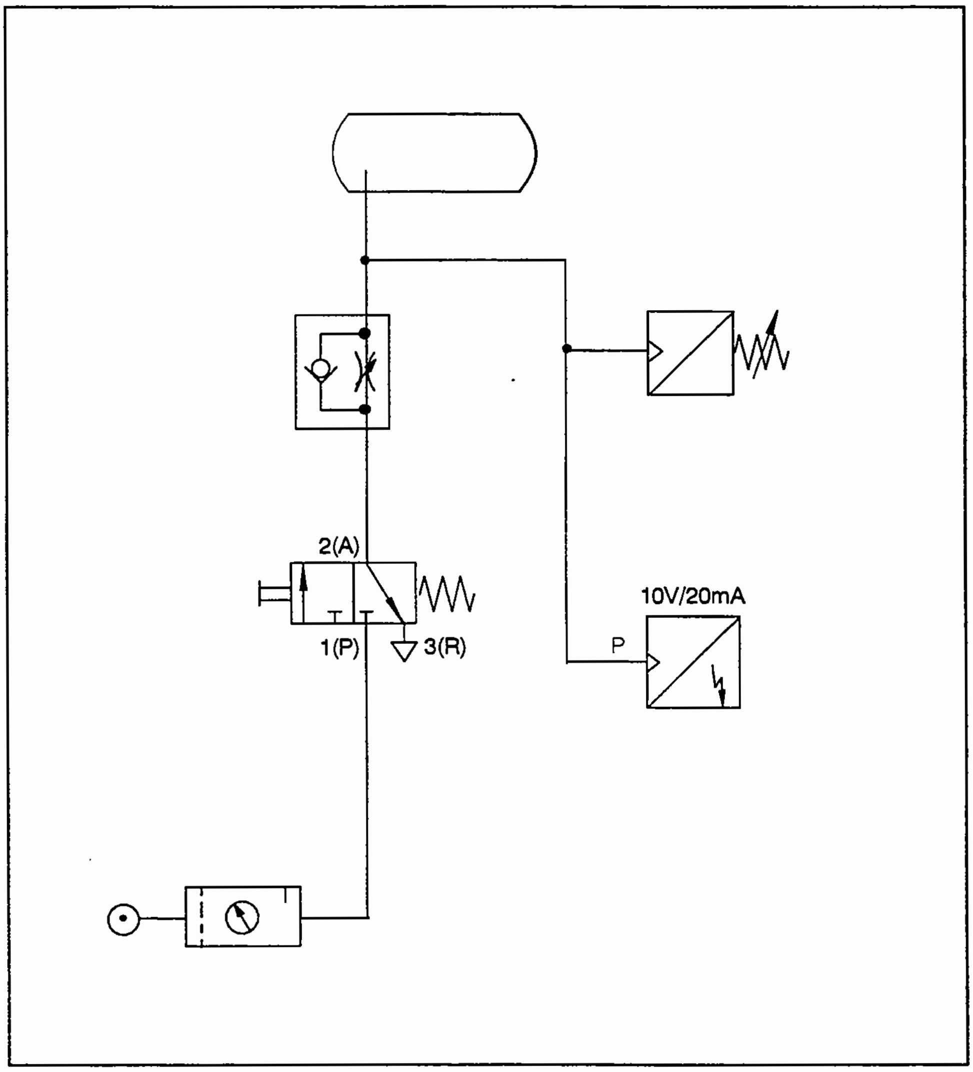


Fig. 13/3: Pneumatic circuit diagram

Operational principle

The reservoir is charged to system pressure by means of the actuated 3/2-way panel mounted valve and the one-way flow control valve. When the push-button is released, the non-return valve closes. The compressed air can escape via the restrictor and the 3/2-way valve.

If the restrictor is closed, the flow is blocked completely. Compressed air escapes, if the restrictor is opened; the pressure in the system begins to drop. This simulates the leakage point. The size of the leakage can be adjusted on the adjusting screw of the restrictor.

In order to adjust the pressure switch D.ER-PEV-1/4-B and to record the t - p curve, the analogue pressure sensor D.ER-SDE-10-10V/20mA is used with a multimeter as an accurate pressure gauge. The pressure sensor is connected to the distribution plate D.ER-VERT-SENSOR.

B 7.1

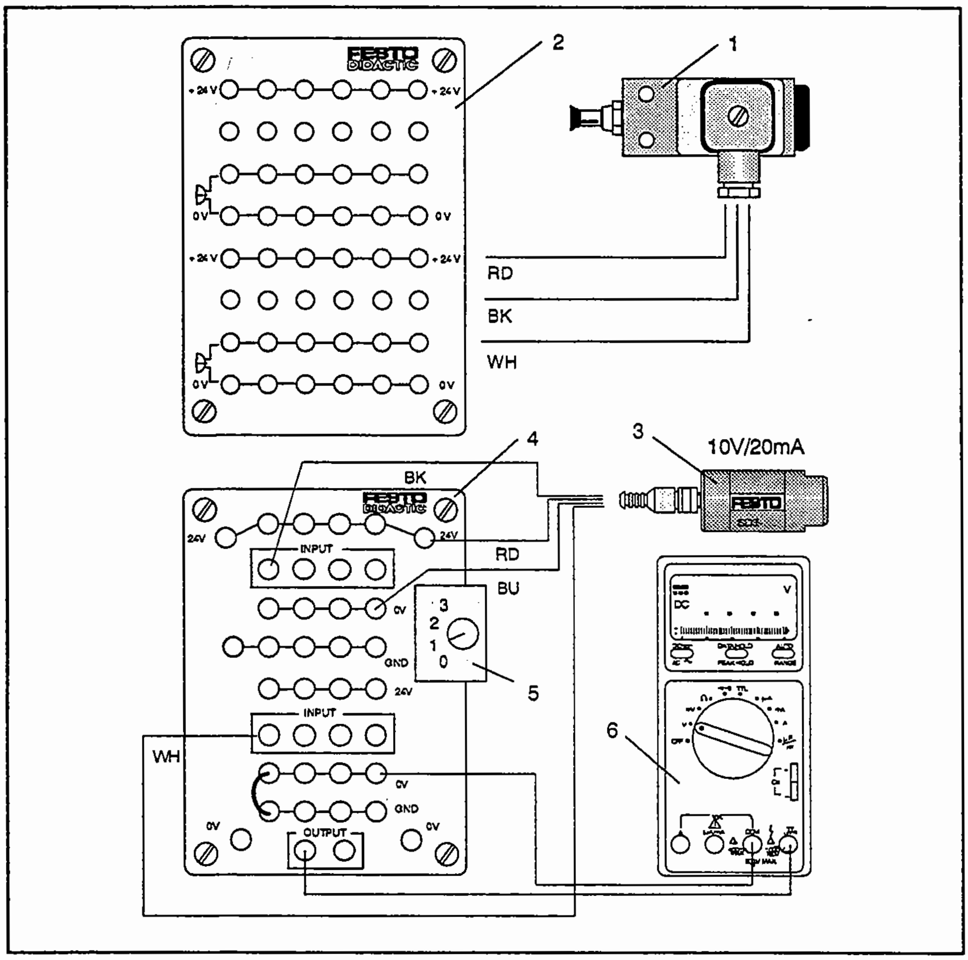


Fig. 13/4: Electrical connection

Comp. Ref. No.	Qty.	Description	Designation
1	1	Pressure switch	D.ER-PEV-1/4-B
2	1	Distribution plate	D.ER-VERT-SENSOR
3	1	Analogue pressure sensor	D.ER-SDE-10-10V/20mA
4	1	Adapter unit	D.ER-AE-101AF
5	1	Signal switching unit	D.ER-SUAE-101
6	1	Digital multimeter	D.AS-DMM
	8	Plug-in adapter	D.MP-B-ME-AS

Table 13/2: Component list

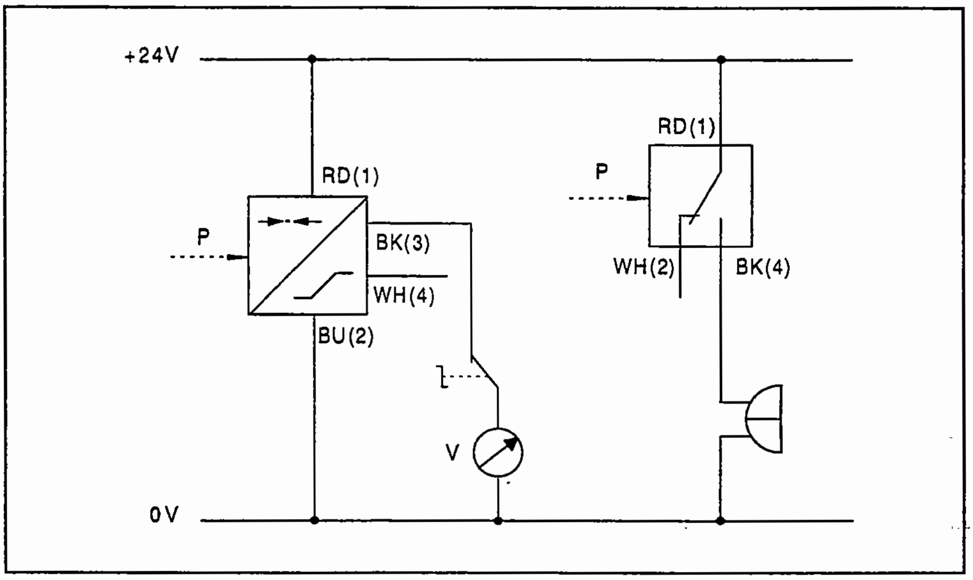


Fig. 13/5: Electrical circuit diagram

To carry out this part exercise, the normally closed contact of the pressure switch is used for signal generation.

Part exercise b)
Setting of the
filling pressure

- In order to adjust the charging pressure, a pneumatic connection must be established between the service unit D.ER-FRC-1/8-S and the compressed air reservoir D.ER-VZS-0.4. The panel mounted valve D.ER-SV-3-M5 remains activated during the process of adjustment. The system pressure at the service unit is set at precisely 4 bar. The pressure is set accurately only if a signal change of the analogue pressure sensor D.ER-SDE-10-10V/20mA can no longer be detected on the multimeter.

Setting of the
response pressure

In this exercise, the pressure switch D.ER-PEV-1/4-B is used in such a way, that an electrical signal is generated if pressure is dropping to the switch-off point (p_u = 2.5 bar). The signal voltage is connected to the distribution unit D.ER-VERT-SENSOR via the normally closed contact.

- Prior to the setting procedure, the reservoir is charged to system pressure (4 bar) and the restrictor closed.
- In order to make the setting, the pressure in the compressed air reservoir is reduced slowly via the flow control valve until a pressure of 2.5 bar is reached. At this point, the flow control valve is closed by the adjustment screw and the air flow blocked.
- If pressure falls below 2.5 bar during the adjustment, then the pressure in the reservoir can be increased again by briefly activating the panel mounted valve. After this, the pressure adjustment can be repeated.

Setting of the pressure switch

- The pressure on the pressure switch is set at 2.5 bar. The adjusting screw of the pressure switch is turned to the left until the pressure switch switches, whereby the buzzer on the distribution plate remains silent. After this, the adjusting screw is turned slowly to the right until the pressure switch switches off and a buzzer sound is generated on the distribution plate via the normally closed contact.

Monitoring of setting

Testing of the setting is carried out as follows:

- Create a system pressure of 4 bar by means of the push-button valve
- Lower the pressure slowly via the flow control valve
- Observe the signal change of the pressure switch when pressure falls below 2.5 bar (buzzer sounds).

Part exercise c)

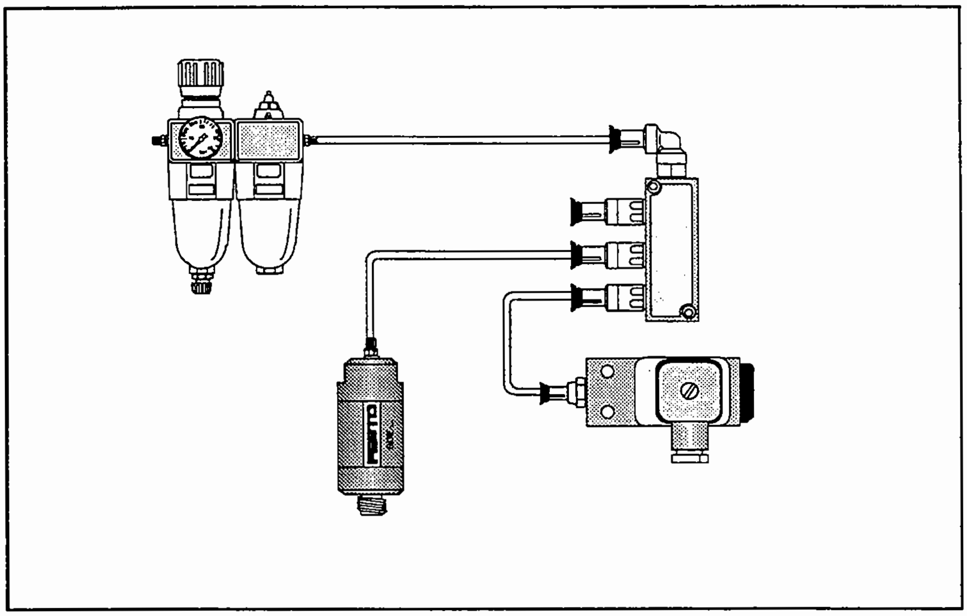


Fig. 13/6: Pneumatic connection

Note

In order to carry out this part exercise, the analogue pressure sensor D.ER-SDE-10-10V/20mA and the pressure sensor D.ER-PEV-1/4-B are pneumatically connected parallel to the service unit D.ER-FRC-1/8-S.

Before starting the measurement, the pressure switch must be in the unactuated state, i.e. the pressure must be less than 2.5 bar.

- In order to measure the switch-on point for rising pressure (p_o), pressure is increased slowly at the service unit until the pressure switch is actuated. Because the pressure switch is used as a normally closed contact, the buzzer sound stops when the switching point (p_o) is reached.
- At this point, the increase in pressure is stopped and the switch-on pressure (p_o) is read on the multimeter.
- Transfer the pressure value to table 13/3 on the worksheet and calculate the hysteresis.

Part exercise d)

To carry out this exercise, the pneumatic circuit of part exercise a) must be constructed again.

- The compressed air reservoir is filled via the panel mounted valve to a charging pressure of 4 bar.
- Immediately after the panel mounted valve is released, timing starts. Timing is completed when the pressure switch is actuated. This period must be 20 seconds. If there are deviations, the throttle adjustment must be corrected and the measurement carried out again.

Part exercise e)

It is recommended that the pressurised reservoir should be re-charged to a pressure of 4 bar via the panel mounted valve for each measuring point. Measurement starts from the moment the panel mounted valve is released.

- Wait until the measuring time for each measuring point is completed. Read the pressure value on the multimeter and enter this measuring value in table 13/4 of the worksheet. The time gap between each individual measuring point is 10 seconds.
- Transfer the values from table 13/4 to the diagram (fig.13/7) of the worksheet and draw the curve.

Question

A compressed air reservoir is charged with compressed air for leak testing. What is the required level of air pressure in the compressed air reservoir for the test to be carried out by means of a mechanical pressure switch?

Measurement	p_o (bar)	p_u (bar)	Hysteresis (bar)
1		2.50	
2		2.50	
3		2.50	
4		2.50	

Table 13/3: Truth table for determining the hysteresis

t (s)	10	20	30	40	50	60	70	80	90	100	110	120
p (bar)												

Table 13/4: Truth table for pressure drop

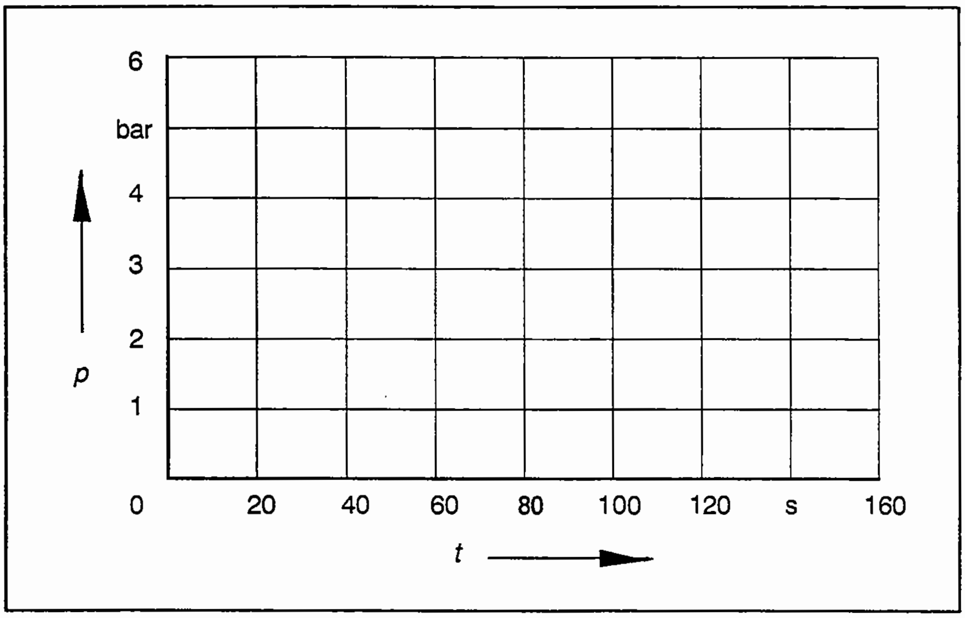


Fig. 13/7: Pressure/time diagram

Answer

Notes

Subject

Sensors for force and pressure

Title

Commissioning of a back pressure switch

Learning content

To learn about the function, connection and the setting of a back pressure switch for filling level monitoring.

Technical knowledge

B 7.1

Back pressure switches signal the filling level of fluids in containers, whereby the riser pipe of a back pressure sensor is lowered into the fluid. When the fluid level rises, the air contained in the riser pipe pushes against the pressure input of the switch.

Problem definition

The water supply to the drum of a washing machine is stopped, when the filling level specified on the washing program has been reached. A back pressure switch is used to monitor the filling level. The back pressure switch is to be set at a given filling level.

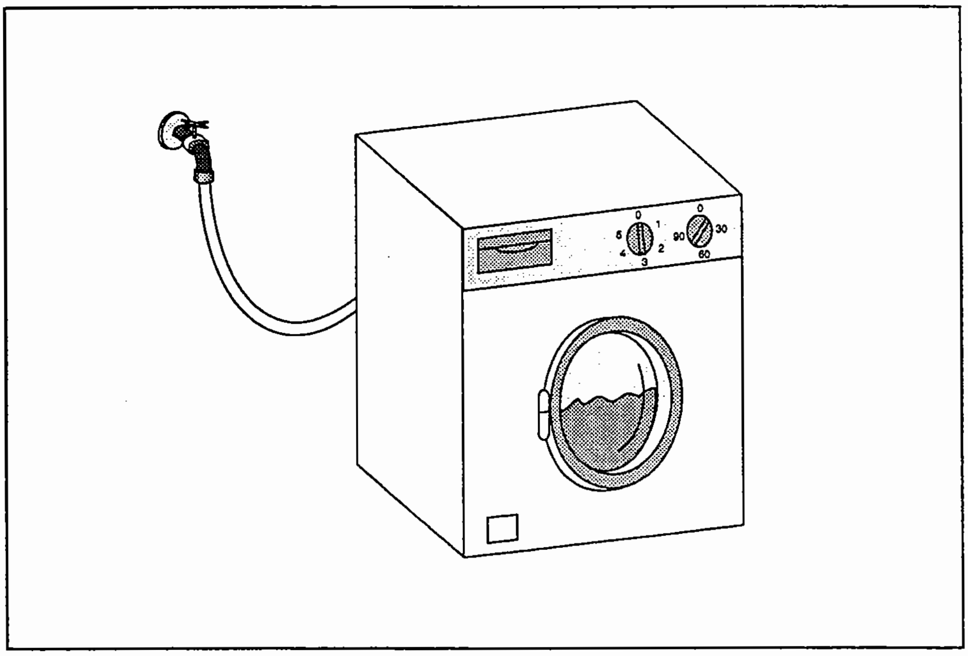


Fig. 14/1: Filling level in washing machine drum

Exercise

a) Assemble the measuring device. Establish the electrical connection between the back pressure switch D.ER-SDS and distribution plate D.ER-VERT-SENSOR.

b) Set the pressure switch so that it switches at a water level of 5 cm.
Check the setting you have carried out.

Please observe the user notes in the introduction section when carrying out the exercises. Appropriate information regarding connection method and additional technology can be found in the corresponding data sheets in the appendix.

Practical implementation
Part exercise a)

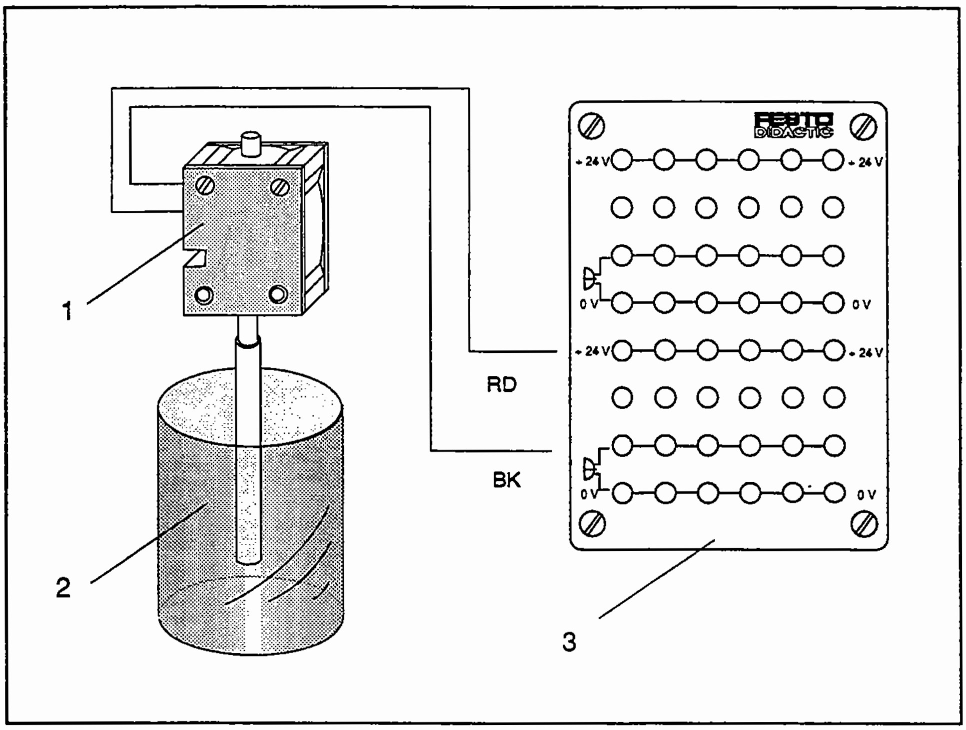


Fig. 14/2: Assembly and electrical connection

Comp. Ref. No.	Qty.	Description	Designation
1	1	Back pressure switch	D.ER-SDS
2	1	Beaker	D.AS-RK
3	1	Distribution plate	D.ER-VERT-SENSOR
	4	Plug-in adapter	D.MP-B-ME-AS

Table 14/1: Component list

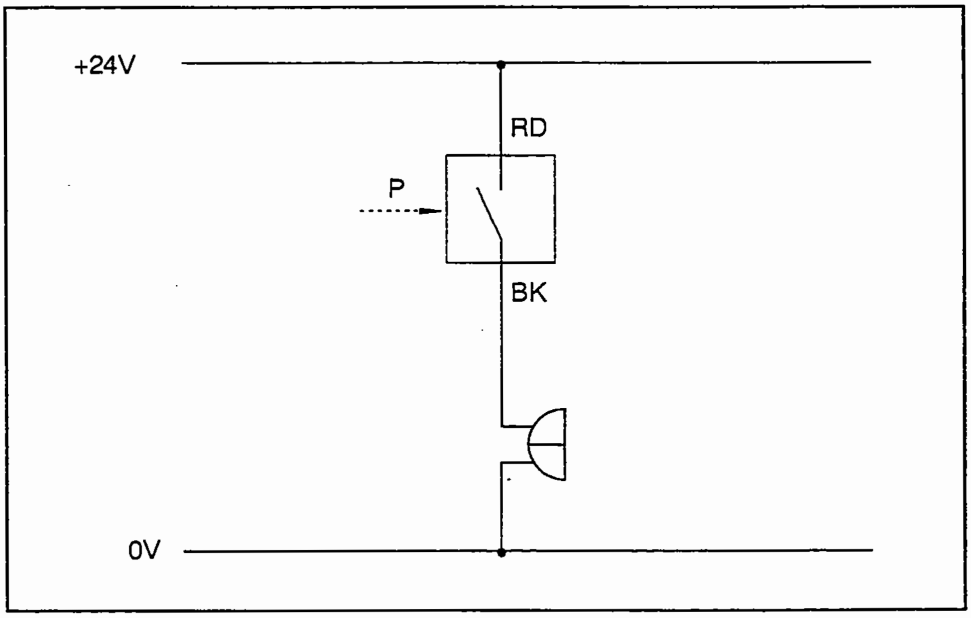


Fig. 14/3: Electrical circuit diagram

Note

The back pressure switch D.ER-SDS contains a normally open contact, which is actuated by means of a pressurised diaphragm. The normally open contact switches the connected voltage signal to the buzzer of the distribution plate. The back pressure switch has a microswitch as a switch contact. A short-circuit will damage the switching contacts if the signal is switched to 0 V and not to the buzzer.

Part exercise b)

- Fill the beaker with water until the tube is immersed up to 5 cm. If necessary, mark the filling level on the beaker.
- If the back pressure switch has switched at this level, the adjusting screw must be turned to the left until the switch resets and the buzzer stops.
- Now turn the adjusting screw slowly to the right until the back pressure switch switches. When the switching point is reached, the buzzer will sound on the distribution plate. Stop turning the adjusting screw immediately after the switching point has been reached.

Checking

- The beaker is emptied prior to checking the setting. Then, the water is slowly poured into the beaker again until the back pressure switch switches. The filling level should now be 5 cm again. If this is not the case, then the setting procedure must be repeated as described above.

Question

What other application possibilities are there for a back pressure switch in the domestic sector?

Fundamentals

Force and force related quantities

1.1 Definition of force

If a force acts on a free moving object, then the state of movement of this object changes. A number of examples can be seen in everyday life:

- a ball is thrown by muscular power
- a car accelerates due to the power of the engine
- a car brakes due to the power of the braking system
- a rocket lifts off due to the thrust of the rocket engine.

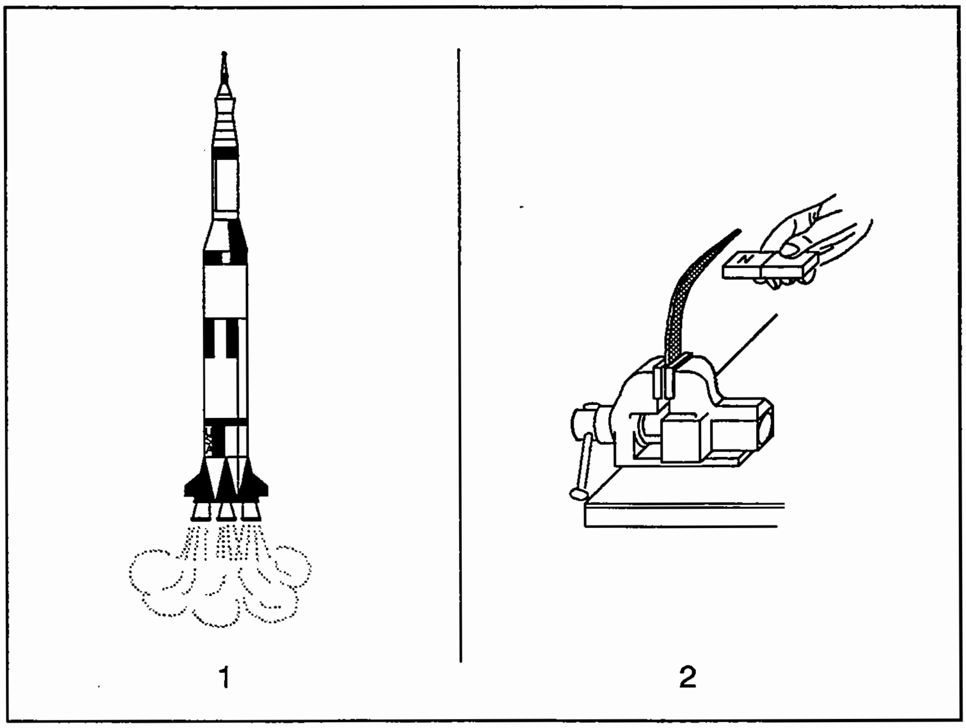


Fig. 1/1: The effect of force

1 Rocket lift-off. For example, the thrust in the initial stage of a Saturn-V rocket is 32 MN (1 MN = 1 Meganewton = 1 000 000 N)
2 The magnetic force of the magnet distorts the leaf spring.

Force is defined according to Newton's second law as the acceleration times the mass of an object *(Isaac Newton, English Mathematician, philosopher of nature and theologean, 1643 - 1727):*

$$F = m \cdot a$$

F *Force*
m *mass*
a *acceleration*

If the object, which the force acts upon, is not moveable, then it is deformed or even broken under the impact of force:

- a flat spring bends under the force of attraction of a magnet
- a sheet of paper is torn
- iron is forged under the force of a hammer.

1.2 Types of force

Everyday experience has taught us that there are many different forms of force. In actual fact, only four elementary types of force are known in physics:

Gravitation

- Gravitation is the term used to describe the mutual attraction of all matter. In general, we experience gravitation as the earth's force of attraction, i.e. any mass possessing object can have weight attributed to it. The fact that weight is not an unchangeable feature of an object, but depends on the gravitational pull exerted on it, is demonstrated by zero-gravity in space or by weight being reduced to a fifth inside the range of attraction of the moon.

Electromagnetic interaction

- Electromagnetic interaction describes the attraction or repulsion of electrically charged particles. Because, in the final analysis, the cohesion of solid objects, the properties of gases and fluids, all chemical and biological reactions and manifestations of heat and light are based on the electromagnetic property of the electron shell of the atom. This is the force, which affects most everyday events.

Strong interaction

- Strong interaction refers to the cohesion of the nuclear particles of a nucleus. It is the source of atomic energy which, on the one hand, comes into effect in an atomic power station and, on the other hand, is utilised in an atom bomb.

Weak interaction

- Weak interaction is responsible for special forms of radioactive disintegration and does not play a significant role in everyday life.

It is not known whether these are all naturally occurring forces or whether they may even originate from one common force. However, in the last few years it has become possible to define electromagnetic force and weak force by means of a common physical theory.

Unit of measurement

The unit of measurement for force is the Newton (N).

A force of 1N accelerates an object of mass 1kg to a speed of 1m/s within 1 second.

An older unit of measurement for force, which does not correspond to the SI international system of units is the kilopond (kp). This is defined as the weight force, which an object of mass 1 kg experiences in the earth's field of gravitation. The following correlation applies:

$$1 \text{ kp} = 9.81 \text{ N}.$$

The correct statement within the framework of the SI units is therefore:
An object of 1 kg mass has a weight of 9.81N on earth.

SI is the abbreviation for *Système International d' Unités*, in English *International System of Measurement.*

The numerical factor in the above equation reflects the gravitational constant $g = 9.81 m/s^2$ of the earth and in many practical applications is rounded up to $10.0 m/s^2$.

Practice-orientated division of forces

In technology, the forces which occur are divided according to application.

- Spring force arises from the elastic deformation of an object.
- A force can be exerted on a piston by expansion of a compressed gas or by fluid under pressure. In a pneumatic cylinder, it is the compressed air and in a combustion engine the combustion gases created when the mixture of petrol and air ignites.
- The force which triggers the switching process in a relay or a contactor is based on magnetic force.
- Friction force brings vehicles to a standstill, and equally retains a nail in a wall.
- Muscular power is created as a result of biochemical reactions, which lead to a contraction of the muscular cells.

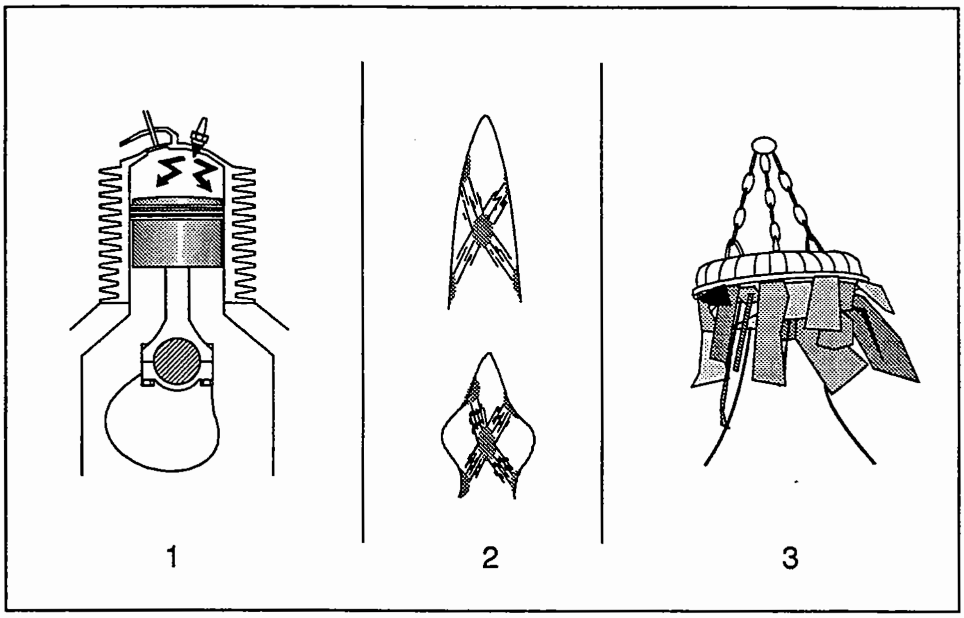


Fig. 1/2: Forms of force

1 *In a combustion engine the explosive force acts down on the piston.*
2 *Muscle power is created by the contraction of muscular cells.*
3 *In this example, magnetic force is used for sorting scrap metal.*

1.3 Force and counterforce

If an object retains its rate of movement despite the action of forces, additional forces have to be applied in order to cancel out these initial forces. Numerous examples of this can be seen in everyday life:

- If an object is held up, its weight is cancelled out due to muscular power.
- The weight of an object presses onto a base, e.g. a table. The base is deformed slightly and as a result develops a counterforce, which cancels out the weight.
- If a vehicle moves at a constant speed, the driving force and the friction forces cancel each other out. The friction forces are made up of the losses in friction in the gear box, the running resistance and the air resistance.

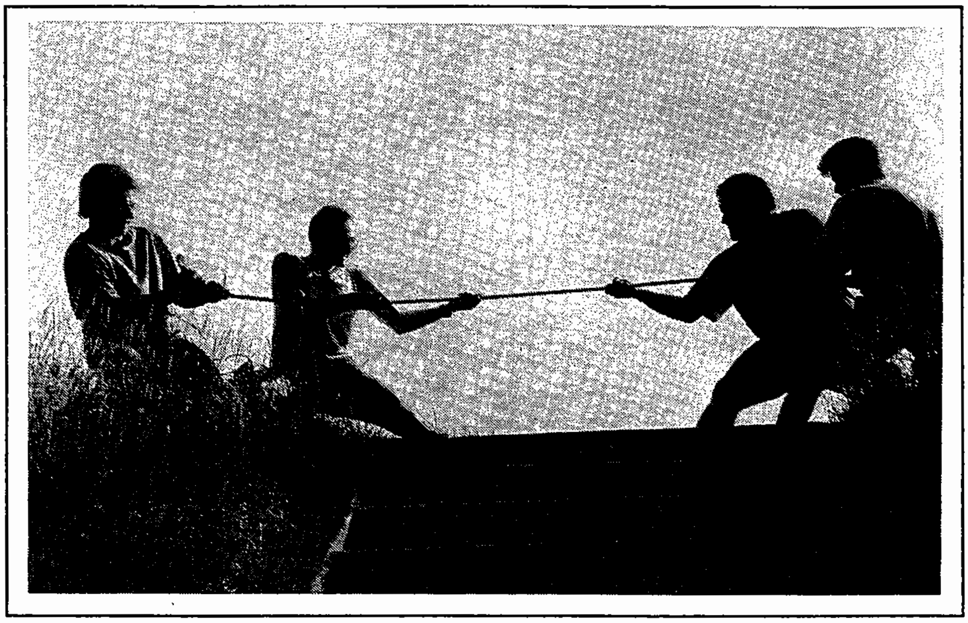


Fig. 1/3: A lot of force and no movement.

A particularly good example is a tug of war between equal opponents. Here, the forces cancel each other out. However, the situation is somewhat more complex, as the forces do not directly act against one another, but are transmitted via a rope which, owing to strain, also develops a counterforce against both teams.

1.4 Elastic and plastic deformation

If an object cannot change its position or, more commonly, its rate of movement, it becomes deformed under the impact of a force. The deformation may be microscopically minute such as in the case of a solid base being compressed under the impact of the weight of an object or more noticably in the case of the deformation of a car in an accident.

Apart from the extent of the deformation, it is important to note whether the deformed object resumes its original shape when the force is removed.

Elastic deformation

This is so in the case of elastic deformation. A well-known example of this is a steel spring.

B 2.2

The change in length of a solid body is proportional to the force acting on it, as described by Hooke's law (*Robert Hooke, English physicist and mathematician, 1635 - 1703*):

$$F = D \cdot s$$

D *Spring constant*
F *Force*
s *distance*

Plastic deformation

In the case of plastic deformation, the object does not revert to its original shape. The material of the object shows signs of yield and, in the case of excessive deformation, cracks. In extreme cases, the object is torn or broken.

Both elastic and plastic deformation can of course occur in the same object. As deformation continues, the initial range is exceeded and deformation becomes plastic.

1.5 Methods of measuring forces

The elastic deformation of an object can be used to measure force. According to Hooke's law, the force is converted into a linear deformation and this linear deformation then becomes the value to be measured.

The simplest type of measuring equipment is the spring balance. The extension of the spring can be clearly seen and can be read on the attached scale. The scale is calibrated in the units (Newton) corresponding to the spring constant (D).

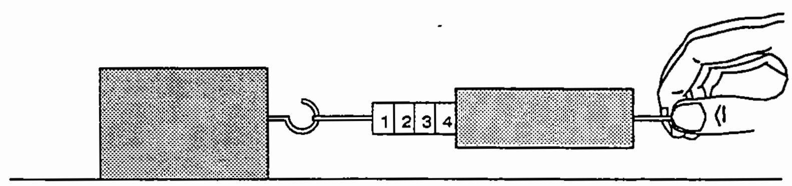


Fig. 1/4: Friction force measured using a spring balance

B 3.2

Also, the force sensors, described later in detail, are based on the same effect. In contrast with the spring balance, the strain or compression of the spring is confined to within a range of 1% of the original spring length and the linear deformation is converted into an electrical signal by means of strain gauges (SG).

It is therefore important to establish, that the strain gauge, – even though it has great significance with regard to measuring technology, – is not the actual sensor, but a combination of a spring component and strain gauge. The strain gauge merely measures a longitudinal change.

Measurement of force on the basis of the elastic deformation of a spring element takes, as is so often in technology, a completely different form to that of its physical definition by means of the change in motion. A measuring device which requires the acceleration of a test object, would indeed not be very practicable.

1.6 Mass

Numerous other physical values, due to their close affinity with force, can also be measured by means of force sensors. These are known as so-called force-related values.

First of all, the mass of an object should be mentioned, as the definition of force using Newton's second law is based on a more fundamental definition of mass.

In practice, the mass of an object is determined by the force of attraction of the earth's gravitational field, i.e. the weight:

$$W = m \cdot g$$

W *Weight force*
m *Mass*
g *Gravitation constant of the earth*

The weighing scales compares the mass of an unknown object with that of a known object.

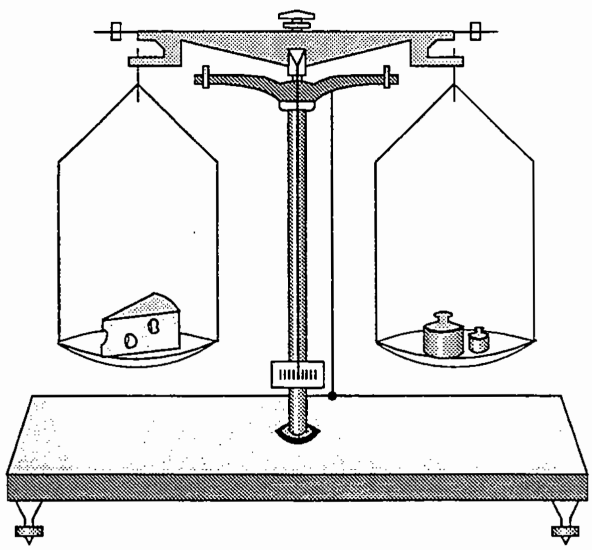


Fig. 1/5: The weighing scales measures masses

It should be noted, that for the weighing scales to function properly as a balance, some gravitational force must be present, its size is unimportant.

Nowadays in practice, mass is determined by measuring the weight using the elastic deformation of a spring element, i.e. in the same way as force measurement. These load cells differ from force sensors only from the way in which the load is applied, which ensures that there is no lateral support, so that the entire gravitational force is recorded. Particular requirements are imposed on load cells by law in certain sectors of the trade by way of the specified method of calibration.

1.7 Pressure

Pressure is a value derived from force. Pressure indicates the action of force per unit area:

$$p = \frac{F}{A}$$

p *Pressure*
F *Force*
A *Area*

The measuring unit for pressure is Pascal (Pa) *(Blaise Pascal, French philosopher, mathematician and theologean, 1623 - 1662):*

$$1\ \text{Pa} = 1\ \frac{\text{N}}{\text{m}^2}$$

Other units are:
1 kp/m2 = 98066.5 Pa
1 bar = 100 000 Pa = 10^5 Pa
1 Torr = 133.32 Pa
1 atm = 101 325 Pa

1 psi = 6 898 Pa (psi is the abbreviation for pound per square inch).

Generally, however, absolute pressure should be specified by the SI unit Pascal. If necessary, the unit 'bar' can be used, which only differs by powers of ten from the Pascal unit. A trend towards using Pascal can be observed in weather forecasts in particular. Whereas previously, air pressure was quoted in millibar, more recently the use of hectopascal has also been adopted, i.e.:

1 mbar = 10^{-3} bar = 100 Pascal = 1 hPa.

The numerical value remains unchanged and the usual order of magnitude is maintained.

Stress

The pressure within solid objects is also known as mechanical stress. Mechanical stress in the elastic range can be determined by measuring the deformation, e.g. by means of embedded strain gauges.
In the majority of cases however, pressure data refers to the pressure within a gas (pneumatic pressure) or a liquid (hydraulic pressure).

Pressure measurement can be divided into three different categories:

Absolute pressure

When measuring absolute pressure, the absolute pressure of the medium is measured in comparison to a vacuum.

Relative pressure

If one of the two mediums is ambient pressure, then this is known as relative pressure measurement.

Differential pressure

However, it is often the pressure difference between two media which is of interest. This is known as differential pressure.

Methods of measurement for pressure

The measurement of absolute pressure in gases or fluids is carried out by measuring the effect of force. As with determining mass, it is possible to compare the effect of the force with a known weight force. This is the principle of measurement, on which the U-tube pressure gauge is based. Inside the U-tube is a fluid, usually mercury. The area above one arm of the U-tube is open to atmosphere and the area above the other arm is exposed to the medium to be measured.

When measuring atmospheric pressure, the column of mercury is raised to approx. 750 mm; this is the method of measurement, from which the outdated mass unit 'mmHg' originates.

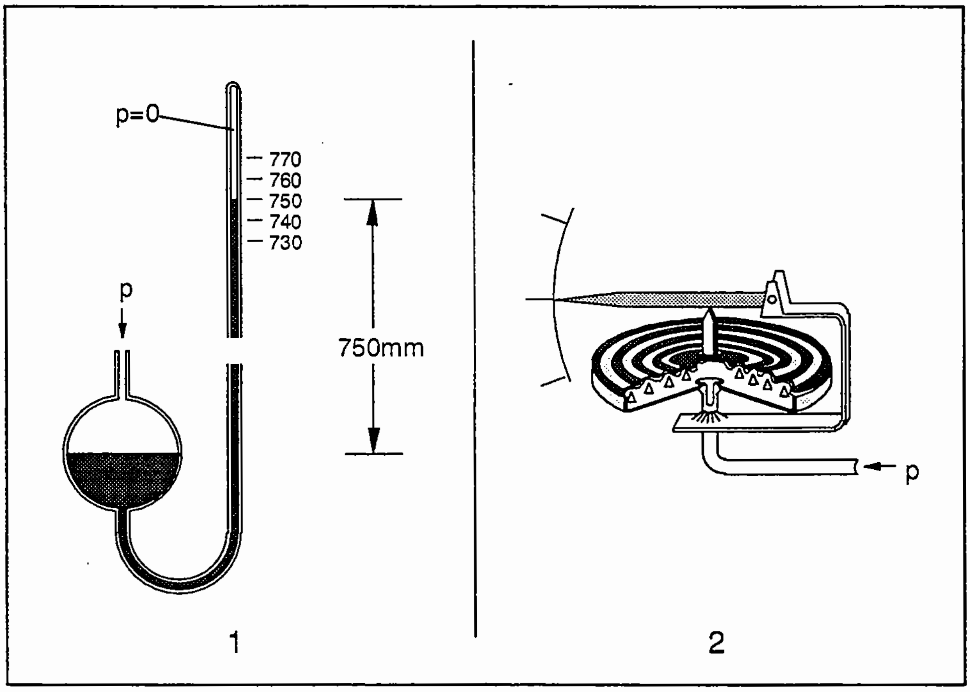


Fig. 1/6: Effects of air pressure

1 Air pressure pushes up a column of mercury to approx. 750 mm
2 The air pressure deforms the diaphragm of the box pressure gauge.

B 7.3

The second method of measurement is based on the elastic deformation of the diaphragm of a dynamometer under the influence of a pressure. This deformation can be transmitted to an indicator or measured electronically by means of a pressure gauge.

1.8 Torque

Torque is defined as a product of the force on a lever arm and the length of a lever arm. Torque does not have its own measuring unit; it is specified by the combined measuring unit Newton meter (Nm).

If a round metal rod is clamped firmly at one end and torque is applied at the other, then the rod is turned around its longitudinal axis. This torsion of the rod also acts in the same way as a spring element and is used in practice (Torsional compliance).

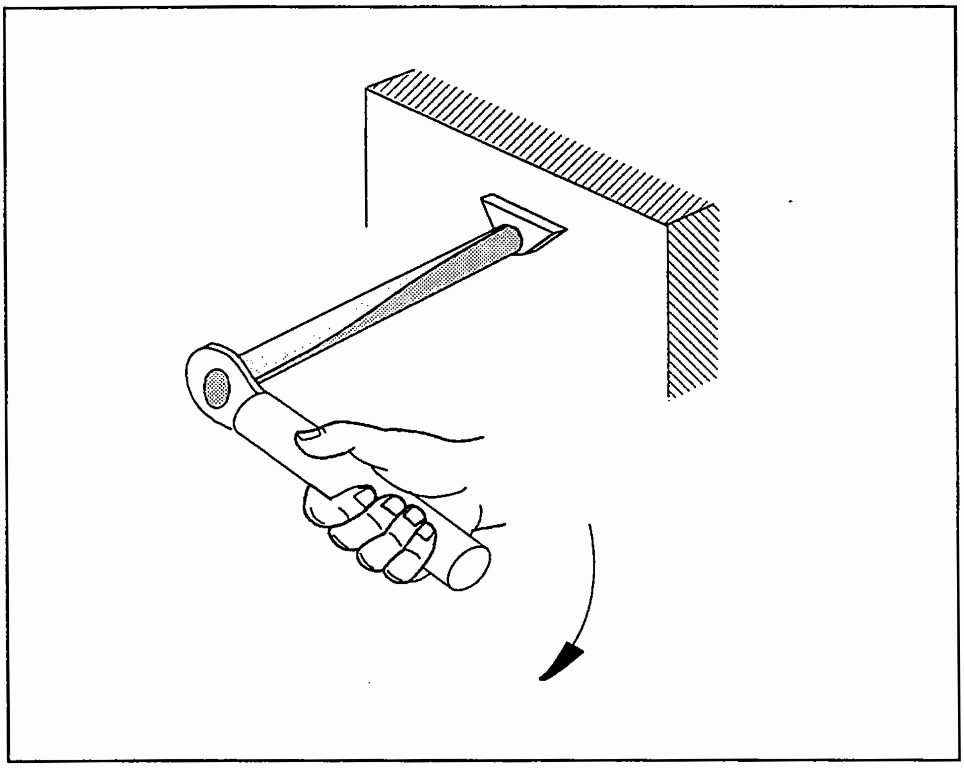


Fig. 1/7: The torque twists the rod

Insofar as the torsion does not exceed the proportional limit of the material, it can be used as a torque gauge. The traditional way of displaying this is by fitting a pointer.

In the case of modern sensors with an electronic output signal, strain gauges are fitted on the surface.

This workbook does not cover torque sensors in any greater detail as, to a large extent, the data concerning force sensors also holds true for torque sensors.

1.9 Acceleration

In accordance with Newton's second law mentioned at the beginning, the relation between force, mass and acceleration is as follows:

$$F = m \cdot a$$

F *Force*
m *Mass*
a *Acceleration*

Acceleration is specified accurately by means of the combined SI measuring unit m/s^2. It has also become common to specify acceleration as a multiple of the earth's gravitational acceleration:

$$g = 9.81\ m/s^2$$

g assumes the role of a measuring unit and must not be confused with the symbol g for the measuring unit of gramme for weight. The measuring unit *g* does not conform to SI.

If a body of known mass is attached to a force sensor, the acceleration can be determined by reading-off the forces. In this way, it is possible to measure acceleration independent from influence of the time and space acceleration process.

In practice, acceleration sensors are therefore also used in the analysis of complex processes of oscillation or statistical impact, which would otherwise not be easily detected, such as for testing in automotive and aircraft industry or for materials testing.

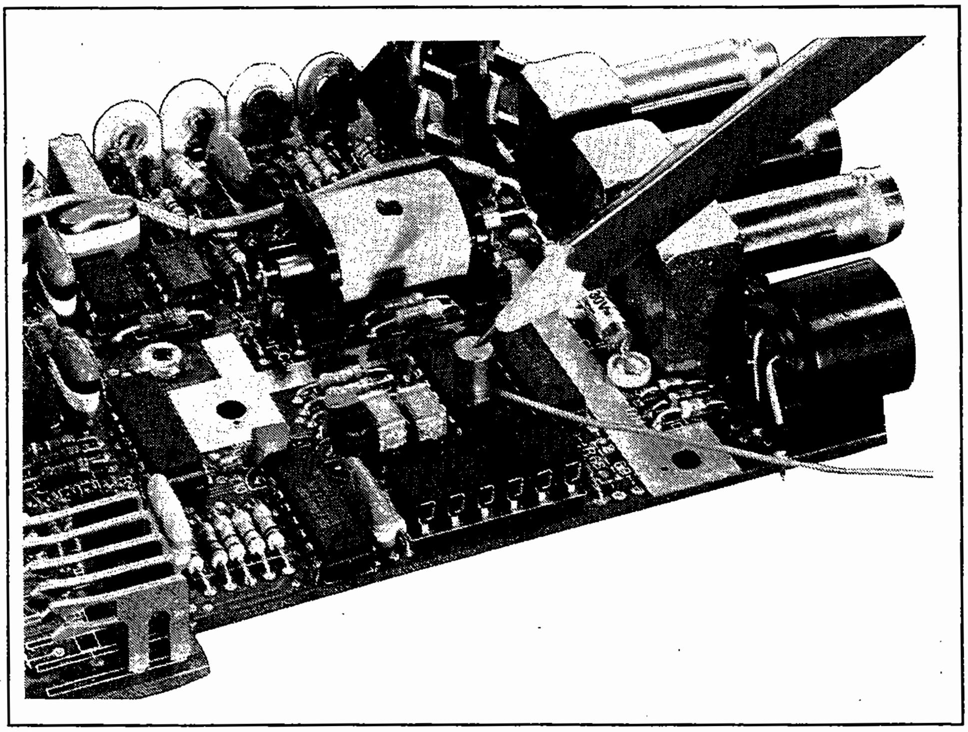


Fig. 1/8: An acceleration sensor is fixed to a printed circuit board during a vibration test. (Photo: Kistler Instrumente GmbH)

Elastic deformation

2.1 Mechanical Stress

If a force acts upon an object which cannot be freely moved, this creates a mechanical stress inside the object (= Pressure) σ:

$$\sigma = \frac{F}{A}$$

F *Force*
A *Area*

Stress in material cannot usually be measured directly by practical means. However, stress produces a strain in a measuring object, which can, for instance, be measured in the form of a longitudinal change on the surface.

The strain ε is defined as a relative longitudinal change in a body:

$$\varepsilon = \frac{\Delta l}{l}$$

Strain ε is non-dimensional. However, in order to clarify the physical origin in the form of two linear dimensions, it is useful to retain cm/m, mm/m, or similar, as a unit of measurement.

Example: A strain of 1% can be indicated as follows:

$$\varepsilon = 0.01 \text{ m/m} = 1 \text{ cm/m}$$

The following does not differentiate between tensile stress and compressive stress. Tensile stress is by definition a positive stress and compressive stress a negative stress. Similarly, no differentiation is made between tension and compression; both are stresses, the first being positive and the latter negative.

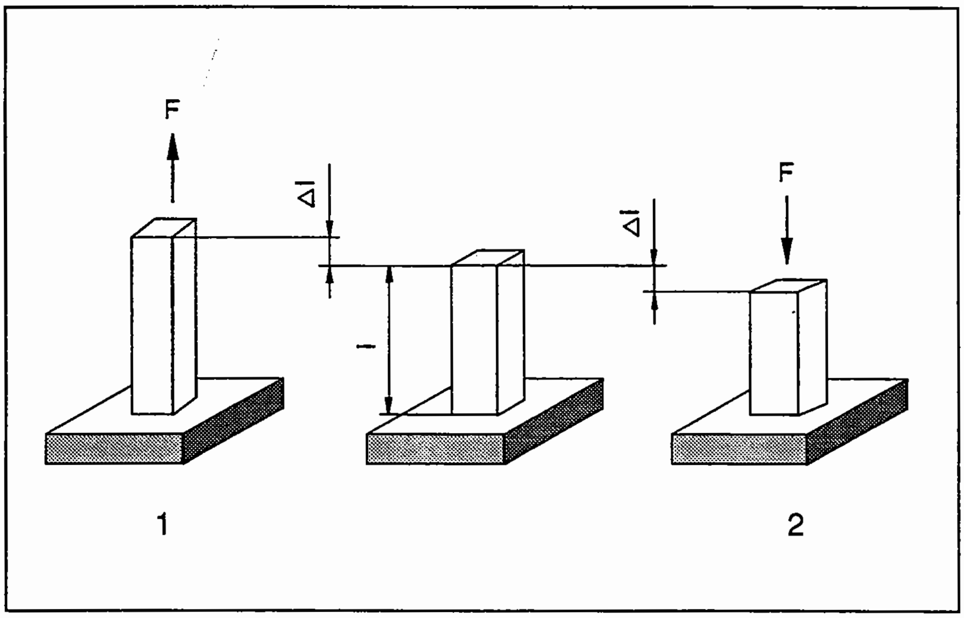


Fig. 2/1: Strain and compression

1 The tensile stress causes elongation.
2 The compressive stress causes a compression.

2.2 Hooke's law

Hooke's law describes the correlation between stress and strain (Robert Hooke, Engl. physicist 1635 - 1703):

$$\sigma = \varepsilon \cdot E$$

E *Modulus of elasticity of object*
ε *Strain*
σ *Stress*

This equation demonstrates the linear relationship between extension and stress. With the exception of a few special cases, the modulus of elasticity *E* is a constant for a given material.

Hooke's law applies only within the range of elasticity. The following illustration demonstrates the relationship between strain ε and stress σ for a tensile test on a steel sample.

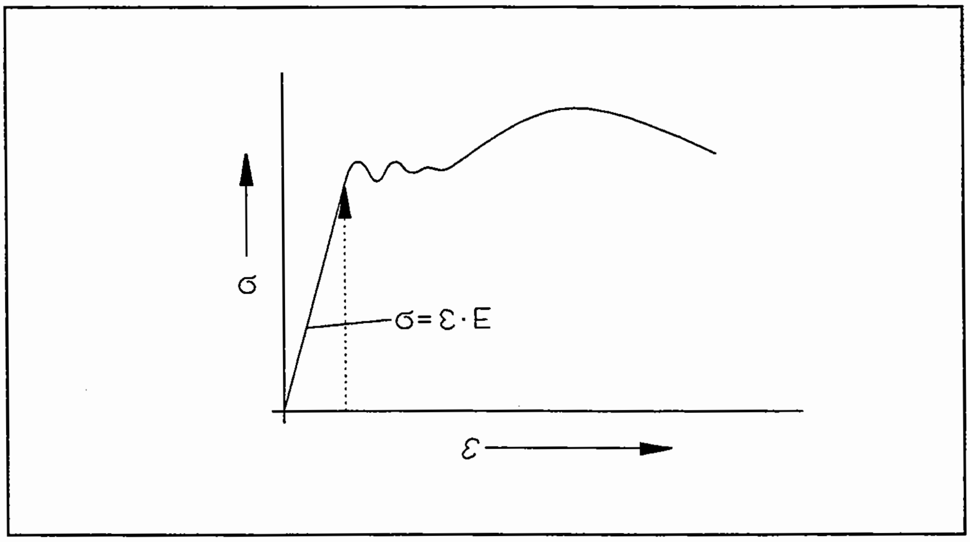


Fig. 2/2: Schematic stress/strain diagram for steel

After an initial linear increase in extension, it then becomes erratic, which is a sign of the material yielding. Once the maximum extension has been reached, the material will break under any additional stress.

Unlike steel, a majority of materials do not display such an obvious transition from the elastic to the plastic range. More often, the elastic and plastic range pass smoothly from one to the other. In such cases, however, deformations are for the most part reversed, but also lead to a permanent change. Such materials are unsuitable as spring elements.

Equally unsuitable as spring elements are materials, which age under a load variation and thereby the limit of proportionality or the modulus of elasticity changes.

2.3 Deflecting arm

The change in size of a rod in the longitudinal sense is used only for force sensors in the area of high forces (100 kN). With low forces, the spring element is constructed differently in order to obtain easily measurable stress. A simple basic component is a deflecting arm clamped on one side (e.g. a cantilever) as used in the experimental section.

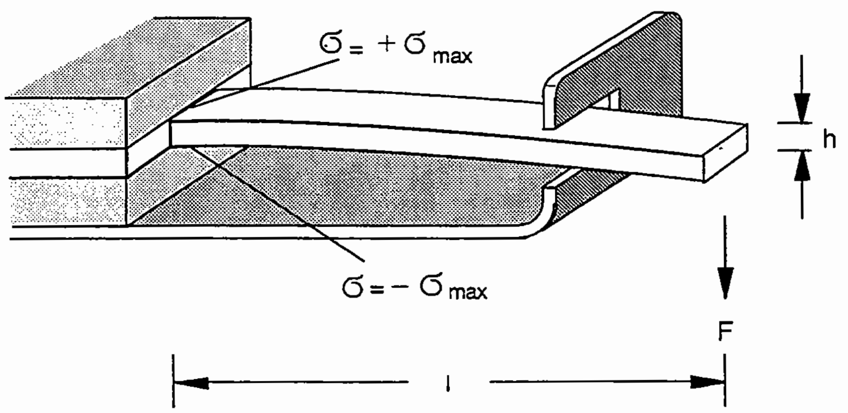


Fig. 2/3: A deflecting arm

If a downward acting force F is applied at the free end, this creates maximum stress at the point of clamping with positive value on the upper side and negative value on the underside. Further examination of the mechanical stress s will be conducted under simplified suppositions:

- rectangular cross-section of deflecting arm
- reduced height *h* of arm compared to length of arm *l*
- reduced travel of free end of deflecting arm compared to length of arm *l*.

A 2

The following focuses on how the extension ε of a deflecting arm depends on the geometrical data (l, h, b) of the arm and the values of the acting forces. The stress at the point of clamping is calculated by means of the following formula:

$$\sigma_{max} = \frac{M_B}{W_B}$$

Taking into consideration numerical values alone, σ_{max} is the same on the upper and lower sides. M_B is the bending moment

$$M_B = F \cdot l$$

and R_B the bending resistance. In the case of the cross section of a rectangular arm (width b, height h)

$$R_B = \frac{b \cdot h^2}{6}$$

Using Hooke's law, the maximum extension at the free end is

$$\varepsilon_{max} = \frac{6 \cdot F \cdot l}{b \cdot h^2 \cdot E}$$

2.4 Torsion rod

The value of torque is established with the help of a torsion rod. A torsion rod is frequently used to determine the torque in drive shafts for example. If the length of the lever arm is known, a torsion rod can also be used to measure force.

A torque M_T on a torsion rod of length l and a radius r leads to a twisting motion Φ:

$$\Phi = \frac{2 \cdot l}{\pi \cdot G \cdot r^4} \cdot M_T$$

G is the torsion or shear modulus of the material.

Similar to a deflecting arm, maximum and minimum strain occur directly on the surface of the spring element. They can be detected by means of strain gauges, which are mounted at ± 45° to the longitudinal axis of the torsion rod. The following applies in respect of strain on the surface of a torsion rod

$$\varepsilon_{max} = \frac{M_T}{R_T \cdot G}$$

R_T is the polar moment of resistance and for a cylindrical torsion rod is obtained by

$$R_T = \frac{\pi}{2} \cdot r^3$$

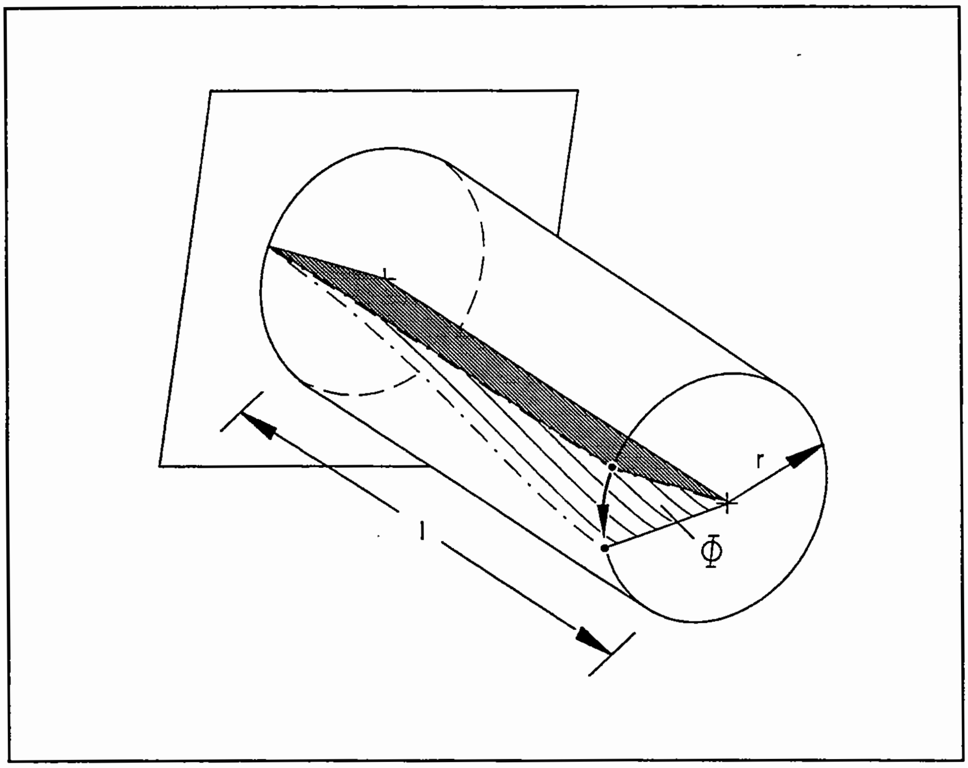


Fig. 2/4: A torsion rod

2.5 Technical design of spring elements

The illustrations below demonstrate a number of technical designs of spring elements. Which type of spring element is used, depends on the purpose of the measurement and magnitude of the forces.

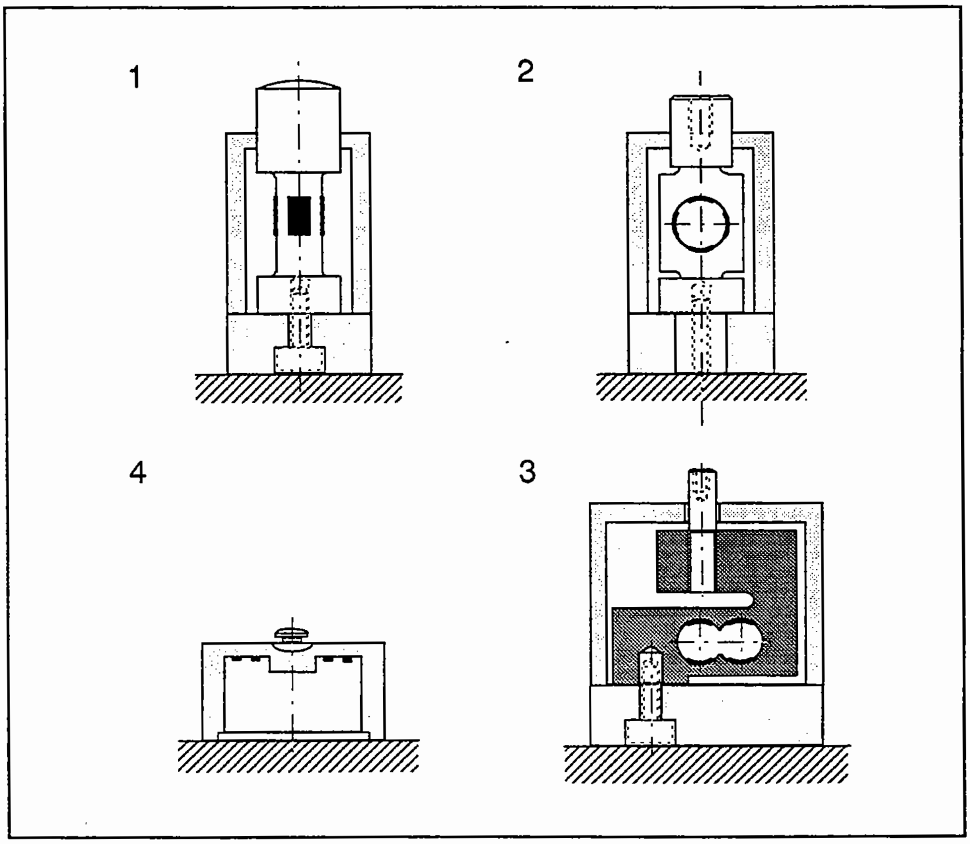


Fig. 2/5: Spring components in the form of force sensors and load cells

1 *Rod-shaped spring component (high nominal loads)*
2 *Ring-shaped spring component (average nominal loads)*
3 *Double deflecting arms (low nominal loads)*
4 *Diaphragm (low nominal loads).*

The positions of the strain gauges are denoted by the thick black lines or black areas.

For extremely high forces (100 kN) a rod-shaped spring element is used. The spring element can also be constructed in the form of a hollow cylinder in order to provide space for a guide rod.

For medium forces (10 to 100 kN), ring-shaped spring elements are used. Under load, the ring is slightly deformed eliptically creating areas with positive and negative strain, which permits the arrangement of strain gauges in a compensating type configuration.

B 4.3

The dual deflecting arm and the diaphragms undergo a wave type deformation under force. Two areas with positive and two areas with negative strain occur, which again can be measured more effectively with a compensating type configuration. Depending on design, the two types cover a wide measuring range for smaller forces.

The force is a set value. In so-called multi-axis dynamometers, the force is split into component forces along specified axis directions which is due to the special construction of the spring element. Fig. 2/6 illustrates such a spring element on the basis of deflecting arms. A total of 16 strain gauges have been fitted, from which the measured values in respect of the forces and torques along the three dimensional axis can be derived.

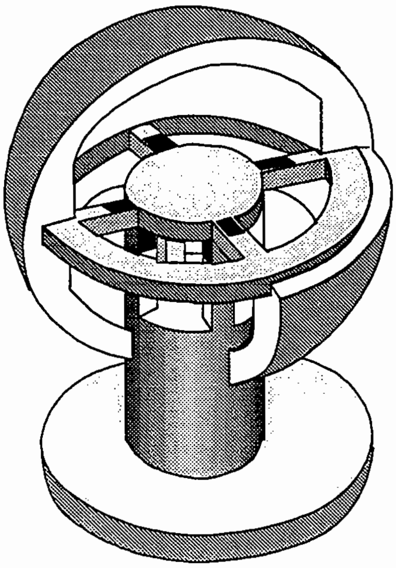


Fig. 2/6: Tactile force/moment sensor based on data by the German Research Institute for Aeronautics and Aerospace Engineering

Additional requirements on the shape of the spring element are:

- hermetically housed force sensor
- explosion-proof design
- trouble-free assembly

Strain gauges and additional force sensors

3.1 Measurement of strain

The strains generated on spring elements in the case of force or pressure sensors are relatively small, e.g. 10^{-6} to 10^{-2} m/m maximum. To illustrate this: A rod 1m long would alter its length in the micrometer range or, in extreme cases, in the millimeter range under such strains. These minor strains occur within the proportional range of Hooke's law.

Prior to the advent of strain gauges (SG), mechanical devices with fitted levers were used to measure very small changes in length. This increased the longitudinal readings by a factor of 1000, whereby these could be read off on a scale. Fig. 3/1 illustrates the tensometer according to Huggenberger.

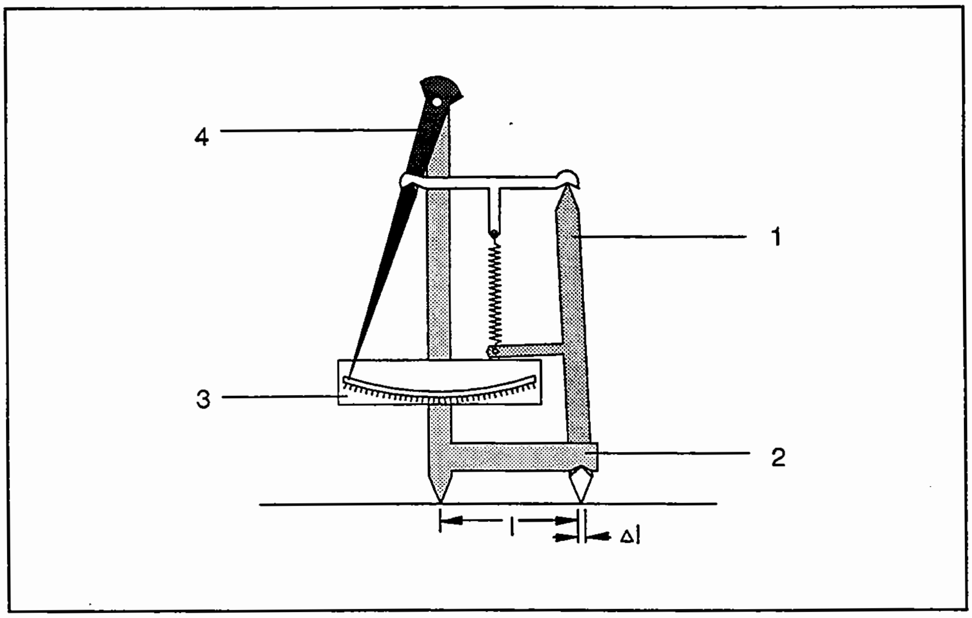


Fig. 3/1: Schematic representation of tensometers according to Huggenberger

1 *Moveable edge with lever*
2 *Body with fixed edge*
3 *Scale*
4 *Lever with pointer*

The measurement of strain with mechanical devices of this type has a number of disadvantages, in particular their sensitivity to vibration.

3.2 Piezoresistive effect

In 1938, the American scientist Arthur Claude Ruge, had the task of examining the strains in a tank under the effect of vibration. Because mechanical measuring methods failed, he attempted to use the piezoresistive effect.

As early as 1843, the English physicist Charles Wheatstone had already mentioned the change in resistance of taut wires in his publication on the well-known bridge circuit. In 1856, William Thomson, – later Lord Kelvin – examined the piezoresistive effect in detail and determined its interrelationships. Fig. 3/2 provides a schematic illustration of the old apparatus.

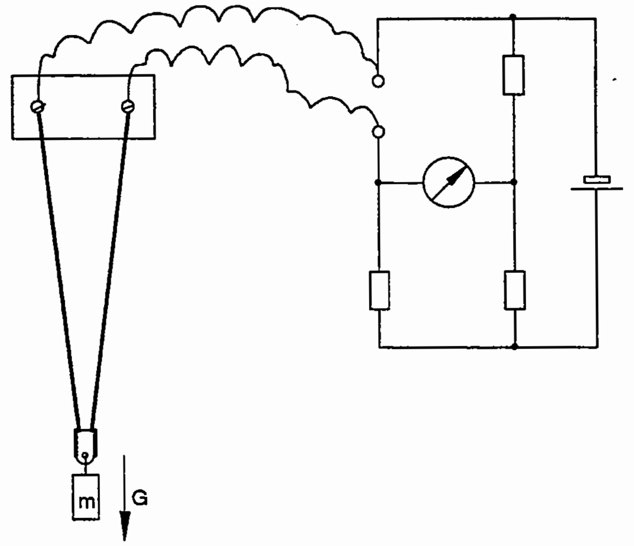


Fig. 3/2: Test configuration to determine the piezoresistive effect according to W. Thomson 1856

The constant wire was strained due to the weight of the mass m and the resistance change was indicated with the help of the Wheatstone bridge circuit.

Ruge fixed a resistance wire in a meander arrangement on a paper base, which in turn was attached to a tank. This constituted the forerunner of the strain gauge (SG) in its current basic form. Due to its success in measuring technology, the strain gauge quickly proved itself useful as a versatile sensor element.

The following observation is based on the premise that the resistance wire is firmly attached to the object in the direction of strain. If the spring element is strained, the wire is also strained to the same extend. A meander-type arrangement of wire in the strain gauge ensures that a considerable length of wire can be accommodated in a small space. The short sections of wire perpendicular to the direction of strain are not taken into account whereas the longitudinal sections are regarded as joined together.

The resistance value R of a wire depends on its length l, the cross sectional area A and the specific resistance ρ, which is an electrical characteristic of the material:

$$R = \rho \cdot \frac{l}{A}$$

B 2.2

All three change according to the strain in the wire. The longitudinal change comes from the definition of strain

$$\frac{\Delta l}{l} = \varepsilon$$

The cross sectional area of the wire is reduced in the case of positive strain (= elongation) and increased in the case of negative strain (= compression). However, the cross-sectional change does not follow the strain to the extent that the volume is maintained. The cross-sectional change is less, which is taken into account by the Poisson factor μ . The Poisson factor for most metals is approximately 0.3. The following applies to the cross-sectional change

$$\frac{\Delta A}{A} = -\mu \cdot \varepsilon$$

The change in specific resistance ρ is denoted by

$$\frac{\Delta \rho}{\rho} = \eta \cdot \varepsilon$$

η is a material constant which depends on the electron density and the electron mobility.

The result for the total change in resistance of a metallic conductor under strain equals

$$\frac{\Delta R}{R} = \frac{\Delta l}{l} - \frac{\Delta A}{A} + \frac{\Delta \rho}{\rho} = \varepsilon \cdot (1 + \mu + \eta) = k \cdot \varepsilon$$

Factor k is an important characteristic value for strain gauges; it is in the region of 2 for most standard alloys.

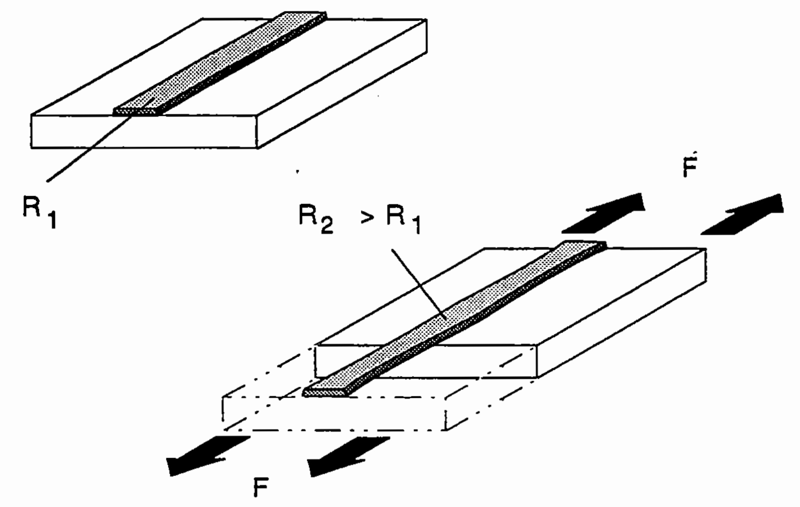


Fig. 3/3: If a strain gauge is extended, the cross sectional area and length of the conductor changes

3.3 Semiconductor strain gauges

In 1954, C.S. Smith carried out tests on the resistive effect of semiconductors. These showed that the change of the specific resistance ρ under strain is considerably greater than that of metallic conductors. The effect is based on the extremely sensitive dependency of the semiconductor bands and therefore the dependency of the electron mobility on the grid distance.

The change in length and the cross-sectional area play only a minor role in the case of semiconductor strain gauges. The resistance change of a semiconductor strain gauge is specified by

$$\frac{\Delta R}{R} = \frac{T_0}{T} \cdot k \cdot \varepsilon + \left(\frac{T_0}{T}\right)^2 \cdot c \cdot \varepsilon^2 \ldots$$

where T_0 represents the reference temperature and T the actual temperature during measurement. Apart from this temperature dependency, the formula also indicates a summand, which is quadratically dependent on the strain ε. The result of this is that the resistance value of the semiconductor strain gauge increases both with tension as well as compression.

Similar to the metallic strain gauges, the k factor is defined as the gradient of the parabola in the operating point $\varepsilon = 0$. If one examines the first addend only at $T = T_0$, this produces a linear relationship between resistance and strain in the form of the tangent shown in fig. 3/4.

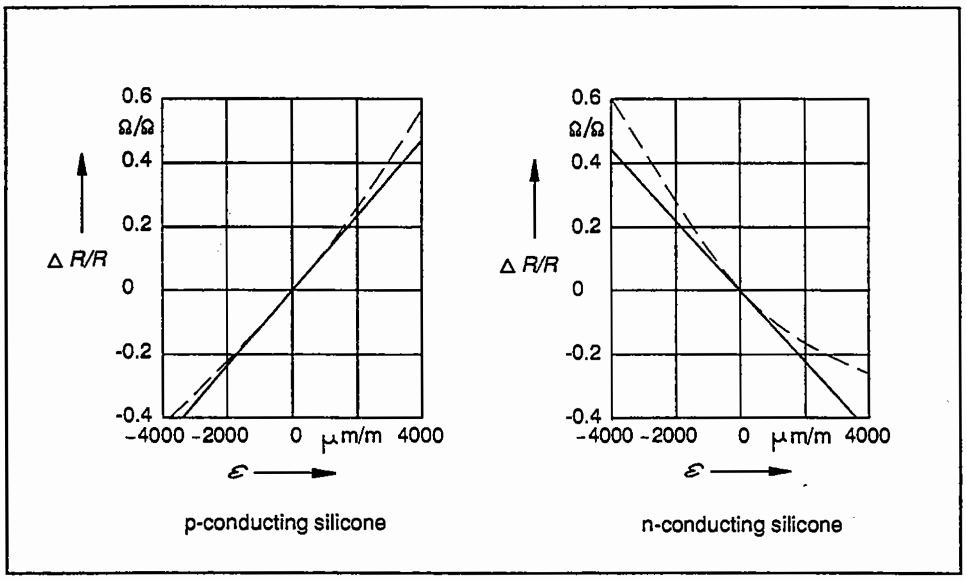


Fig. 3/4: Characteristic curve of semi-conductor strain gauge

The k factor can by virtue of choice of notation be positive as well as negative. Its absolute value is approximately 100.

In comparison with metallic strain gauges, semi-conductor strain gauges have the advantage of a 50 times larger measuring signal. However, there are a series of disadvantages, such as strong temperature dependence and a non-linear characteristic curve. Semi-conductor strain gauges are often used where small dimensions are important. Sensors with semi-conductor strain gauges may partly contain electronic temperature compensation.

B 7.4

3.4 Technical design

Strain gauges (SG) are available in a variety of technical designs. These are divided into wire, foil and semiconductor strain gauges depending on the resistance.

Wire strain gauges

Wire strain gauges consist of a resistance wire, which is attached to a base material. These are used primarily for large surface area strain gauges.

Foil strain gauges

Foil strain gauges consist of a metallic resistance foil, which is attached to a base material and etched in the required form in the same way as circuit boards. The overall size is reduced thus lowering production costs.

Semiconductor strain gauges

Semiconductor strain gauges are diffused into high purity silicon. The method is similar to that used for chip production.

Standard strain gauges

Standard strain gauges are rectangular in shape. The active grid surface provides a measure of the sensitivity. Square strain gauges are used to measure strains at a point. Elongated strain gauges are used if strain is to be determined over a wider area. This is rarely the case with transducer designs, but is more likely required for material testing on non-homogeneous structures, e.g. concrete.

Special and multiple strain gauges

The numerous types of special strain gauges are due to the special characteristics of their applications. On the right of fig. 3/5, one such special strain gauge is illustrated. This particular type is made up of four individual strain gauges and was selected so as to ensure optimum measurement of the deformation of the circular diaphragm in a pressure sensor.

Resistance value

The resistance value of strain gauges is usually around 120, 350 or 600 Ω.

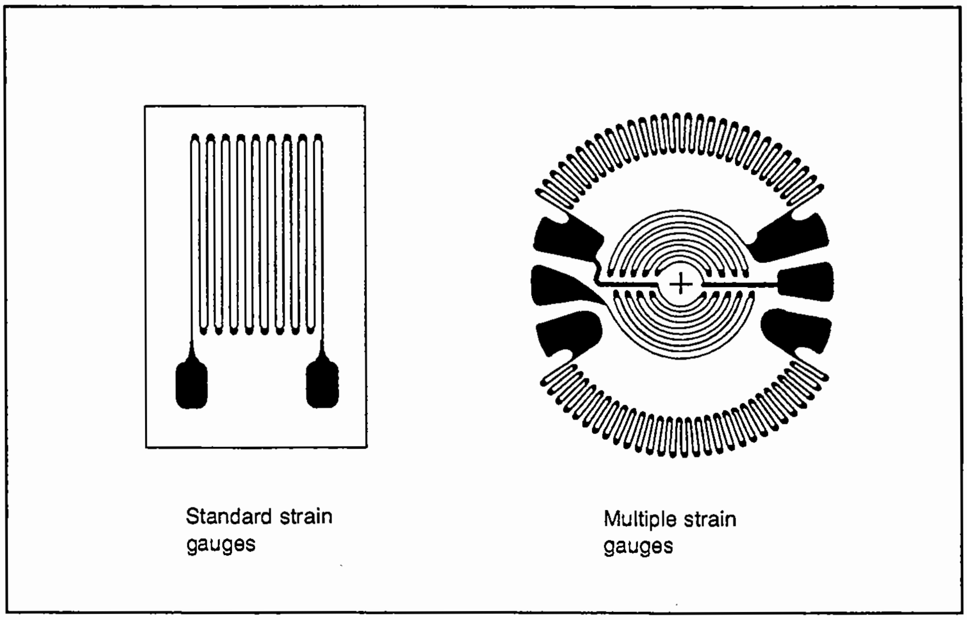


Fig. 3/5: Construction of a strain gauge

3.5 Application of strain gauges

Strain gauges (SG) are usually linked to the base material in such a way that its total strain is transmitted to the strain gauge.

Attachment by means of adhesives

The standard method of attachment is by synthetic adhesives. Industry provides special dual-compound adhesives for strain gauges, which are derived from adhesives in general use. Cold setting adhesives are easy to use. They cover a temperature range between approximately -200° to +100 °C. For transducers, the temperature range of -10° to +40 °C should not be exceeded in order to avoid any loss in accuracy.

Heat-setting adhesives cover a temperature range of -250° to +300 °C. This requires the base and the strain gauge being placed in a heating furnace which, though possible when mounting force sensors, is often not practicable in the case of larger structures to be measured.

For quick tests, strain gauges can also be fitted using single-component adhesives based on cyanoacrylate "instant adhesives".

With all types of adhesives, care should be exercised in applying the adhesive in a thin bubble-free layer.

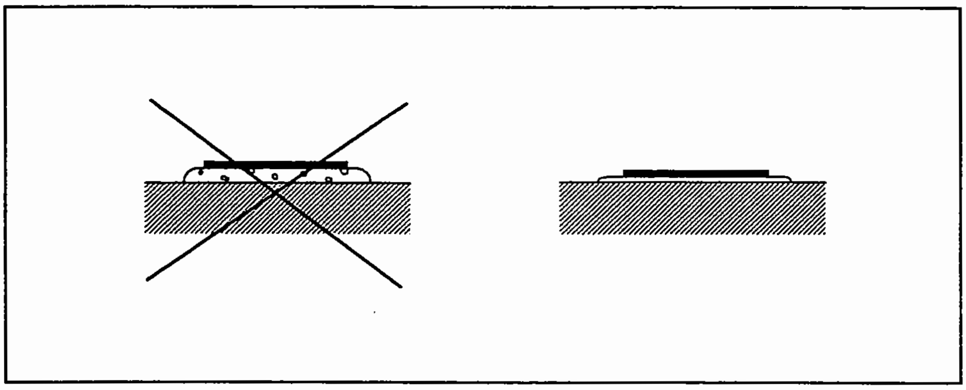


Fig. 3/6: Assembly precautions

Embedding in ceramics

Even higher temperature ranges can be reached by embedding strain gauges without a base, so-called free-grid strain gauges, in ceramic bonding agents. Once the ceramics have been fired, the strain gauge can be exposed to a temperature of up to 500 °C. Ceramics emit less gas in high vacuum than plastics.

Welding

The welding of strain gauges specifically designed for this purpose, by means of the spot welding method, is a relatively simple procedure. The temperature limits depend purely on the strain gauge. However, the weldable foil at the base has a very high rigidity, therefore application is limited to that of thick-walled objects.

Housing

Strain gauges (SG) must be covered with a coating of varnish in order to protect them from environmental effects. However, a layer of varnish offers only limited protection. In the case of measuring sensors, strain gauges are therefore enclosed in a hermetically sealed sensor housing.

3.6 Additional force sensors

Apart from strain gauges (SG), other sensor elements are also used in the construction of force or related sensors.

Piezoelectric sensors

Some materials, such as quartz or turmalin, display a piezoelectric effect. Under stress along specified crystal axes, a charge builds up at the ends of the crystal. The surface density of the charge is proportional to the stress and is measured by means of a charge sensitive amplifier.
Piezoelectric sensors have the advantage of combining spring elements and sensor elements and as such possess a reduced mass and the ability to register rapidly ocurring processes. The high rigidity of quartz permits trouble-free measurement. The main disadvantage is the charging signal. Strictly speaking, this merely permits the measurement of changes in charge as a result of load variation. Therefore, static loads can only be measured with a piezoelectric sensor within a time limit, because with time the charge generated is used up by even the slightest current flows. The current flows are created due to imperfect insulation resistances or drift of the pre-amplifier. For this reason, piezoelectric sensors are used mainly in fast operating processes such as oscillation and pulse analyses.

Inductive Sensors

With inductive force sensors, the change in length of a spring element is transmitted as displacement to the core of a coil. Through the varying depth of imersion of the core, the oscillation circuit, of which the coil forms part, is mistuned.
The electrical signal of the oscillation circuit can be evaluated and displayed according to the principle of a differential transformer and displayed. Inductive force sensors therefore operate according to the same operational principle as inductive displacement sensors.

Magnetoelastic sensors

On so-called magnetoelastic sensors, the core of the spring element itself alternates, being either extended or compressed. The change in form causes a change in the inductivity of the coil.

Capacitive sensors

In the case of capacitive pressure sensors, a membrane in the pressure sensor is used as an electrode of a plate capacitor. The deflection of the diaphragm changes the capacity of the capacitor, which can be electronically evaluated.
Domestic bathroom scales often operate according to the principle of capacitive force sensors. The weight is introduced onto deflecting arms; their movement slightly alters distance between two capacitor plates, and the resulting change in capacity is evaluated electronically.

Acquisition of measuring data

4.1 Measuring chain

Sensors alone do not constitute a means of acquiring measured data. Fig. 4/1 illustrates the area immediately surrounding a sensor in the form of a measuring chain. This includes the coupling of the sensor to the process (1), the actual sensor (2), the signal evaluation circuit (3), the supply of auxiliary power (6), the signal amplification (4) and signal recording (5).

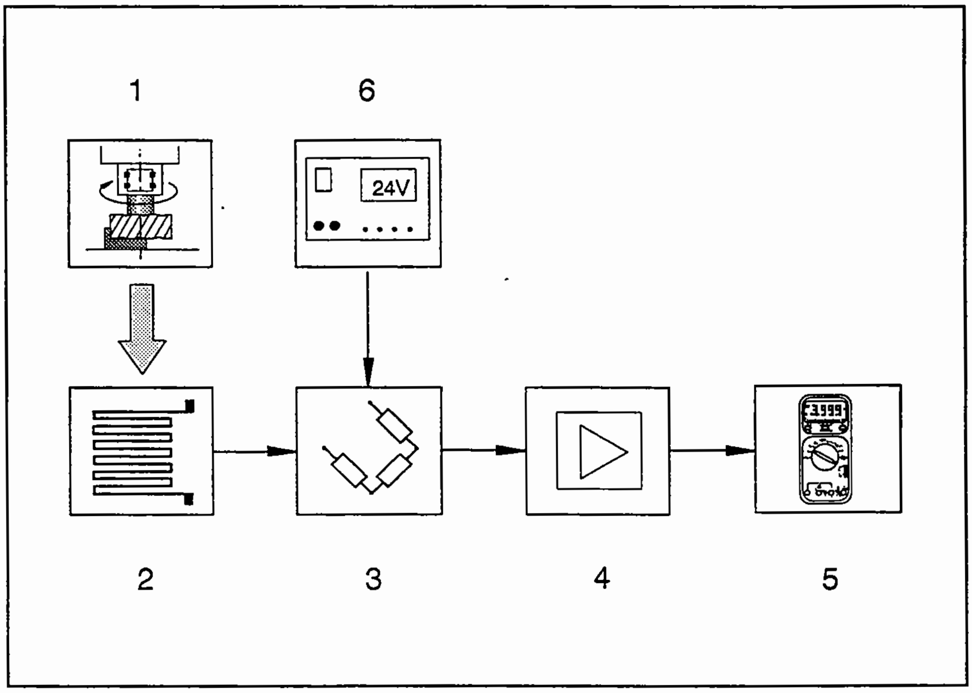


Fig. 4/1: Measuring chain

Strain gauges (SG) are passive sensors as they are not capable of providing an electrical signal. Here, we shall examine in detail the conversion of a resistance change in a strain gauge into a voltage signal with the help of a Wheatstone measuring bridge.

The above illustration shows a Wheatstone measuring bridge (3) in the form of a quarter-bridge, i.e. only one of the four resistors is a sensor. In the half-bridge circuit two resistors are sensors and in the full-bridge circuit all four resistors are sensors.

The use of several sensors in a bridge circuit means that the effects of interference can be compensated for. Temperature drift is a possible source of interference. Often, multiple strain gauges are already arranged into semi- or full-bridge circuits.

4.2 Wheatstone measuring bridge

The Wheatstone measuring bridge consists of two voltage dividers for the input voltage V_I, consisting of resistors R_1 and R_4 as well as R_2 and R_3.

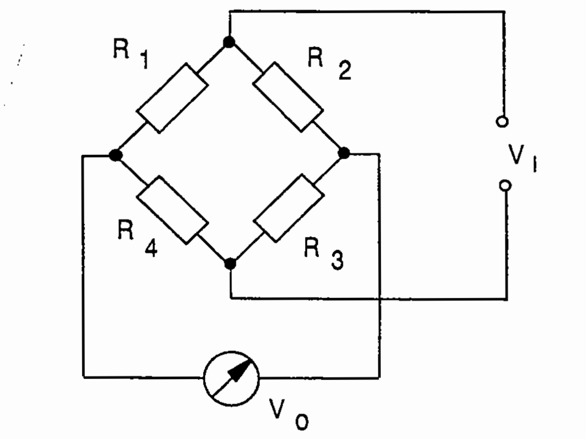


Fig. 4/2: The Wheatstone bridge circuit

The output voltage V_O is measured across the corner points (R_1 / R_4) and (R_2 / R_3)

$$V_O = \frac{R_1}{(R_1 + R_4)} \cdot V_I - \frac{R_2}{(R_2 + R_3)} \cdot V_I$$

$$\frac{V_O}{V_I} = \frac{(R_1 \cdot R_3 - R_2 \cdot R_4)}{((R_1 + R_4) \cdot (R_2 + R_3))}$$

The bridge is balanced, i.e. $V_O = 0$, if R_1 and R_4 are equal to R_2 and R_3

$$\frac{R_1}{R_4} = \frac{R_2}{R_3} \quad or \quad R_1 \cdot R_3 - R_2 \cdot R_4 = 0$$

The equation shown on the righthand-side contains just the numerator shown in the preceding equation. The bridge is accurately balanced, if all four resistors are of equal size.

A 3

The following examination is based on a balanced bridge. In practice, it will not be possible to set up precisely this arrangement, which is why measuring amplifiers have a separately adjustable zero point adjustment for V_O. However, the assumption does not invalidate the result, but simplifies the examination. Furthermore, one should proceed on the basis that the bridge output is not loaded, V_O will therefore be measured with a measuring instrument of very high internal resistance. On the basis of the balanced status, R_1 to R_4 should change slightly. This applies to strain gauges (SG), as the resistance change is based on minor strains.

B 3.2

$$\frac{\Delta R}{R} = k \cdot \varepsilon$$

If higher order terms are neglected, the following is obtained after conversion

$$\frac{V_O}{V_I} = \frac{1}{4}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right)$$

Quarter-bridge

In a quarter-bridge circuit R_1 acts as the strain gauge. The remaining resistors are fixed resistors, i.e. $\Delta R_2 = \Delta R_3 = \Delta R_4 = 0$. The above equations equal

$$\frac{V_O}{V_I} = \frac{k}{4} \cdot \varepsilon$$

Accordingly, a half- bridge circuit with R_1 and R_2 as strain gauges gives

$$\frac{V_O}{V_I} = \frac{k}{4} \cdot (\varepsilon_1 - \varepsilon_2)$$

This is based on the assumption that both strain gauges have the same k factor, i.e. are of the same design.

Full-bridge

The corresponding result regarding a full-bridge circuit with four strain gauges of identical k factor is

$$\frac{V_O}{V_I} = \frac{k}{4} \cdot \left(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4\right)$$

The following important rule can be deduced from the equation:

Changes in value of two adjacent strain gauges in the bridge circuit are subtracted.
Changes in value of two opposing strain gauges in the bridge circuit are added.

From this, it is possible to derive ways of boosting the output signal and of suppressing interference signals.

4.3 Compensating the effects of interference

The measuring signal of a strain gauge is not just based on the strain of the spring element. Other physical values such as temperature, humidity, ambient pressure, magnetic fields or nuclear radiation all influence the result.

Let us take the frequently occurring case of temperature change as a typical example of interference. To simplify matters, it is assumed that temperature change results in a thermal volumetric expansion and thus causes an expansion ε_T in the direction of measurement. This is superimposed on the actual strain ε_M caused by mechanical deformation:

$$\varepsilon = \varepsilon_M + \varepsilon_T$$

$$\frac{\Delta R}{R} = k \cdot (\varepsilon_M + \varepsilon_T)$$

A 5

Two strain gauges are used in order to carry out interference-free measurements.

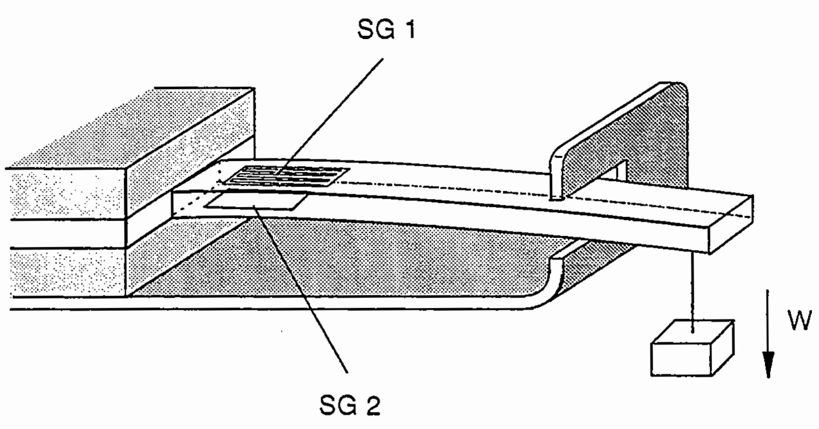


Fig. 4/3: Temperature compensation using two strain gauges

These are placed on the spring element so that they are subject to an identical amount of strain, but in opposing directions.

$$\varepsilon_{M_1} = -\varepsilon_{M_2} = \varepsilon_M$$

However, as regards proximity, both strain gauges are subject to the same temperature effects, hence

$$\varepsilon_{T_1} = \varepsilon_{T_2} = \varepsilon_T$$

The two strain gauges are connected to adjoining branches of a half-bridge. The effective signal equals:

$$\frac{V_O}{V_I} = \frac{k}{4} \cdot ((\varepsilon_{M1} + \varepsilon_{T1}) - (\varepsilon_{M2} + \varepsilon_{T2}))$$

$$\frac{V_O}{V_I} = \frac{k}{4} \cdot (\varepsilon_M + \varepsilon_T + \varepsilon_M - \varepsilon_T)$$

$$\frac{V_O}{V_I} = \frac{k}{2} \cdot \varepsilon_M$$

The result shows that the effective signal due to mechanical strain was doubled, while the interference signal due to temperature change was eliminated.

As illustrated by the example, compensating the effects of interference requires the careful placing of the strain gauge on to the spring element. The examples illustrated below are suggestions for different areas of application.

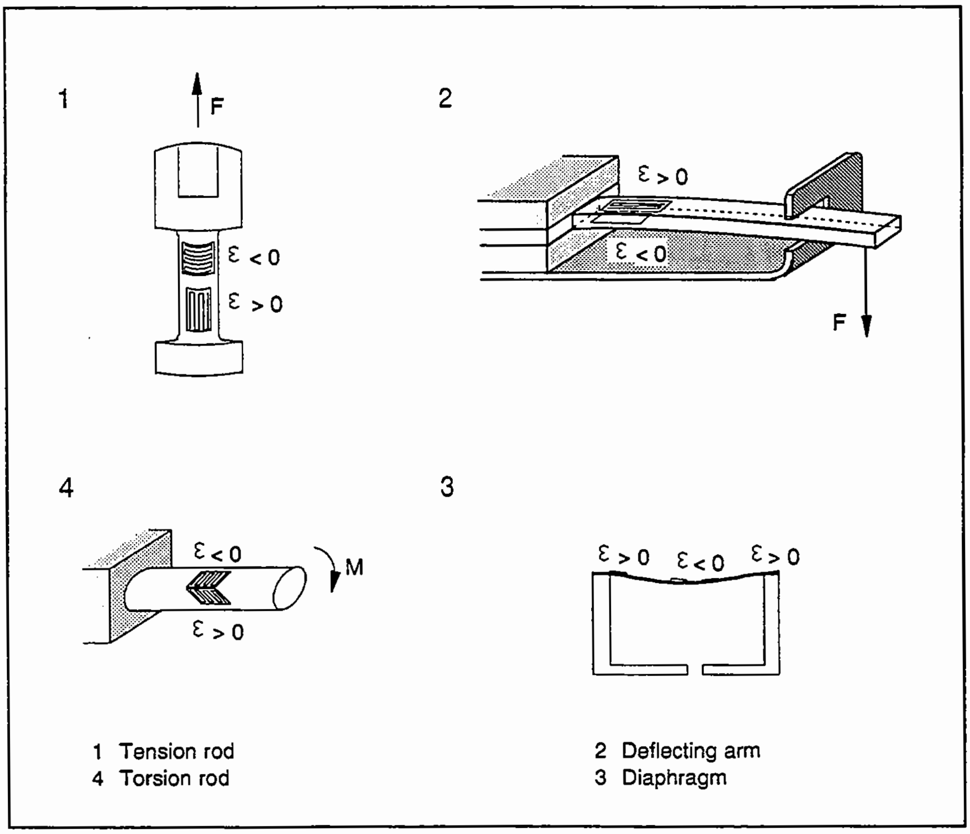


Fig. 4/4: Compensating configurations of strain gauges

4.4 Elimination of line interference

The interconnecting cables between the strain gauge (SG) and Wheatstone bridge have a slight, though not insignificant resistance, which increases in line with the cable length. In addition, the resistance of the cable depends on the temperature.

Measuring cable in a full bridge circuit

With a full bridge circuit (see Fig. 4/5), all four resistors of the bridge belong to the sensor in the form of strain gauges. It can be assumed that they are connected via short lines. In the case of multiple strain gauges, the bridge structure is in fact part of the strain gauge. Interference as a result of these connections can therefore be largely discounted.

The cables supplying bridge voltage V_I act as series resistors, through which part of the bridge voltage drops. This results in a reduced bridge voltage V_{IC}

$$V_{IC} = V_I \cdot \frac{R_B}{(R_B + R_{C_2} + R_{C_3})}$$

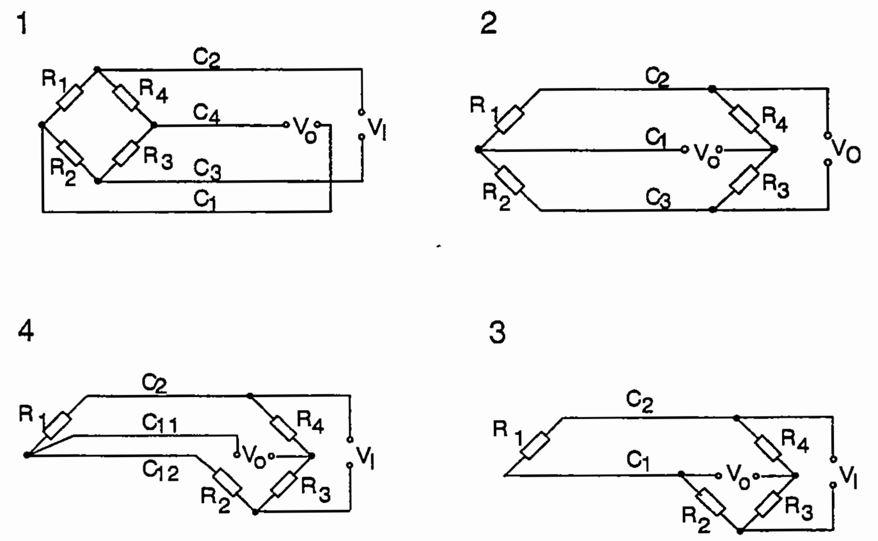
This leads to a reduction in the sensitivity of the bridge

$$\frac{V_O}{V_I} = \frac{k}{4} \cdot (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4) \cdot \frac{R_B}{(R_B + R_{C_2} + R_{C_3})}$$

whereby R_B is the bridge resistance

$$R_B = \frac{(R_1 + R_2) \cdot (R_3 + R_4)}{(R_1 + R_2 + R_3 + R_4)}$$

With four roughly identical bridge resistors $R_1 \approx R_2 \approx R_3 \approx R_4 \approx R$, the bridge resistance is approximately $R_B = R$. The resistances of the cables running to the measuring device, R_{C_1} and R_{C_4}, are in series to its high value input resistance and therefore are not significant.



1 Full bridge
2 Half-bridge
4 Quarter-bridge in three-wire technology
3 Quarter-bridge in two-wire technology

Fig. 4/5: Cable connections in bridge circuits

Measuring cable in a half-bridge circuit

In the half-bridge circuit, cable connections exist between the strain gauges and the fixed resistors. These are part of the bridge and can in some instances have an effect on the result. However, if the two strain gauges are used in a compensating configuration, then equal resistance changes of the connecting cables C_2 and C_3 are compensated for. To do this, they should be made of identical material and exposed to the same environmental conditions.

The resistance of the cables acts as a series resistor to the strain gauges thus reducing their sensitivity. If the resistance value R of the two strain gauges as well as the resistance value R_C of both cables is equated, this becomes

$$\frac{V_O}{V_I} = \frac{k}{4} \cdot (\varepsilon_1 - \varepsilon_2) \cdot \frac{R}{(R + R_C)}$$

The resistance of cable C_1 is not critical, as this leads to a high impedance measuring amplifier input.

Measuring cables in a quarter-bridge circuit

With two-wire technology, as illustrated in fig. 4/5, interference and resistance changes in the cables directly affect the result because they are in series to the strain gauge.

It is possible to compensate for this by using three-wire technology, because cable C_2 lies in the bridge branch of R_1 and cable C_{12} in the bridge branch of R_2. An identical amount of resistance change and interference in these two cables is cancelled out due to the fact that they are located in adjacent bridge branches. The sensitivity of the strain gauge is reduced by the resistance value R_C of the two cables

$$\frac{V_O}{V_I} = \frac{k}{4} \cdot \varepsilon \cdot \frac{R}{(R + R_{C_2})}$$

As with the half-bridge, no particular demands are placed on cable C_{11}, as it leads to the high resistance measuring amplifier input.

Compensating strain gauge

If, for reasons of space or for any other reason, it is not possible to fit a minimum of at least two strain gauges in a compensating configuration on the spring element, a quarter-bridge circuit should be used. This can be improved by means of a compensating strain gauge. The compensating strain gauge is of the same type as the actual strain gauge. It is fitted on a section which is not exposed to mechanical stress, though displaying roughly the same temperature characteristics. The two strain gauges are connected to adjacent branches of the bridge circuit. In this way thermal effects are eliminated in the same way as with the half-bridge circuit, but duplication of the signal does not take place. The use of compensating strain gauges requires three-wire technology.

4.5 Industrial force sensors

In industrial force sensors the possibilities of compensation are explored fully and even expanded by means of the Wheatstone bridge circuit. Fig. 4/6 illustrates the connection of four main strain gauges in one force sensor. The bridge circuit is expanded with the addition of further correcting strain gauges, temperature-dependent resistors and fixed resistors.

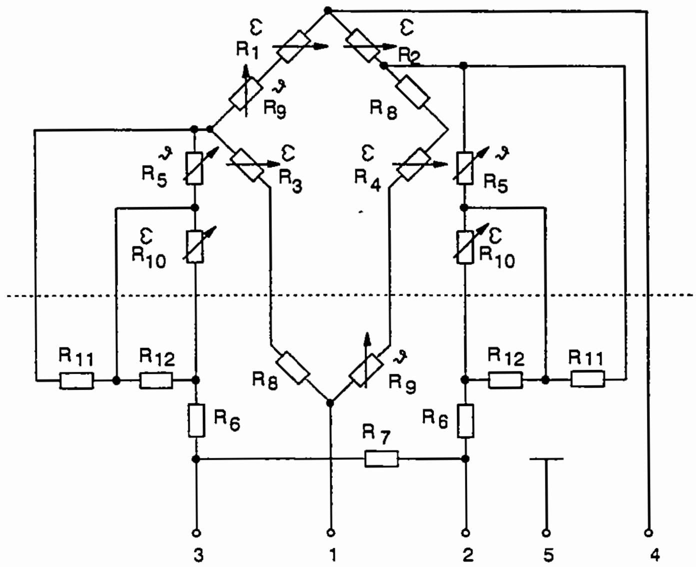


Fig. 4/6: Circuit diagram of an industrial force sensor (based on data by Hottinger Baldwin Messtechnik)

The following denote:

R_1 - R_4	Strain gauges
R_5, R_{11}	Temperature compensation of sensitivity
R_6	Adjustment of sensitivity (Calibration)
R_7	Resistance compensation of input
R_8	Bridge zero-balance
R_9	Temperature compensation of zero point
R_{10}, R_{12}	Linearity correction

The elements above the broken line are located on the actual spring element and the elements below the line in the terminal box.

The supply voltage (V_I) is connected to points 2 and 3 and the measuring signal (V_O) is derived from connections 1 and 4. Connection 5 is joined to the cable shielding and, in the case of some force sensors, also to the housing of the force sensor.

4.6 Measuring amplifiers

In general, the Wheatstone measuring bridge, owing to the variation in its components, be it the strain gauges or the fixed resistors, will never be exactly balanced even in the normal state. This does not affect the accuracy of the result for minor deviations.

Zero-balance

However, this factor does require the continuous subtraction of a quiescent value. In order to achieve more easily readable measuring values, measuring amplifiers offer the possibility of zero-balance adjustment. The zero-balance is set in such a way that, in the unloaded state of the sensor, the value 'Zero' is displayed at the output of the measuring amplifier. Some measuring amplifiers automatically carry out a zero-balance 'at the push of a button'. With zero-balance, the quiescent value is subtracted electronically in the measuring amplifier.

Amplification

The measuring amplifier amplifies the voltage signal of the Wheatstone measuring bridge, which is generally in the millivolt range, e.g. by a factor of 2000 into the volt range. It should be noted, that an incomplete zero-balance in conjunction with such a high amplification can lead to a restricted measuring range. The amplifier cannot amplify the signal beyond its operating limits as determined by its voltage supply. In the case of devices with very high amplification which can be adjusted in stages, the zero-balance must therefore be corrected prior to each stage of increased amplification.

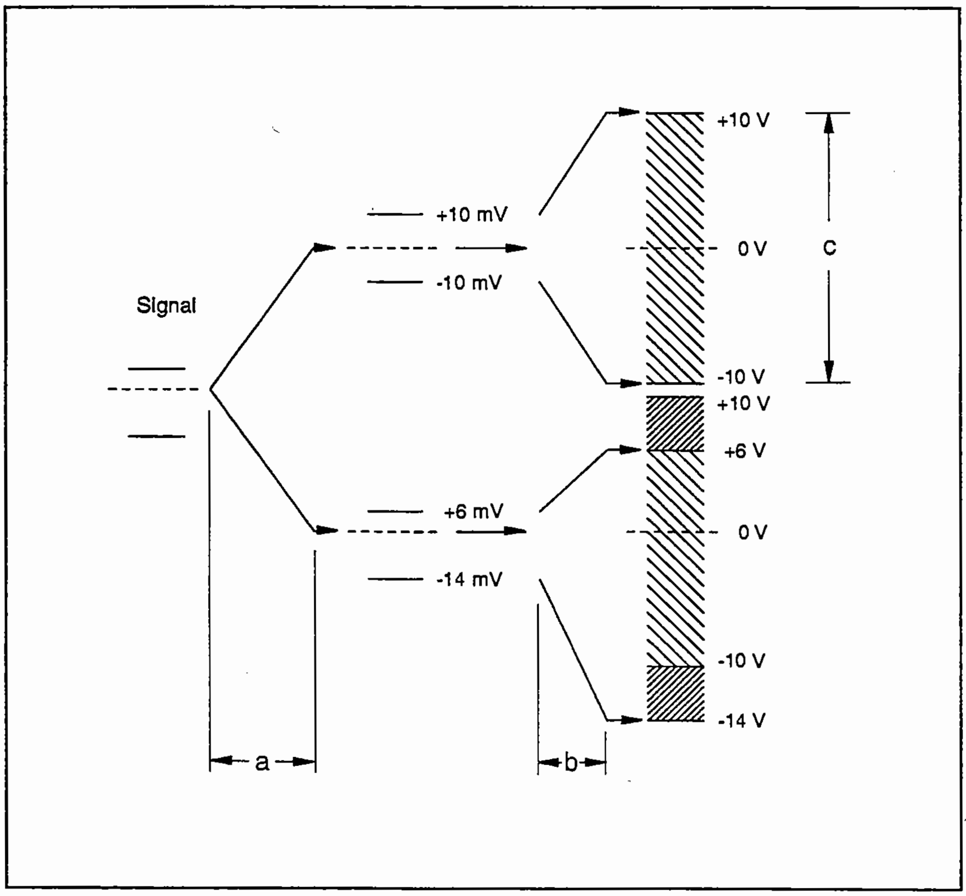


Fig. 4/7: Correlation between zero-balance (a), amplification (b) and operating limit (c)

Linearisation

In straightforward cases, there is a linear correlation between the physical value x and the electrical signal y of the analogue sensor

$$y = k \cdot x \qquad \text{(k is the sensitivity factor of the sensor)}$$

However, the relationship is often much more complicated than in the above linear example. Nevertheless, in order to obtain a result which can be easily evaluated, linearisation circuits are installed in the signal processing, which compensate for non-linearity of the sensor signal.

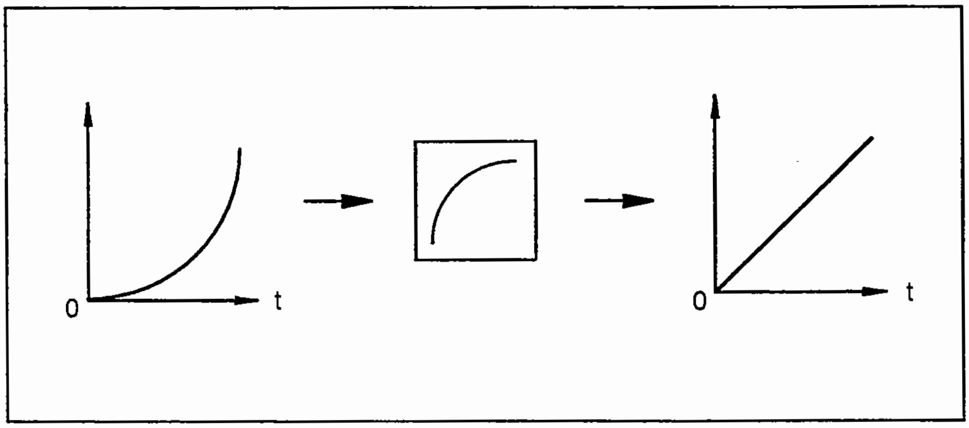


Fig. 4/8: Linearisation of sensor signal

A trend can be observed with computers in automated systems in so far as sensor signals are measured as directly as possible and the linearisation is carried out in the computer. With linearisation being omitted from the measuring chain, the risk of interference on the measuring signal is reduced. Furthermore, linearisation in the computer can be carried out to higher accuracy and in more complex cases. Linearisation in the computer can also be carried out after installation by means of changes in the program or improved by way of program data.

4.7 Output circuits

In simple cases, the measuring amplifier generates a sufficiently large voltage signal, which is immediately displayed on a voltage instrument or processed by a controller.

Unit signals

The output signal of a transducer is frequently transformed into a standardised range of values:

For bipolar signals, e.g. pressure and vacuum	-10 V ... +10 V
For unipolar signals, e.g weight	0 V ... +10 V.

With these standard signals, sensors can be easily exchanged with those of different manufacturers. They are also frequently used in other types of sensors, which again facilitates the use of standardised input circuits for subsequent processor technology, e.g. a logging device or a controller.

Current output

In automated systems, there can be fairly long cable lines, which act as antenae for interferences. In order to minimise the effects of such interferences, measuring amplifiers generally have a current output. When a current signal is transmitted, the receiver - e.g. the AD converter - has a very low input resistance, practically 0 Ω. Trapped interference voltages are short-circuited via these slight internal resistances. However, the short-circuit does not apply to the measuring signal; this is generated via a constant current source, usually in the range of 0 to 20mA.

The term 'short-circuit' used here should not be confused with that of the well-known faulty short-circuit in power cables, which carries with it a damaging high current.

Quiescent signal

For automatic fault detection, a quiescent signal is often added for the transmission of sensor signals. The following signal ranges apply: Voltage signal: 1 V ... 5 V, current signal: 4 mA ... 20 mA. A current signal of 4mA for a Festo pressure sensor D.ER-SDE-10-5V/20mA corresponds to 0 bar (0 Pa), 20 mA full scale deflection corresponds to 10 bar (1 MPa). A current below 4 mA, in particular 0 mA, suggests a fault, e.g. line interruption, line short-circuit, failing of the sensor, of the auxiliary power or of the measuring amplifier.

4.8 Signal processing in digital systems

In order for an analogue signal to be processed further in a digital system, e.g. a programmable logic controller or a computer, it must be digitised. This means it is converted into a digital numerical value, which is generally coded by the binary numbers 0 and 1, on the basis of a binary number system.

AD conversion

For this, a number of analogue digital conversion processes are available, which cover a wide range of conversion speeds and conversion accuracies. Accordingly, the technical complexity of the analogue digital converter (AD converter, ADC = analogue to digital converter) also varies. However, this workbook does not deal with the subject in detail.

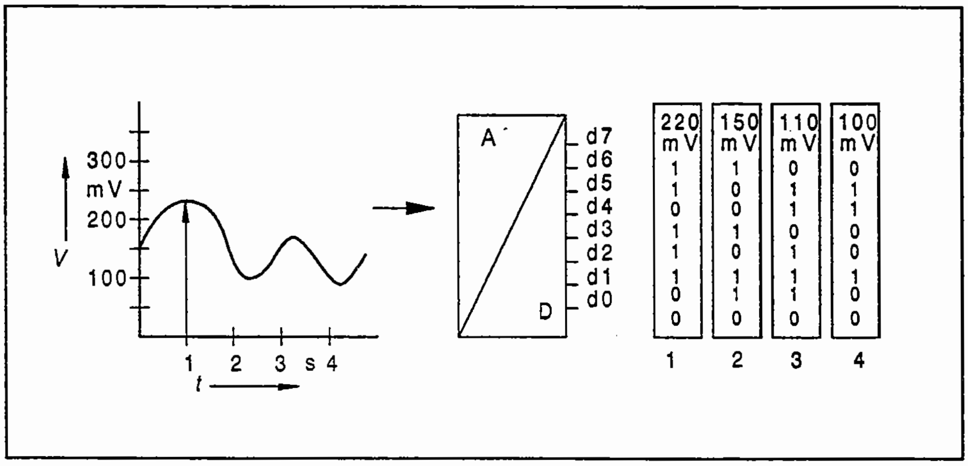


Fig. 4/9: AD converter

Impedance conversion

Binary sensors, such as pressure switches, do not require analogue digital conversion for further processing of the signal in digital systems. The sensor signal is by its very nature already digital; if necessary, it will merely need to be adapted to the current and voltage standards of digital technology by means of an impedance converter (instead of a measuring amplifier) :

PLC voltage signal	"Off"	0 V ... 5 V
PLC voltage signal	"On"	11 V ... 32 V
TTL voltage signal	"Off"	0 V ... 0.8 V
TTL voltage signal	"On"	2.0 V ... 5.5 V.

The switching states represent the numerical values 0 and 1.

4.9 Signal transmission

In many applications, sensor signals have to be transmitted over long distances. This creates the possibility that the transmission lines may pick up interference which can distort the sensor signal. A number of basic rules must be observed:

The wires between sensor and subsequent circuit are the most receptive to interference.

If it is not possible to keep the lines short, then these should be shielded: i.e. metal plaiting is used to protect the signal lines and possibly the auxiliary power cables. The shielding is grounded at the input of the connected circuit. If several sensors are used, the shieldings are grounded in a star arrangement.

The signals after the amplifier are less sensitive due to the gréater signal amplitude.

Current signals are advantageous because, due to the low internal resistance of the current circuit, interference has only a limited effect.

Digital signals are least susceptible to interference.

If a suitable method of digital transmission is selected, even very large distances can be achieved without distortion of information. By means of optical coupling elements, it is possible to overcome high potential differences between sensor systems and further processing systems.

Wiring

In general, when installing signal and auxiliary power cables, care should be taken that these do not run alongside machine power supplies. As illustrated in fig. 4/10, they should be separated as far as possible. If there is unvoidable crossover, this should be over as short a distance as possible.

The electrical supply system for the auxiliary power, the measuring amplifiers and the converter should be largely separate from the electrical supply system of the machinery. Preferably, separation should take place immediately after the transformer station into the machine network and the area designated "clean" network.

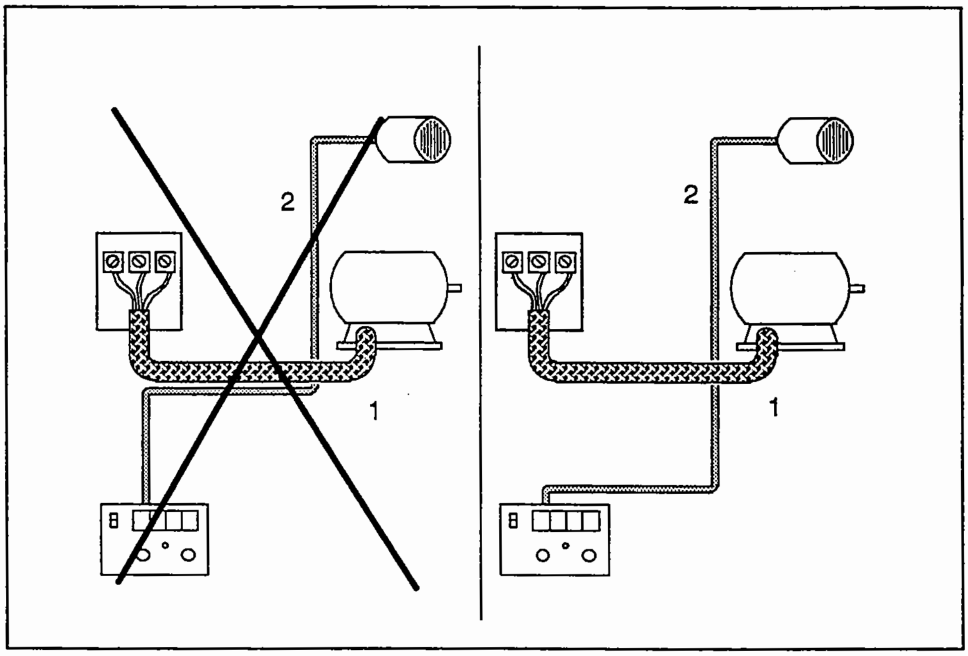


Fig. 4/10: Separation of wiring

1 Power supply
2 Signal and auxiliary power supply

Telemetry

If the sensor is in an inaccessible position or on a rotating part, it may be necessary for the sensor signal to be transmitted without wiring. Possible means of transmission are radio or infrared light. With respect to interference-free transmission, the sensor signal should be in the form of frequency modulation, pulse-duration modulation or in digitised form.

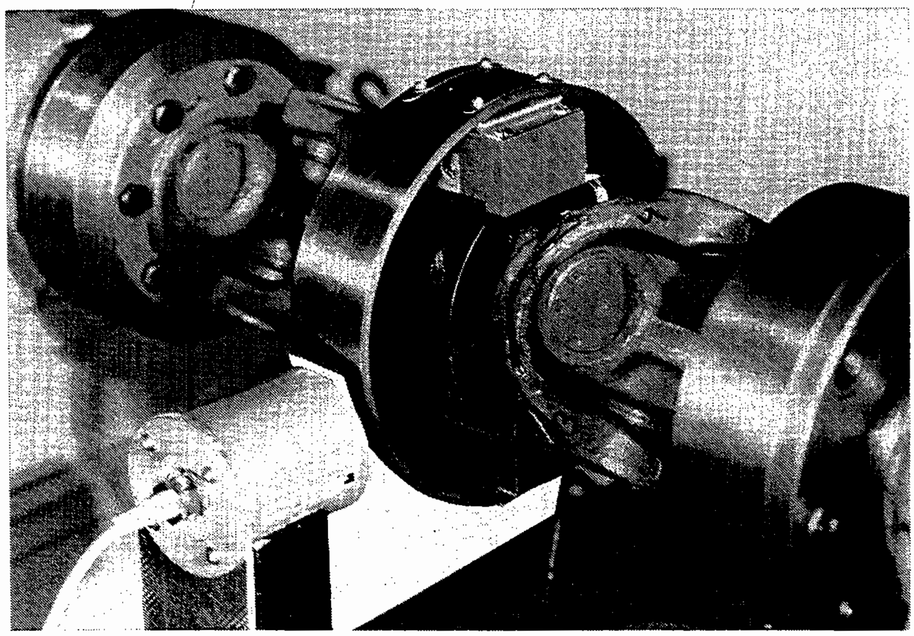


Fig. 4/11: Contactless transmission of torque signal from a shaft to a stationary receiver (Photo: Hottinger Baldwin Messtechnik GmbH)

4.10 Calibration

In most cases, the relationship between measured quantity and display is established via a non-integer factor. In order to simplify reading, it is necessary to establish simple relationships, such as:

1 N corresponds to 1 mV.

A large number of display units can be calibrated, i.e. the sensor signal is multiplied by an appropiate factor for the required correlation to be established. This is a purely electronic conversion which does not have any effect on the accuracy of the actual measurement. Depending on the design of the display unit, the conversion takes place on an analogue basis via operational amplifiers or on a digitial basis by means of a corresponding arithmetical operation.

If pointer type instruments are used, calibration can also be carried out by means of a simple modification of the reading scale.

As a rule, calibration is carried out by the manufacturer, if the sensor, measuring amplifier and display unit are delivered as one. If the sensor is exchanged, recalibration may be necessary.

However, if the measuring system is assembled by the user himself, then calibration by means of comparison with a known sensor/display combination, or by alternative means, must also be carried out.

A calibration can never be more accurate than the actual measurement of the reference point. There is therefore in all areas of sensors a need for accurately working reference devices or reference methods to carry out calibration.

Technical design of force and torque sensors

5.1 Direct force measurement

With direct force measurement, the force sensor is located in the force field. This type of measuring configuration always determines the entire force irrespective of the point of application. However, measuring inaccuracy increases to the extent in which the direction and application of force deviates from the optimum configuration specified by the manufacturer.

B 2.5

In the case of direct force measurement, the measuring range and hence the size and design of the sensor depend on the actual forces occurring. This can be a disadvantage with a frequently changing measuring range.

Force sensors

Force sensors are divided into categories designed for tensile load only, compressive load only or for both versions, whereby the decisive factor is not so much the sensor itself, but more often the problems of attaching the sensor to the force area.

The majority of force sensors should be loaded in an axial direction. In order to create a concentric and axial application of force, sensors for measuring compressive loads are fitted with concave shaped attachments. In contrast, measuring sensors for tensile loads are often fitted with bearing eyes.

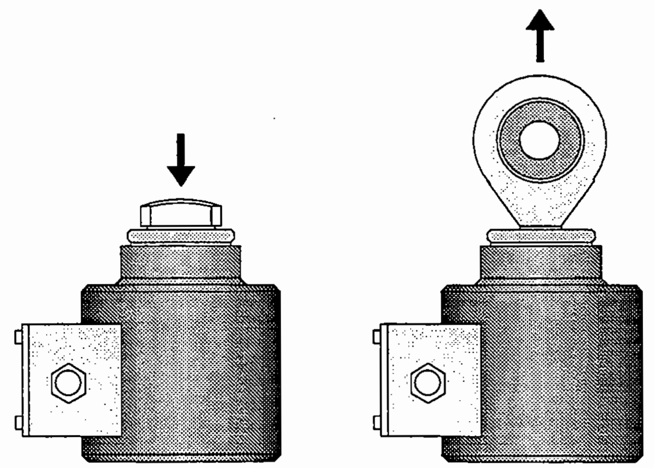


Fig. 5/1: Force sensor

5.2 Indirect force measurement

B 5.7

With industral monitoring tasks, cost-effective solutions must be found for force measurement. In the case of force bypass, only part of the force to be measured is detected by the force sensor. The total force is calculated on the basis of the given structural conditions.

With indirect force measurement, the bypass force can be calculated so as to ensure a consistent measuring range whereby one single sensor type can be used. A disadvantage is sensitivity with regard to displacement of the point of application and possibly a deterioration in linearity and a change in hysteresis.

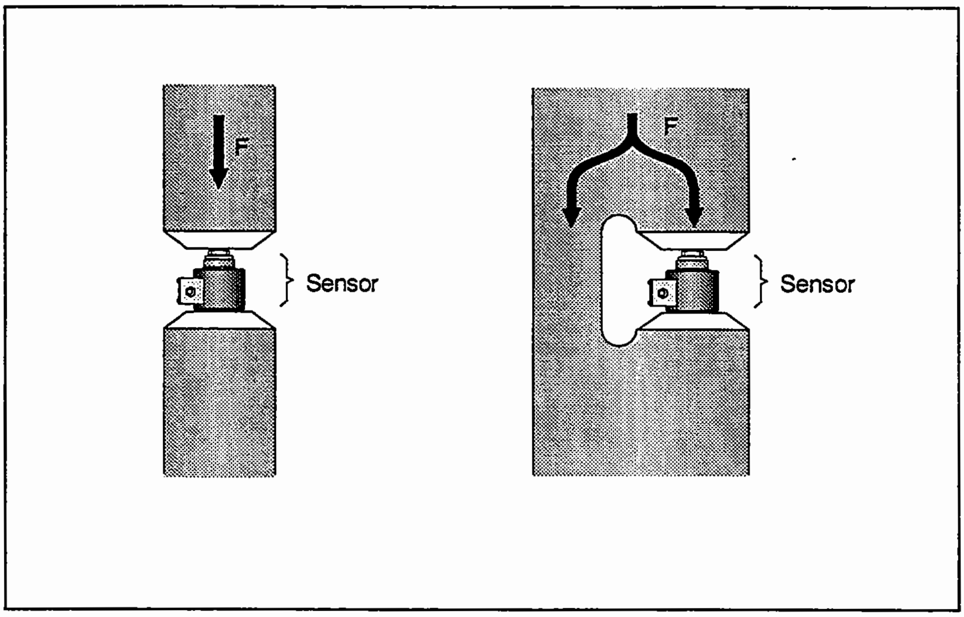


Fig. 5/2: Direct and indirect force measurement

5.3 Weight sensors

In the case of weight sensors, the direction of force is determined by gravity. For this reason the assembly position of the sensor is specified. However, particular measures are taken, in order that they always indicate the same weight even if the applied force is misaligned. This can be achieved by means of parallelogram control, which converts the force into a bending moment or torque. These are measured by means of deflecting arm strain gauges or torsion bar sensors.

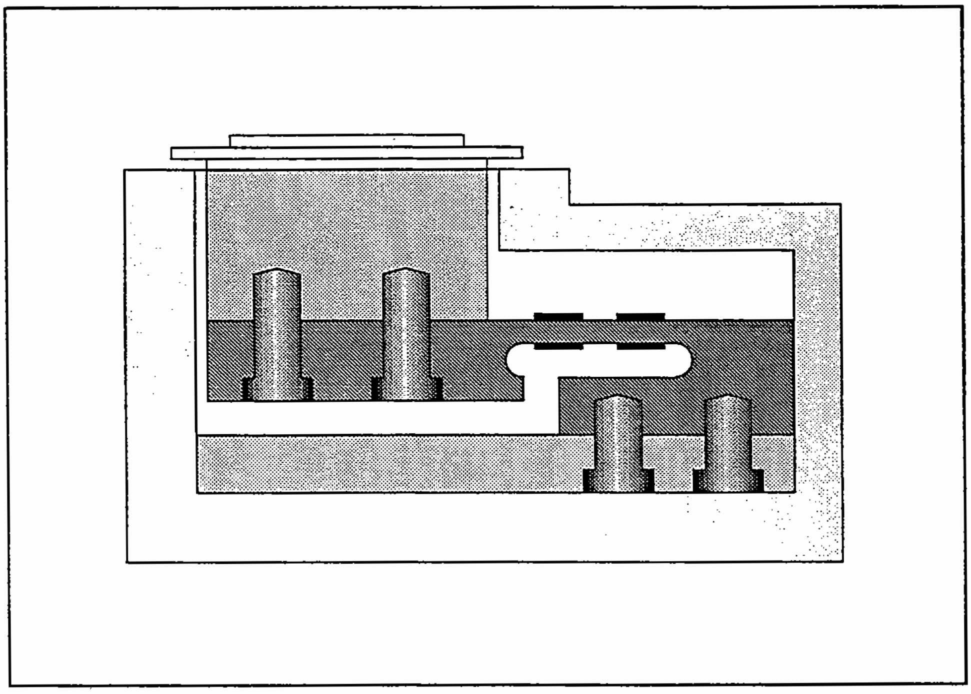


Fig. 5/3: Introduction of force on a weight sensor

5.4 Measurement of force components

Force is a directional quantity, which can be divided into several components. In the case of single-component force measurement, only the force component in a specified direction is of interest. Sensors for single-component measurement must register this force component only and must be insensitive towards all transverse forces, which stem from the remaining force components.

Single-component force measurement

The selection of force components can be determined by the design of the spring element. An easier method is to use the piezoelectric effect of quartz, which shows a distinct directional dependence. Two quartz plates are cut in such a way that the crystallographic axes point in the required direction. The quartz plates are mounted between two steel plates which, on the one hand, introduce the forces and, on the other hand, form the load connection. Detection of the created load is effected by means of an electrode between the two quartz plates. Thus, this simple sensor already contains all the necessary components. The characteristic features of quartz are its eminent suitability as a spring component of high rigidity, its directional sensitivity and the direct conversion of strain into an electrical signal.

Multi-component force measurement

A multi-component force sensor consists of a stack of six quartz discs with electrodes in between, which are built into a steel housing. Each quartz disc must be cut in a certain direction. Although the same force F acts on each quartz disc, each of these emits only one load signal, which corresponds to the force component in that direction. No mechanical means of component separation are therefore required.

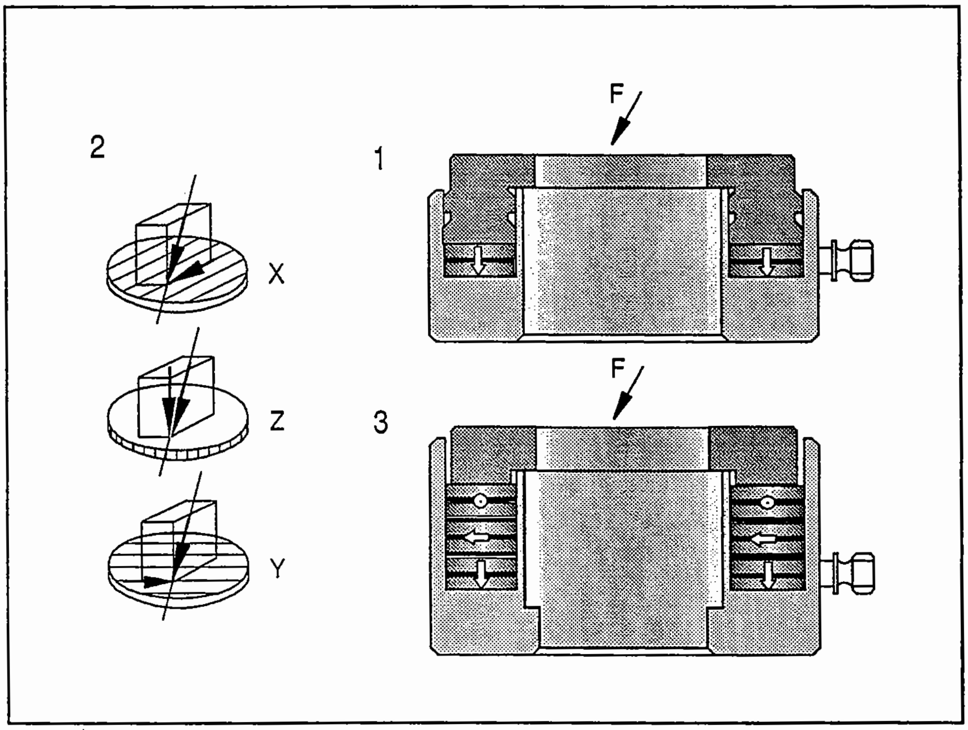


Fig. 5/4: Component force measurement

1 Schematic assembly of a single component force sensor
2 Alignment of quartz plates in a multi-component force sensor
3 Schematic assembly of a multi-component force sensor

5.5 Torque measurement

B 2.4

In order to measure the torque on a shaft, a torque sensor system is installed between the two shaft ends. The torque sensor itself consists of a section of shaft whose torsion is measured by means of a strain gauge.

The measuring signal needs to be transmitted from the rotating shaft to a stationary processor. To achieve this, there is either the less complicated slip-ring method or the more complicated, but wear-resistant, contactless method of transmission. With contactless transmission, a frequency modulated signal is generally transmitted by inductive means from the shaft into the enclosing housing.

The torque shaft can be either free-floating or on bearings. With the first version, half couplings are sufficient to flange-mount the torque sensor; with the second version, whole couplings are required.

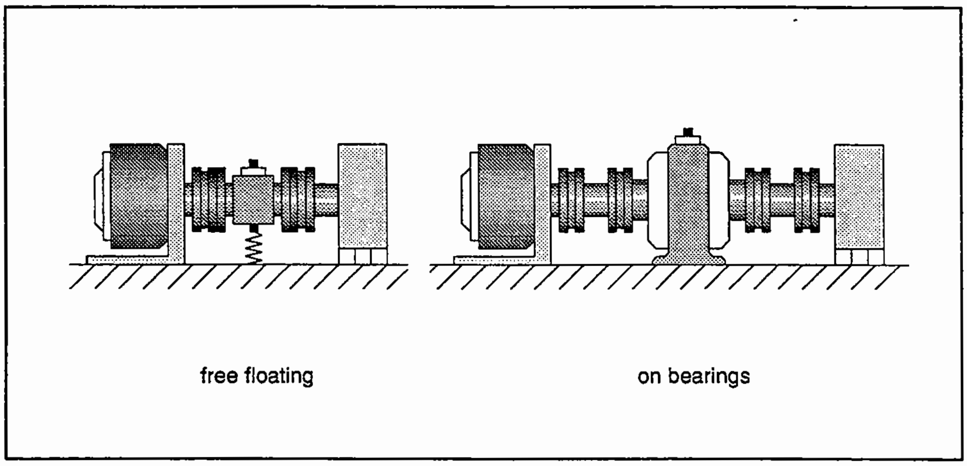


Fig. 5/5: Typical installation of a torque sensor

Performance measurement

Measuring the torque of shafts can easily be combined with rotational speed measurement, thereby providing a complete sensor system for the measurement of mechanical performance.

5.6 Dynamometer

A multi-component dynamometer in its simplest form consists of three, in practice however normally four piezoelectric three-component force sensors, which are positioned between a base plate and a cover plate and are prestressed by means of expansion bolts. Multi-component force sensors have been described in chapter 5.4.

The four force sensors have a total of twelve signal outputs, which are individually converted into voltages in load-sensitive amplifiers. The signals are subsequently fed to differential and integrating amplifiers.

The force component in the x direction is obtained by the addition of the signals from the quartz disc. The same applies for the y and z direction.

If a difference of signal between two quartz discs is generated, the torque perpendicular to the plane in which the force direction and connection line are in, may be obtained.

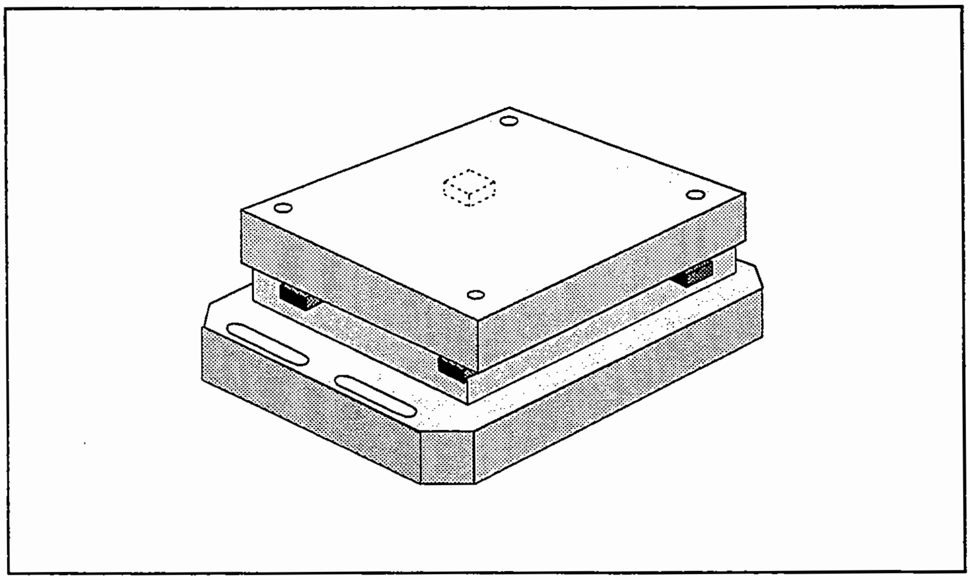


Fig. 5/6: Multi-component dynamometer

In this way, all applied forces and moments within a sensor system can be determined by means of a multi-component dynamometer.

5.7 Measuring plugs and strain gauge sensors

Measuring plugs and strain gauges are used for the indirect measurement of force in mechanical structures.

Measuring plugs

Measuring pins are available in designs for the measurement of radial and axial forces. These extremely rigid piezoelectric sensors are prestressed and fixed into special measuring bores. Structural stresses create a change in the prestressing and are thus registered by the sensor. The load on the machine or structure can be determined on the basis of the measuring signal.

Measuring plugs are used in transoms, machine carriers or toggle levers, where direct measurement of force cannot be carried out economically and the standard requirements for accuracy are met by measuring plugs.

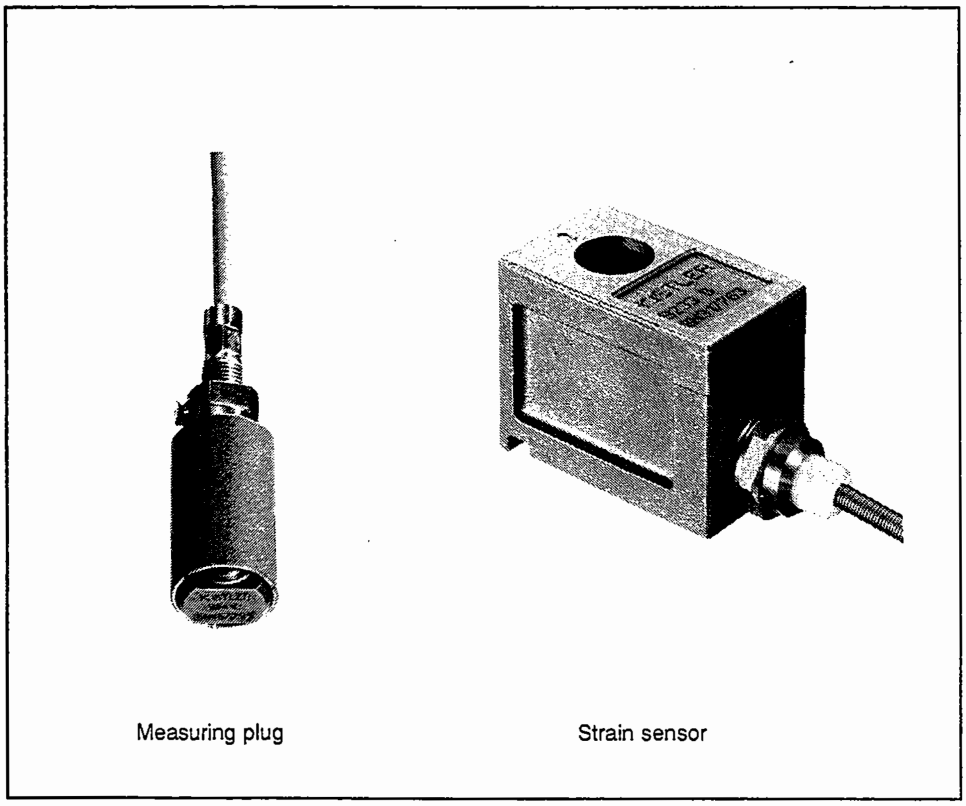


Fig. 5/7: Sensors for indirect force measurement (Photo: Kistler Instrumente GmbH)

Strain sensors

If it is sufficient to know the loading on the surface of a mechanical structure, strain gauges can be mounted directly onto an appropriate base or carrier. Alternatively, strain sensors can be screwed on. These contain strain gauge elements (strain gauges or piezoelectric crystal) which, under the force of the screws are held by friction against the carrier, thereby experiencing the same strain as the carrier under load.

Application of force sensors

6.1 Areas of application for force sensors

Force sensors are frequently used in test and research laboratories. Experimental observation of forces is useful in the control of product or process characteristics and the results provide a feedback for the design team. By appropriate design, the forces can be directed along certain lines for achieving an optimum mechanical strength. Oversized parts can be reduced to the required size thus saving costs and materials.

Force sensors are also used in quality assurance, where certain characteristics of a product are tested. Moreover, they are increasingly being used in production, i.e. between development and quality assurance. The production-related use of sensors permits the early detection of break-downs, thereby reducing downtimes as well as rejected goods.

Sensors used in production are normally integrated in automation of the plant so that the controller can immediately take the intended steps such as the adjustment of alarm parameters, warning signals or shut-down.

The following illustration of examples is neither complete nor does it represent sensors which are most frequently in use. Moreover, the use of sensors in consumer appliances has been excluded from these examples, as workbook 1130 comes under the main heading of automation. The main purpose of the examples is to explain the above mentioned areas of application by means of descriptions, illustrations and photographs. The illustrations cover areas of research and development, production technology, assembly technology, material flow systems, materials management and quality assurance.

6.2 Research and development

Control elements in goods of daily use are constructed according to their ergonomic requirements. This includes the position and shape of the control elements and in particular the forces required for operation.

Driving a car in traffic places high demands on the sensory performance, concentration, reactive ability and energy of the driver. Therefore ergonomics applies in particular to the control elements of a car.

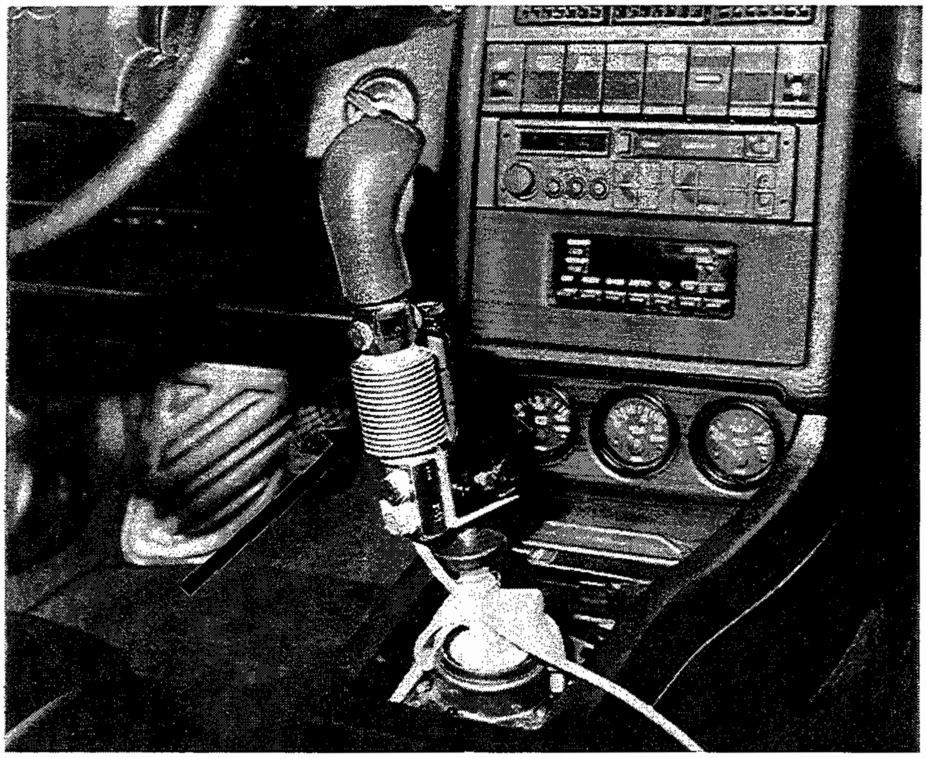


Fig. 6/1: Measurement of actuating forces during gear changing in a test vehicle (Photo: Reports in Applied Measurement Vol 5 (1989) Nr. 1)

This illustration shows the use of a force sensor system which measures the force components occurring on the gear lever in several axes. The force measurement affects both the construction of actuating elements as well as the design of the gears.

6.3 Production technology

The most important objective of tool monitoring in metal cutting is the detection of broken tools and the safe rapid shutdown of the machine tool. In this way, consequential damage to the machine tool itself is avoided. However, monitoring of tools also protects against overload as a result of programming or processing errors or faulty workpiece clamping.

The force sensors are built into the lines of force of the machine tools. In a straightforward solution, the force sensor and the axial bearing, which is required anyway, are combined. The feed force causes strain in the bearing, which is detected by means of strain gauges.
Differential information can be obtained by using a multi-component dynamometer. It is possible to insert the dynamometer into the workpiece holder.

B 5.6

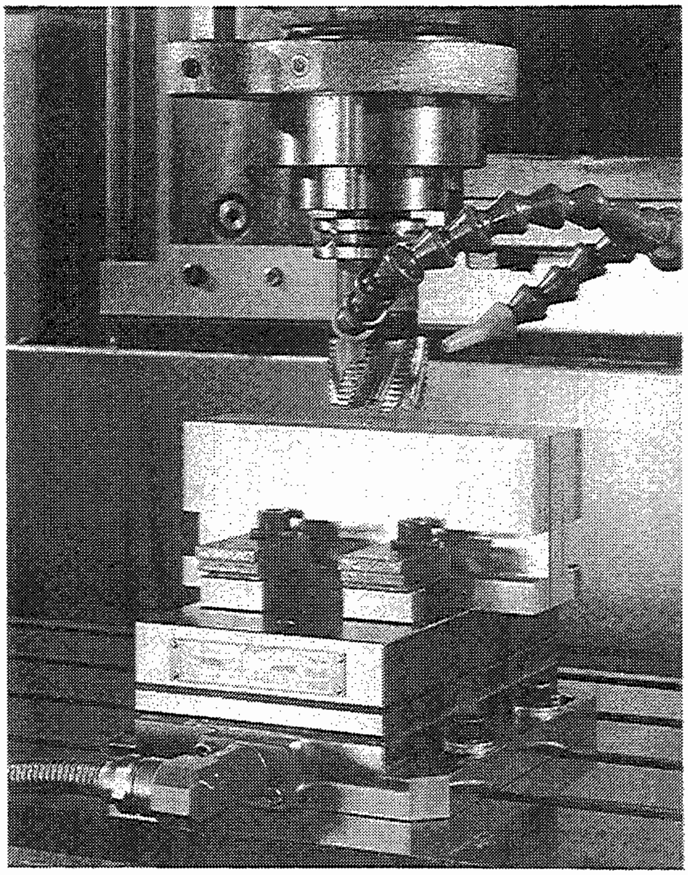


Fig. 6/2: Monitoring feed force and torques in a modern machine tool (Photo: Kistler Instrumente GmbH)

The evaluation of signals by control computers is carried out on the basis of previously input limit values. Because the required forces can be divided into the individual processing steps, these are recorded simultaneously with the processing steps as part of a fact finding procedure. The program subsequently calculates a tolerance band which includes the ideal force pattern. In the subsequent production runs, deviation above or below the the tolerance band effects the triggering of the previously defined alarm control, e.g. return of the workpiece, rapid shutdown of the drive or an alarm indicator.

6.4 Assembly technology

The automation of assembly processes by means of automatic handling devices or robots places considerable demands on the accurate fitting and alignment of workpieces, if a reliable control function is to result. By using position sensors or image processing systems, the requirements regarding accuracy can be relaxed, because the automatic device is guided on the basis of sensor signals. In the case of joining processes, closed-loop position control can also be carried out using force sensors, which are installed in the gripper joint of the robot.

Illustration 6/3 below shows a robot with force sensors in the area of the gripper joint. Deformation of the spring element is measured by means of optical sensors. The schematic drawing illustrates the characteristic forces which occur at different stages of fitting a bolt.

Force sensors in the gripper joint of a robot are also used for operations such as cleaning-up castings.

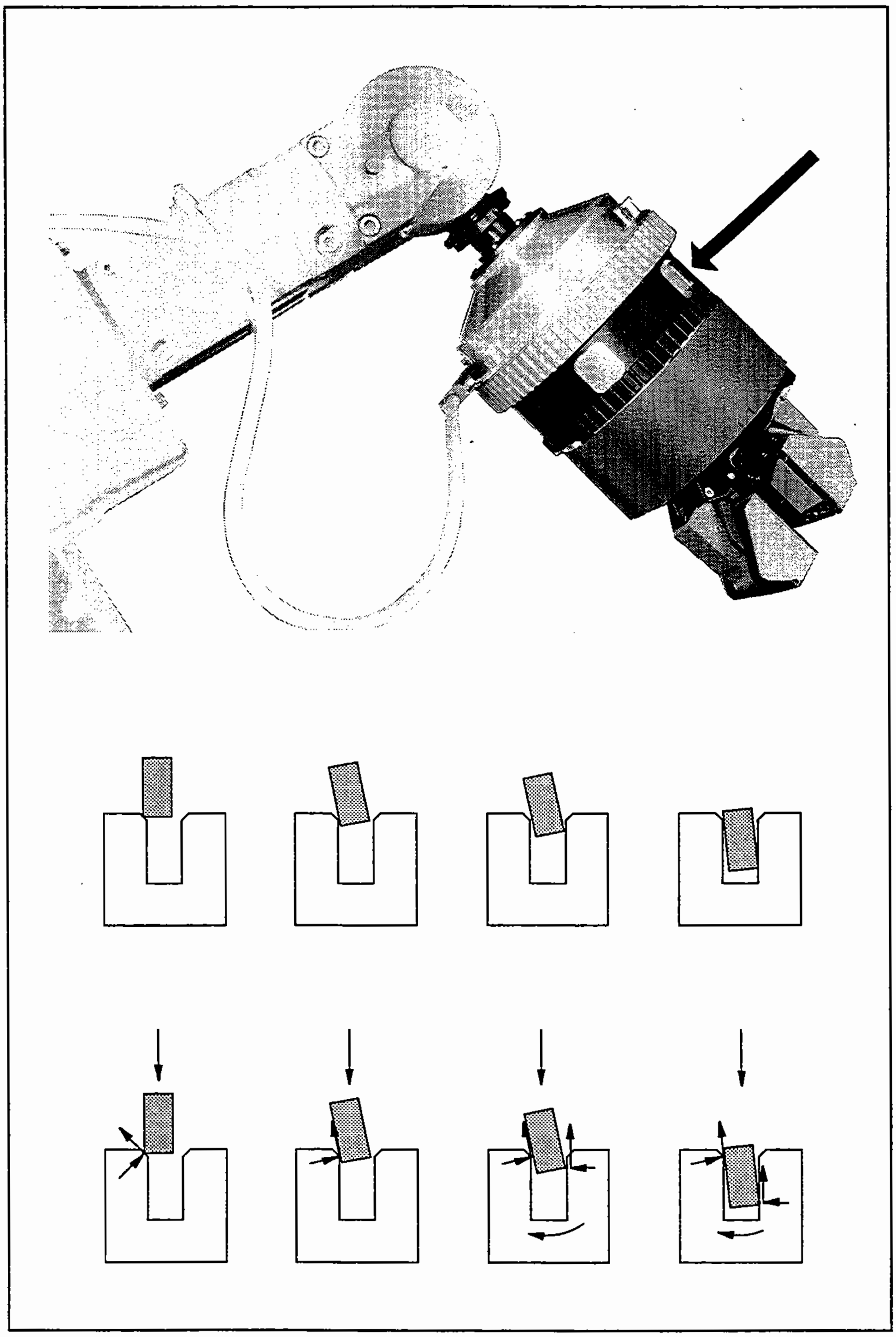


Fig. 6/3: Force sensors in the gripper manipulating joint of a robot (Photo: German Research Institute for Aeronautics and Aerospace Engineering)

6.5 Material flow systems

Force sensors are used in material flow systems in order to monitor permanent material feed.

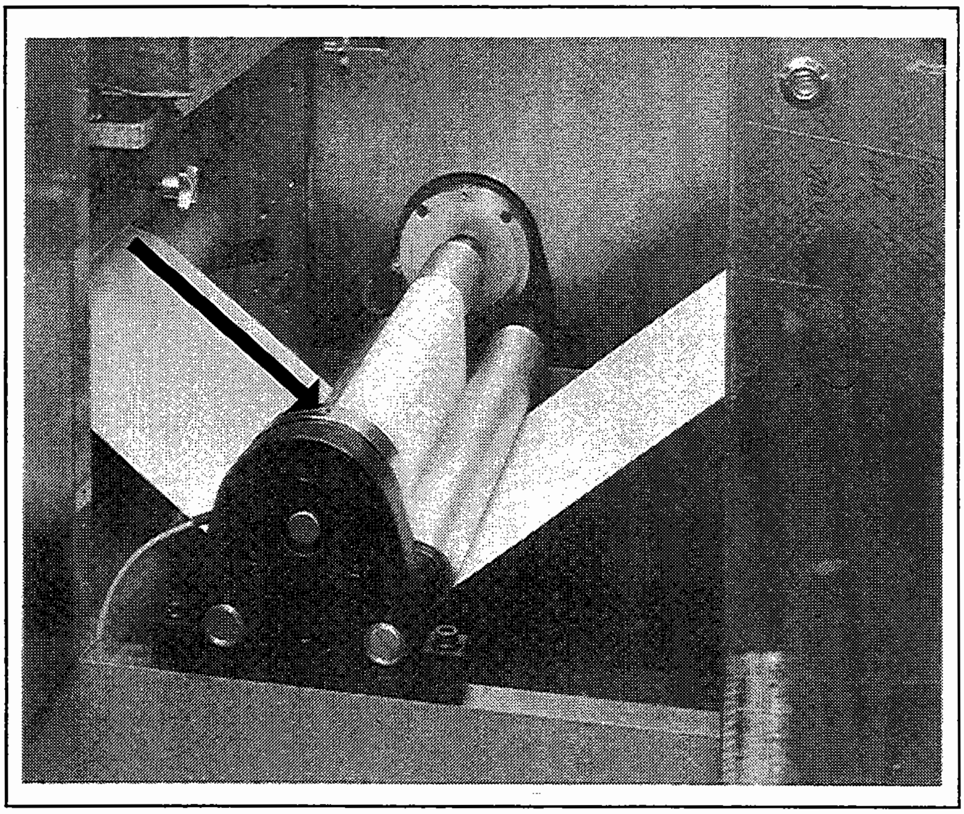


Fig. 6/4: Use of radial force sensors to monitor the supply of film material (Photo: Hottinger Baldwin Messtechnik GmbH)

This illustration shows the feeding of a plastic film which passes over three deflecting rollers, which are kept apart by means of a specified force. This force opposes the longitudinal stress in the film material. The middle deflecting roller houses a radial force sensor, whose signal should remain constant under the given operating conditions. If there are faults in the film material, this results in deviations above or below a tolerance band, which results in a preprogrammed alarm being activated.

6.6 Materials management

Knowledge of the material quantities available is of key importance in materials management. Material quantity can, for example, be determined by the weight of the materials.

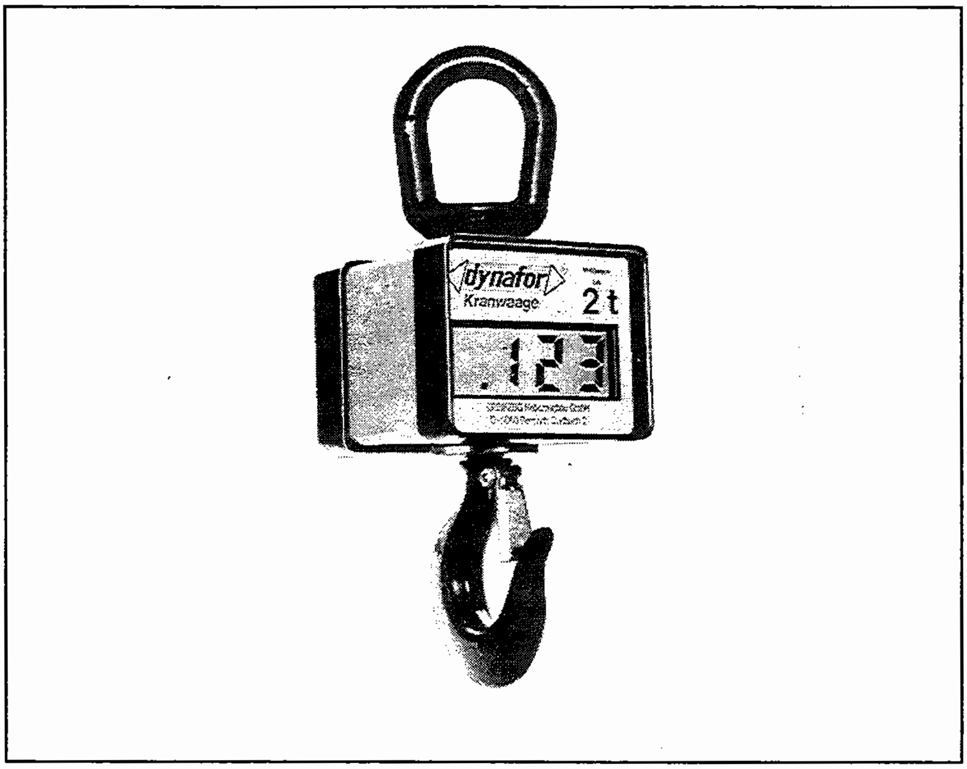


Fig. 6/5: A crane scale for weights of up to 2 tons or approx. 20 kN (Photo: GREIFZUG Hebezeugbau GmbH)

This illustration shows a crane scale, which can be used between crane hooks and slings. With this method, incoming material can be simultaneously weighed and unloaded. The loading process which is necessary anyway is combined in one operation with the monitoring of incoming goods.

6.7 Quality assurance

One important characteristic of a measuring plug is its retention force, i.e. the maximum axial force, which causes the plug to be extracted. The plug retention force is examined regularly as part of quality assurance.

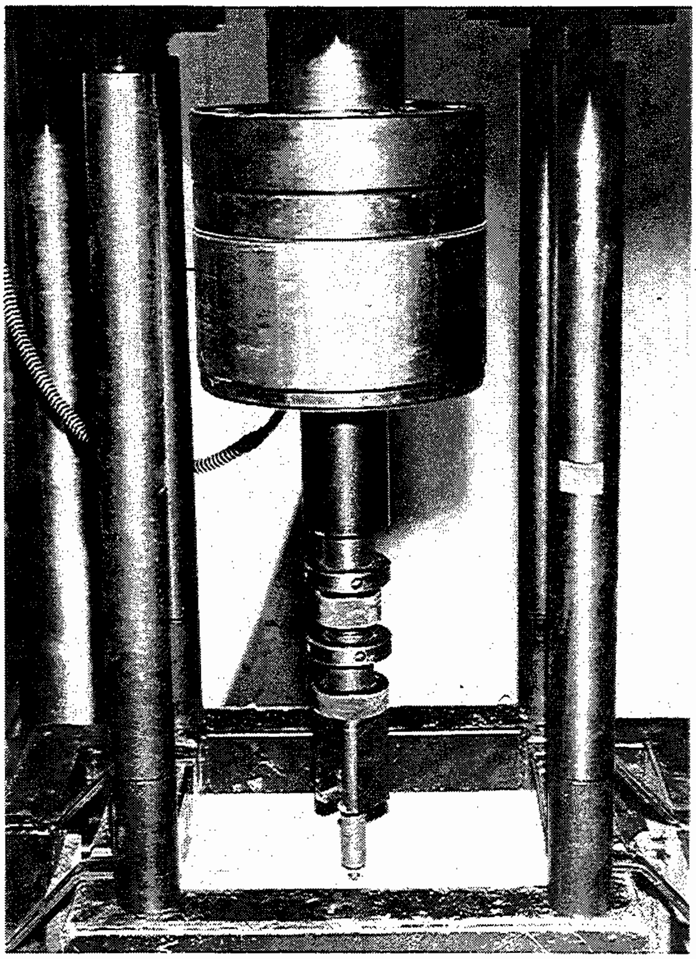


Fig. 6/6: Tensile test on a plug
(Photo: Fischerwerke Artur Fischer GmbH & Co.KG)

This illustration shows a tensile test on a plug, which is fitted at the base of a concrete plate. The force is introduced via four laterally mounted hydraulic cylinders, the force sensor can be seen in centre above. The displacement measuring device, however, cannot be seen in the picture. When attempting removal, which generally results in a large crater-shaped eruption of the concrete plate, a force/extension diagram similar to fig. 2/2 (p. B-20) can be recorded.

Technical design of pressure sensors

7.1 Pressure sensors

B 2.1

Pressure is the condition of stress within a gas or a fluid, which is demonstrated by the dynamic effect on the surface of the surrounding container. Pressure within solid objects, although of the same physical value, is known as stress.

Pressure sensors with binary as well as analogue signals are generally used for measuring pressure depending on the application. The former are known as pressure switches. For analogue pressure sensors, the shorter term pressure sensor has become the accepted, although this is the generic term. Pressure sensors are divided into absolute pressure sensors, relative pressure sensors and differential pressure sensors depending on the measuring principle involved.

Absolute pressure sensor

Absolute pressure sensors measure the absolute pressure of the medium; the point of reference is vacuum (p = 0 Pa). The absolute pressure sensor has a vacuum gauge head. One wall of the gauge head is in the form of a thin diaphragm and is distorted under the pressure of the medium to be measured. The gauge head cannot contain an absolute vacuum. In practice, the gauge

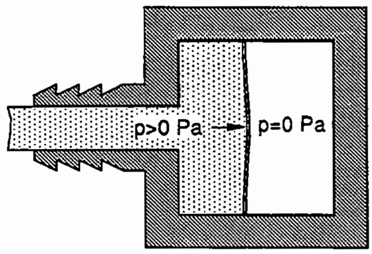


Fig. 7/1: Schematic representation of an absolute pressure sensor

head with the reference pressure is evacuated to approximately 0.1 Pa, which roughly corresponds to a millionth of atmospheric pressure. These sensors are not suitable for vacuum technology, where the absolute pressure is comparable to the residual pressure in the gauge head. In these cases, totally different methods of measurement are used such as, for example, measurement of heat conductivity or the ionisation of residual gas.

Relative pressure sensor

A 10

Relative pressure sensors measure the differential pressure in relation to ambient pressure, which is designated by P_{amb}. The suffix amb is the abbreviation for the latin word *ambiens*, which means *unrestricted*. Ambient atmospheric pressure in open systems is, however, not constant and depends on the meteorological and geographic conditions. However, for many operating conditions, the relation to ambient pressure is relevant. Relative pressure sensors may be further divided into positive pressure sensors (for positive differential pressure) and vacuum sensors (for negative differential pressure). The gauge head of relative pressure sensors contains an outlet to atmosphere.

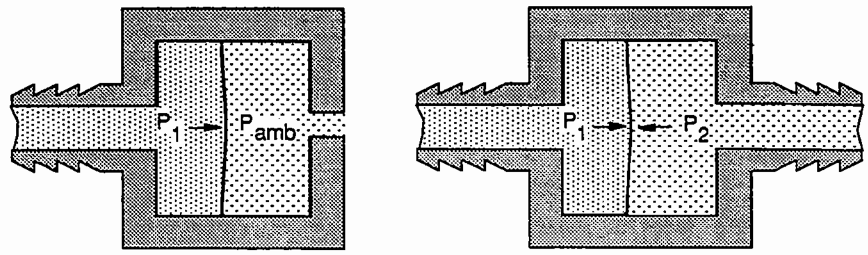


Fig. 7/2: Schematic representation of a relative and a differential pressure sensor

Differential pressure sensors

A 12

Differential pressure sensors do not differ from relative pressure sensors as regards the principle of measurement. They measure the differential pressure between two closed systems and in addition have two connections.

7.2 Diaphragm pressure switch

A 10

With this type of pressure switch, the diaphragm in the pressure container is deflected under the effect of the medium to be measured or a closed metal bellows is stretched against a spring force. The resulting movement is transmitted to the switch. The switch-on point is fixed by setting the switching distance with the help of an adjusting screw.

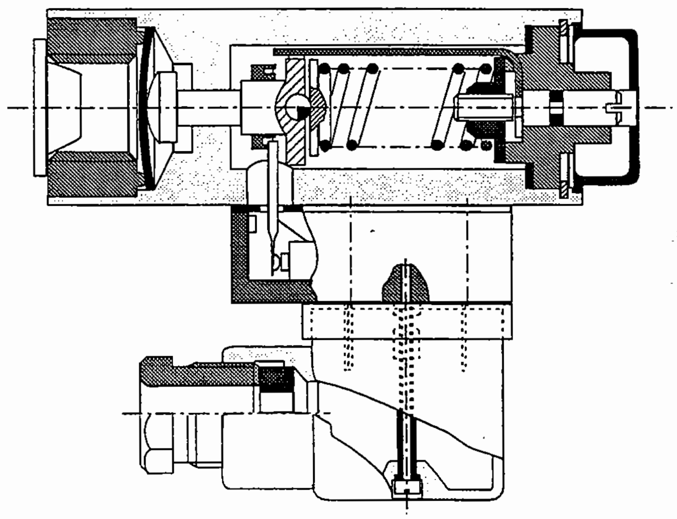


Fig. 7/3: Schematic representation of a diaphragm relative pressure sensor

Mechanical pressure switch

The switch can be constructed in the form of a conventional microswitch or as a hermetically sealed reed contact. In the latter case, the switching action is effected contactlessly by the field of a permanent magnet. The contacts are situated in a small glass tube which contains a protective gas to help prevent sparking during switching.
Mechanical switches have the advantage that they can switch both direct and alternating current.. However, a disadvantage is that when the contact blades switch, one bounces off the other several times prior to coming to rest. This so-called contact bouncing creates several switching pulses in the millisecond range, which must be suppressed if further processed in electronic systems.

Pneumatic-electronic switch

A 12

Electronic pressure switches which operate without contact bounce and produce a discrete signal change, are also common. However, these can often only switch direct current in a particular voltage range specified. Designs with electronic AC switches or universal current switches are also available.

Electronic switches can be connected to electronic controllers without any additional precautions being taken against contact bounce.

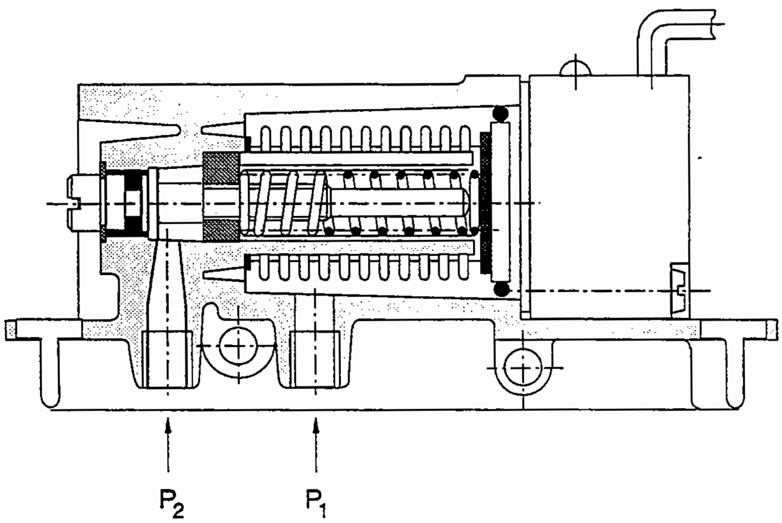


Fig. 7/4: Schematic representation of a pneumatic-electronic switch

The above illustration shows a Festo pneumatic-electronic switch type PEN-M5. An inductive proximity sensor reacts to the movement of the base part of the metal bellows. The length of the bellows depends on the differential pressure between the connections P1 and P2 as well as the fixed spring tension.

In electronic pressure switches, electronic proximity sensors of the inductive or capacitive type can be used. They measure the distance to the diaphragm and thus indirectly their deflection under the effect of pressure.

7.3 Pressure sensors with strain gauges

In the case of analogue pressure sensors, the curvature of a diaphragm is evaluated as a function of pressure. Similar to force sensors, deformation is registered via strain gauges. As a rule, four strain gauges, which are connected as a full bridge, are fitted onto the steel diaphragm. The shape of the strain gauge corresponds to the curvature of the diaphragm so as to achieve a linear relationship between signal strength and pressure. In modern production systems, the strain gauges are fitted directly onto the diaphragm by a laminar process. With ceramic diaphragms, the strain gauges can be applied complete with connecting wires by means of the screen printing process.

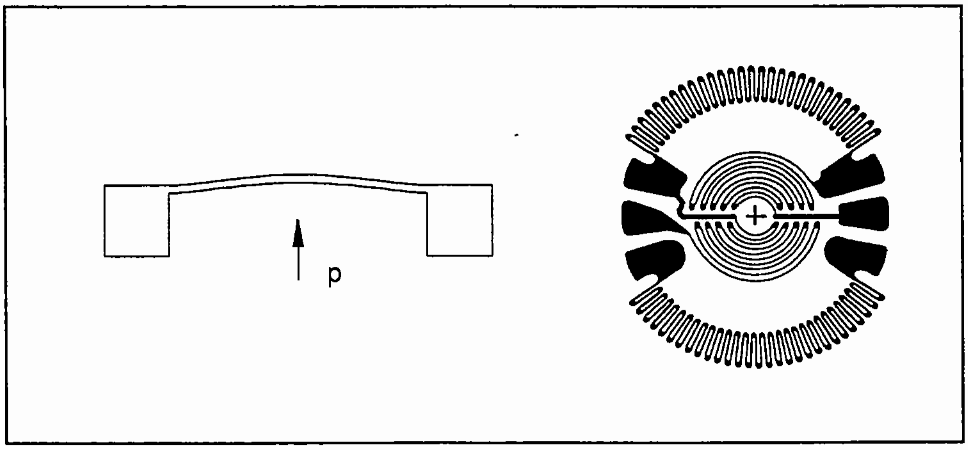


Fig. 7/5: Pressure sensors with strain gauges are used primarily for high pressure ranges (> 50 MPa, 500 bar) and rough conditions

7.4 Monolithic pressure sensors

Monolithic pressure sensors are constructed entirely from a silicon crystal. The diaphragm consists of a base material, which is slightly etched at the relevant point. The resistance paths of the strain gauges are diffused into the diaphragm. Even a measuring amplifier can be integrated into a silicon crystal.

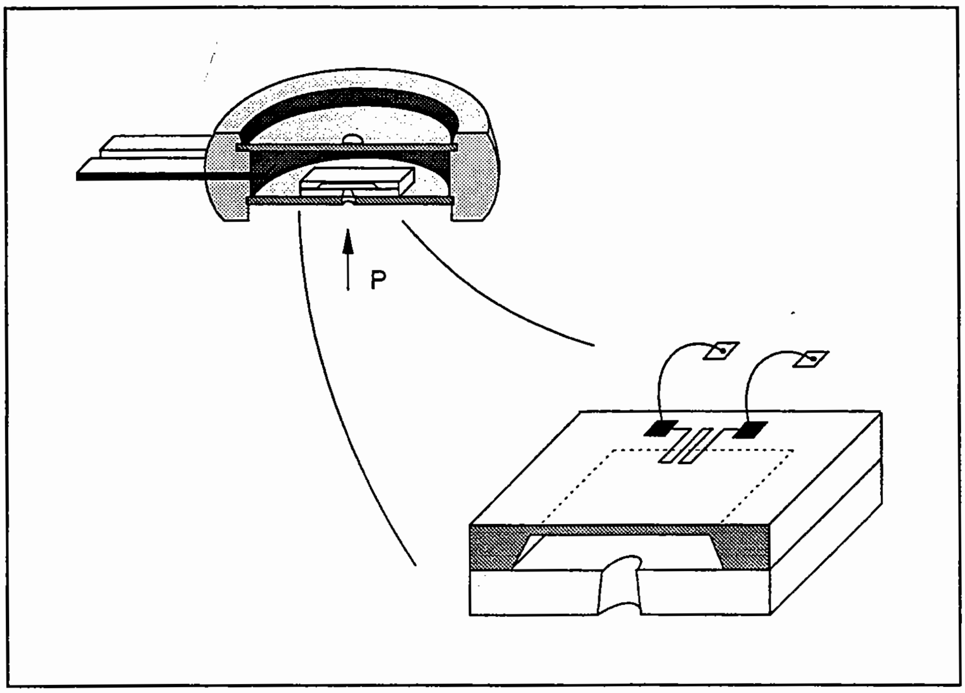


Fig. 7/6: Monolithic pressure sensor (the actual sensor element is shown in the enlarged section)

Monolithic pressure sensors may exist in very small sizes. The area of the silicon crystal, for instance, is only 2.5 x 2.5 mm^2, and the silicon diaphragm has a thickness of 0.04 mm for a measuring range up of to 10 kPa and 0.5 mm for a measuring range of up to 100 MPa. With such small dimensions, the additional volume of the gauge head, compared to the total volume of the pneumatic or hydraulic system, can generally be ignored in the calculations.

B 3.2

The construction of all strain gauges, and possibly the compensation resistors, on a single crystal produces equal thermal influences thus eliminating thermal drift and hysteresis. Silicon has the advantage of remaining in the proportional band practically up to breaking point; it does not have any measurable hysteresis and has high endurance. Moreover, strain gauges based on a semiconductor are approximately 50 to 100 times more sensitive than metallic strain gauges.

Not least, the photochemical processes of chip production facilitates mass production, which means favourable prices.

7.5 Piezoelectric pressure sensors

With piezoelectric pressure sensors, the pressure acting on the front surface transmits a force onto an internally situated piezoelectric crystal, e.g. quartz. Because of the measuring principle of the piezoelectric effect, piezoelectric pressure sensors are suitable primarily for measuring time-dependent pressures or even pulse-like pressure waves, e.g. in ballistics. Piezoelectric pressure sensors can measure extremely high pressures up to 10 000 bar (corresponding to 1000 MPa) and can be used in a very wide range of temperatures. Pressures from hot plastic melts of 400 K, for instance, can be measured by means of piezoelectric pressure sensors.

7.6 Special designs

Pressure sensors are also available for special applications.

Pressure/temperature sensor

Pressure/temperature sensors contain a pressure and a temperature sensor in one housing. Both variables can thus be measured at one single measuring point. Pressure/temperature sensors are used for monitoring thermal reactions, where both pressure as well as temperature vary to a great degree.

Water-cooled pressure sensors

Where a pressure sensor is exposed to high temperatures, it can be fitted with special adapters which permit water cooling. As a rule, the outside surface of cylindrical pressure sensors is cooled; the outside surface with the diaphragm must remain open so as not to introduce any measuring inaccuracies.

Pressure wave sensors

Pressure-wave sensors are used for the purpose of measuring rapid pressure changes, such as those occurring in ballistics or pulsating load type tests. Sound pressure sensors fall into the same category. These measure purely the alternating component of pressure characteristics. These are, for instance, used in sonar depth measurements. From sound pressure sensors it is only a small step to microphones. Microphones work, among other principles, on a piezoelectric basis, such as the well-known crystal microphones.

7.7 Indirect pressure sensors

Indirect pressure measurement is used in instances where, due to the aggressiveness of the medium or inappropriate operating conditions such as excessive temperature, the direct application of pressure sensors is out of the question. Also, if a device in a restricted space is to be subsequently equipped with a pressure sensor, the use of an indirect pressure sensor is often the only solution.

With indirect pressure sensors a round pin (2 in Fig. 7/7) is inserted into the side of a pressure container and sealed in such a way that there is no leakage but it can nevertheless be easily moved longitudinally. The pressure in the container exerts a force onto the pin, which can be calculated in relation to the bottom surface of the cylinder. The pin actuates a force sensor (1) at a safe distance from the medium and generates the required electrical signal. The mode of operation of an indirect pressure sensor is therefore similar to that of a pneumatic or hydraulic cylinder.

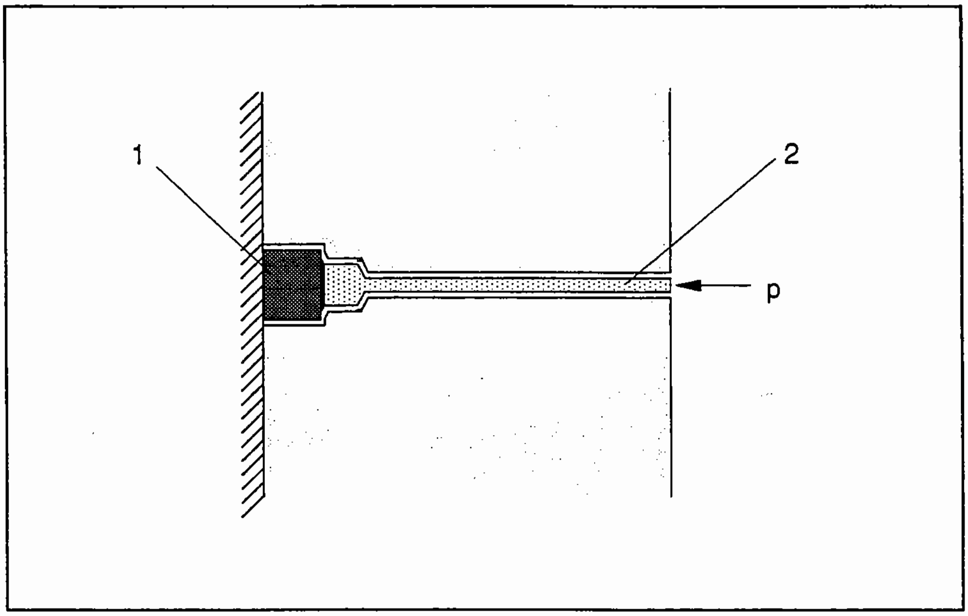


Fig. 7/7: Indirect pressure sensor

A disadvantage with indirect pressure sensors is the friction loss on the pin. This leads to a distortion of the measured data, which usually has to be corrected on the basis of empirical values.

7.8 Operating conditions

With a pressure sensor, one side of the diaphragm is exposed to the medium to be measured. In the case of differential pressure sensors, both sides are exposed. With aggressive substances, the manufacturer's recommendations regarding the suitability of a pressure sensor must be observed. Table 7/1 illustrates such an example.

Medium	Suitability
Petrol	+
Benzene	0
Compressed air (lubricated and unlubricated)	+
Natural gas (dry)	0
Crude oil	–
Acetic acid	0
Paraffine	+
Hydraulic fluid	+
Methane	+
Lactic acid	0
Mineral oils	+
Ozone	+
Phosphoric acid	–
Nitric acid	–
Hydrochloric acid	–
Sulphuric acid	–
Sea water	–
Turpentine	0
Water	–
+ resistant / 0 conditionally resistant	– non-resistant

Table 7/1: Suitability of pressure sensor with aluminium housing

Pressure sensors in an aluminium housing have only a limited resistance against various media. Better resistance can be obtained by means of housings made of stainless steel.

The gauge head of a silicon pressure sensor can be protected by means of passivation. In this way, the silicon is converted into silicon nitride on the surface. The sensor can also be protected by a layer of silicone, which transmits the pressure without loss. This is the case in the example shown in above table where only aluminium and silicone have been used for the housing, because these are the components which come into contact with the medium.

Should the direct protection of the sensor prove inadequate, it is separated from the medium by another diaphragm, e.g. stainless steel. This diaphragm must be very ductile so as not to influence the result. The pressure is transmitted from this membrane to the sensor by means of silicone oil.

Applications for pressure sensors

8.1 Areas of application for pressure sensors

The contents of chapter 6 regarding areas of application for force sensors apply equally to pressure sensors, although pressure sensors have been used in production for much longer than force sensors: classic examples are the pressure gauge or pressure switch used for instance for monitoring boiler pressure or pressure in ducts or for monitoring a cooling circuit.

Today's pressure sensors, however, have little in common with pressure sensors from the steam-machine age. As a rule, pressure sensors are compact electronic measuring devices, such as required in modern production automation. A number of sample applications are described briefly in the following pages to give an idea of the scope of the subject and the multitude of sensors available. However, it is not possible to give a complete account of these here; the examples described are merely a random selection.

8.2 Research and development

Pressure sensors are used for a variety of measuring tasks in the development of internal combustion engines. The recording of pressure in the combustion chamber of an engine is a particularly interesting case. During suction, the cold air enters the combustion chamber. Due to compression, the temperature rises to several hundred degrees. After ignition, a further increase in temperature of up to approximately 1600 K occurs. The radiation temperature can be as high as 3000 K. This temperature change is experienced by the sensor up to 100 times per second and yet in spite of this it is to measure pressure only, regardless of the effect of temperature.

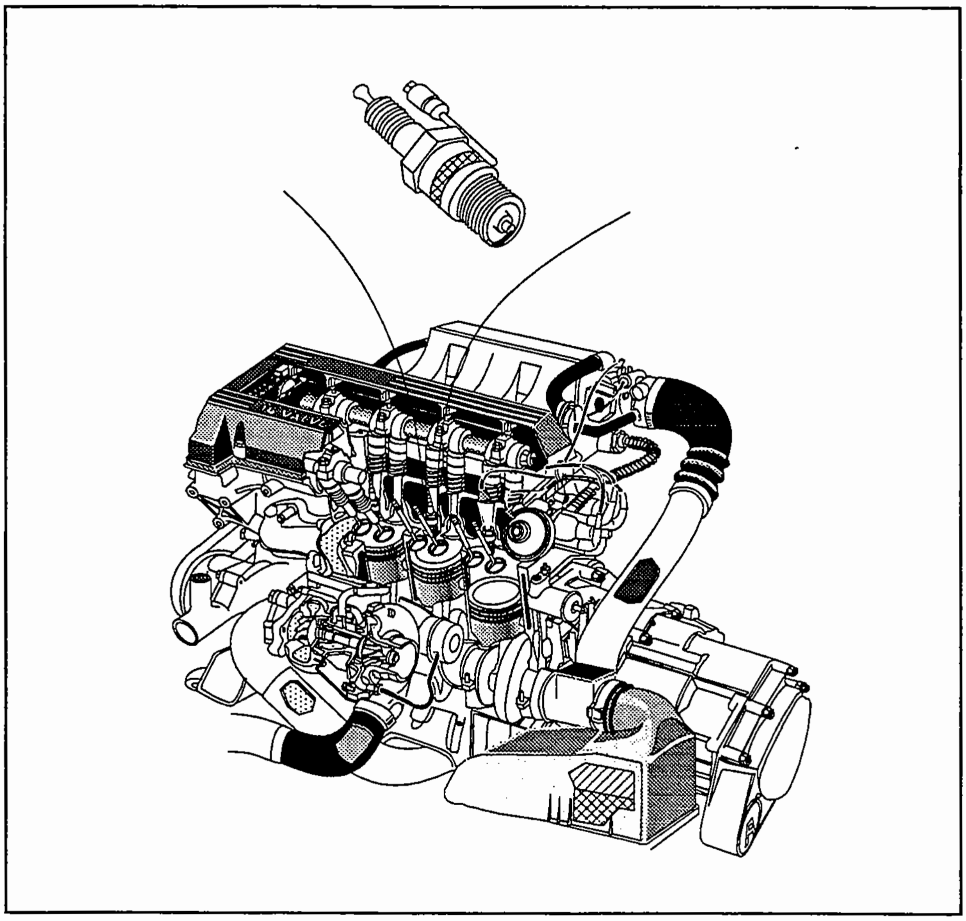


Fig. 8/1: Combustion engine in test laboratory (based on data by Kistler Instrumente GmbH)

The detailed sketch in fig. 8/1 illustrates a pressure sensor, which has been integrated into a special spark plug. In this way, it is possible to carry out the measurement without any modifications to the engine, which might distort the result. As there are no difficulties with assembly, it is also possible to carry out series measurements.

8.3 Production technology

With die-casting technology, the cavity between two half-moulds made of alloy steel is filled with liquid plastic (thermoplast). After the mould has cooled down and the plastic has hardened, the finished part can be ejected from the die-casting machine.

One important process parameter of die-casting is the pressure of the liquid plastic. Moulds are therefore being fitted increasingly with a pressure sensor (8/2). Deviations from the ideal pressure curve suggest incorrect setting of a process parameter such as injection pressure or material input. Variations in the thermoplastic characteristics of plastic material or wear of the die-casting machine or the mould forms are also possible causes.

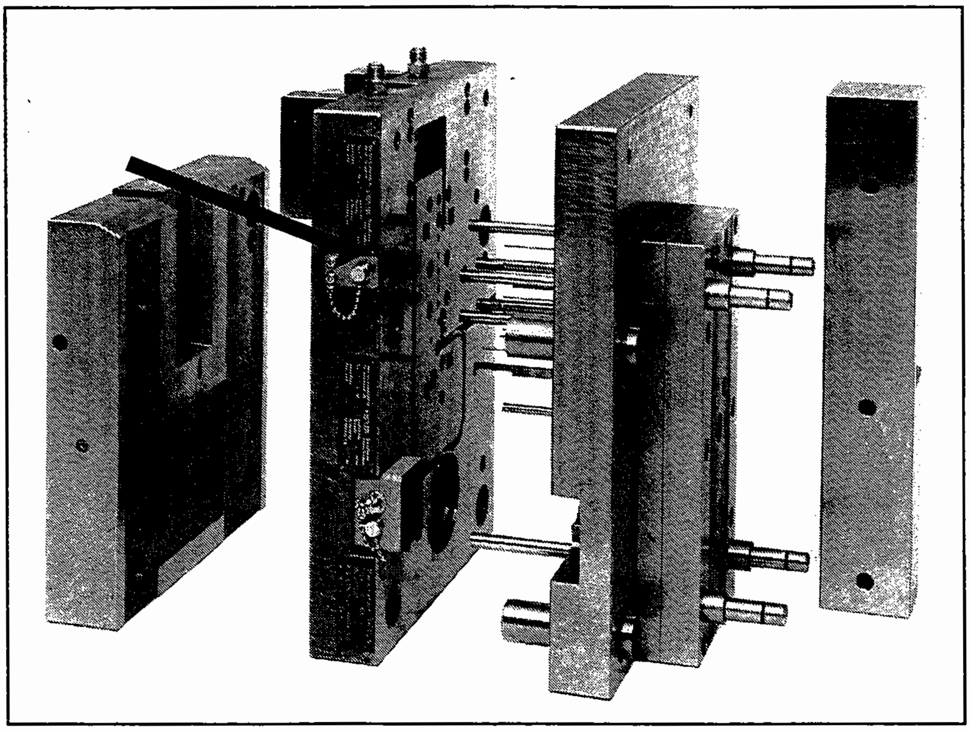


Fig. 8/2: Monitoring the internal pressure of a mould during plastic injection moulding (Photo: Kistler Instrumente GmbH)

With simple die-casting parts, it is sufficient to register maximum pressure. In the case of more complex parts, the entire pattern of pressure over a working cycle is recorded and compared with the specification including the tolerance band. In the case of specifically safety-related parts such as components of anti-lock systems for motor vehicles, the pressure characteristics are electronically stored for each individual part and archived.

Pressure sensors in injection moulds have to be flush mounted with the diaphragm positioned at the front. The sensor must be especially rigid in order not to leave any visible imprints on the injection moulded parts.

8.4 Assembly technology

Robots are often used in the assembly of housings, whereby self-tapping screws are positioned by means of a screw fitting device.

One problem is the monitoring of continuous supply and the correct alignment of the screws.

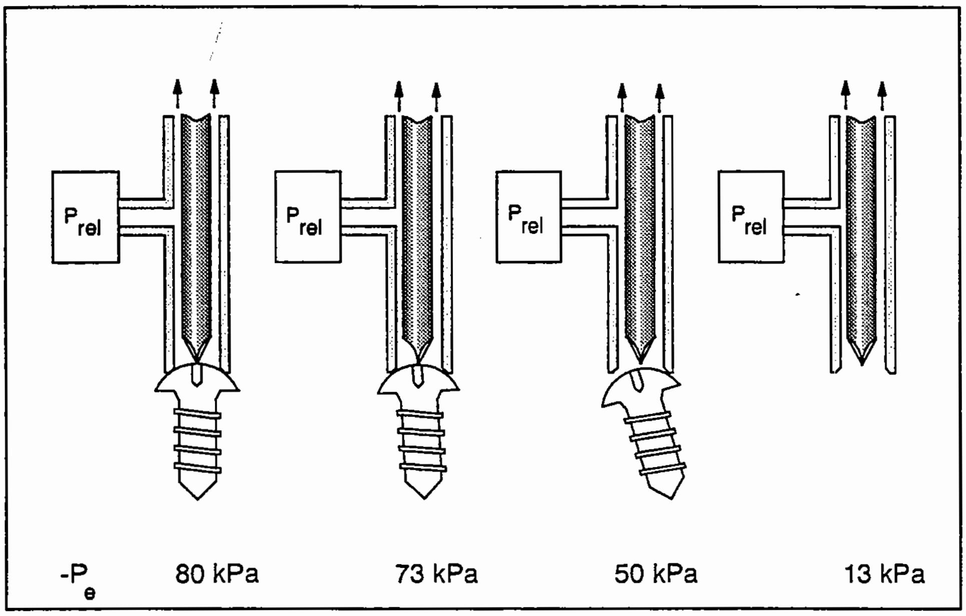


Fig. 8/3: Monitoring the supply and alignment of screws by detecting a vacuum

The screws are retained by means of a vacuum until the process of assembly is complete. The above monitoring task can be carried out by simply measuring the vacuum in the pneumatic system. On the basis of the resulting vacuum, it is possible to differentiate between screws which are placed correctly or at an angle as well as missing screws. Similar automatic monitoring is also used for vacuum grippers in handling systems.

8.5 Process technology

Pressure sensors are used in process technology wherever a process requires the supply of gases or fluids in correctly measured quantities in the broadest sense. Applications are diverse: from food processing to cosmetics and the chemical industry to oil refinery, to mention but a few.

In power stations too, pressure sensors are used in large quantities.

Fig. 8/4: Monitoring of pressure in pipes (Photo: Hottinger Baldwin Messtechnik GmbH)

With pressure sensors, pressure in pipes can be adjusted or monitored. In the first instance, a regulator controls a transporting device or a pressure reducer on the basis of a pressure signal. In the second instance, the signal is is conveyed to a display unit or limit values are monitored. In some cases, periodic monitoring of the measuring point is all that is required. As illustrated in fig. 8/4, this can be done by means of mobile pressure gauges.

8.6 Materials management

Simple length measuring systems can be used for measuring the filling level in a tank or a silo, e.g. a float with mechanical rod linkage and a potentiometer. Depending on the characteristics of the medium, contactless distance measurement or inductive or capacitive limit switches may be applied. One simple alternative for fluid mediums is to measure the hydrostatic pressure at the base of the container.

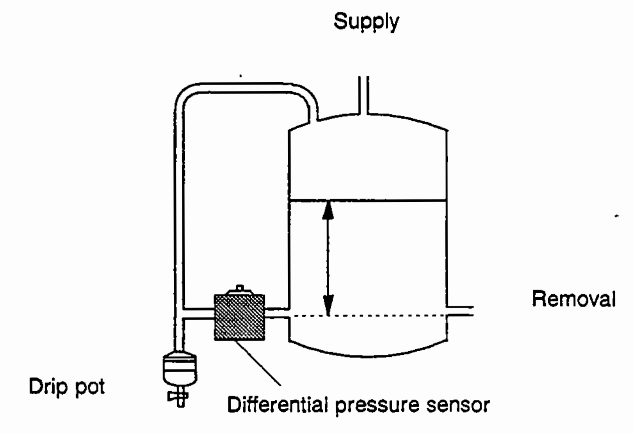


Fig. 8/5: Measurement of filling level by means of differential pressure method

If the container is under pressure, a second pressure measurement must be carried out above the fluid level. Only the difference between the two pressures can determine the height of the fluid column. As illustrated in Fig. 8/5, a single differential pressure sensor is sufficient in the case of the differential pressure method.

8.7 Quality assurance

Containers, pipes and distribution components for fluids or gases must be leak-proof. This is an obvious requirement for all pneumatic and hydraulic installations. However, it applies particularly with regard to the transport or storage of poisonous or radioactive substances. Leaks can be checked by filling the test object with air and in special cases also with helium, up to a defined testing pressure. Pressure drop over a period of time is recorded by means of a pressure sensor. The greater the leak, the quicker the pressure drop.

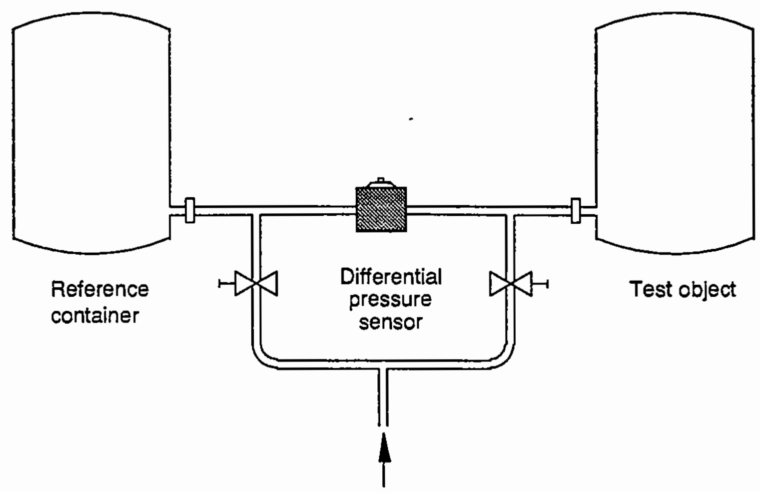


Fig. 8/6: Leakage test by means of measuring the differential pressure

The smaller the volume of the test object, the faster will be the pressure drop due to leakage. To obtain immediate results with a minimum of calculation for the purpose of quality assurance, a reference container and the test container are filled at the same time. This guarantees the same pressure and volume. In particular, thermodynamic effects in the form of temperature or pressure changes and subsequent cooling are eliminated. Both are subsequently separated and a differential pressure sensor is used to determine whether the pressure in the test object drops quicker than that in the reference container.

This method even permits testing where a certain amount of leakage is permissible. In this case, the reference container indicates leakage which is just permissible. Any pressure drop in the test object beyond that classifies this as a reject.

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Illustration number	Source
1/8, 5/7, 6/2, 8/2,	Kistler Instrumente GmbH, D-7302 Ostfildern 2
3	Festo KG, D-7300 Esslingen
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Solutions

Exercises

Force measurement

Pressure measurement

Part exercise b)

B 2.1

Under tension, the resistance of a strain gauge increases; when compressed, the strain gauge is shortened, and the resistance is reduced. The resistance changes are very small (a few milliohms).

Resistance of an unloaded strain gauge:	**350** Ohm
Change in resistance ΔR_{SG} =	**0.2** Ohm
The resistance of a loaded strain gauge is:	
	☒ greater ☐ smaller ☐ remains the same

Table 1/2: Qualitative signal change of a strain gauge with tensile stress

Part exercise c)

Resistance of an unloaded strain gauge:	**350** Ohm
Change in resistance ΔR_{SG} =	**0.2** Ohm
The resistance of the loaded strain gauge is:	
	☐ greater ☒ smaller ☐ remains the same

Table 1/3: Qualitative signal change of a strain gauge with compressive stress

Part exercise d)

Percentage resistance change $\Delta R_{\%}$ =	**0.057%**

Table 1/4: Percentage resistance change

Answer

The shape of the strain gauge changes in the same way as the surface of the deflecting arm, because the strain gauge is attached to this spring component. If plastic deformation of the deflecting arm occurs with the introduction of a large force, then the resistance value of the unloaded strain gauge also changes. In this case, the resistance of the strain gauge deviates slightly from its initial output resistance.

Part exercise b)

If a deflecting arm is loaded, one side is always under tension and the other side under compression. This means that one strain gauge is stretched and the opposite strain gauge compressed. As a result of this, the resistance changes possess different signs.

Ideally, the sum of the resistance changes of the two strain gauges connected in series should therefore equal zero irrespective of the load on the deflecting beam. Because of production conditions, however, all individual strain gauges (SG) are different. Therefore, very slight resistance changes may occur when the tests are carried out.

Resistance of the unloaded strain gauge: **700** Ohm
The resistance of the loaded strain gauge is:
☐ greater ☐ smaller ■ remains the same

Table 2/2: Qualitative signal change if pressed downwards

Part exercise c)

Resistance of the unloaded strain gauge: **700** Ohm
The resistance of the loaded strain gauge is:
☐ greater ☐ smaller ■ remains the same

Table 2/3: Qualitative signal change if pressed upwards

Note

When a deflecting arm is loaded, the strain gauges on the opposite side undergo a similar, but opposing change in resistance. This characteristic is used for signal evaluation.

Answer

If plastic deformation of the deflecting beam occurs due to the application of excessive force, then the resistors of the strain gauge in the unloaded status also change. Due to the bending load, the resistance change of the two strain gauges is opposing and of an equal amount. Therefore, the total resistance does not change.

B 4.3

Part exercise c)

On the tension side, the strain gauge is stretched and its resistance increases. Due to this resistance change, the voltage drop increases across the strain gauge. The millivolt signal resulting from this is amplified to the volt range in the signal amplifier.

The signal change on the amplifier output lies in the:
☐ Millivolt range ■ Volt range

Table 3/2: Qualitative signal change

Amplification factor	a = **500**
Amplification output voltage	V_O = **0.36** Volt

Table 3/3: Amplification output voltage

Part exercise a)

Depending on the deflecting arm force sensor and the measuring bridge amplifier, the results in this sample solution may vary slightly from the measured values determined by you.

Mass (g)	Force (N)	Voltage (V)
0	0.0	0
20	0.2	0.02
50	0.5	0.05
100	1.0	0.11
200	2.0	0.22
500	5.0	0.57

Table 4/3: Table of values for sensor characteristic curve

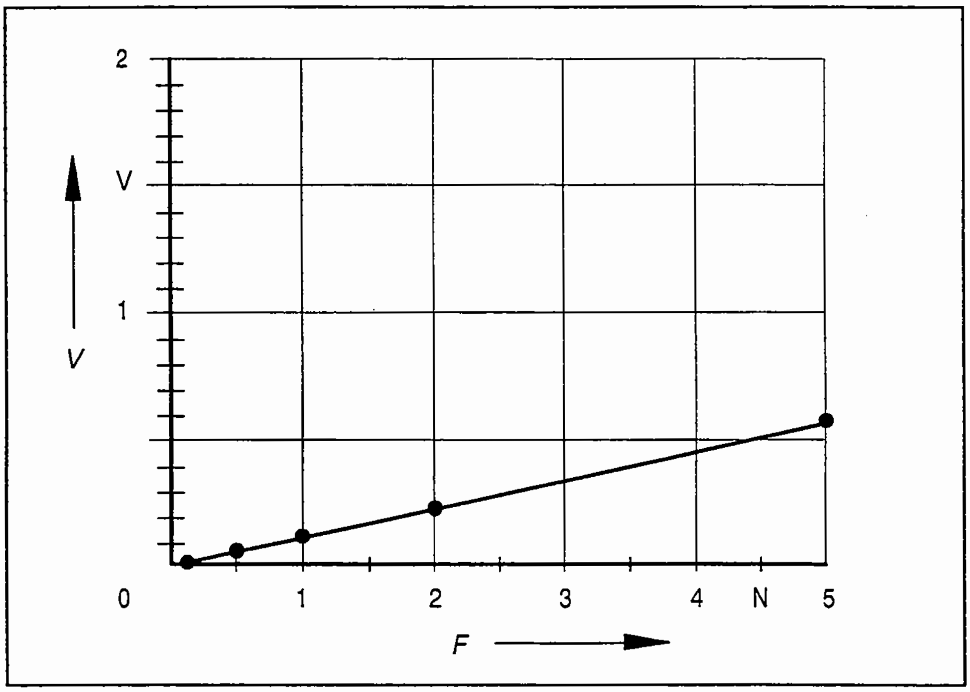


Fig. 4/5: Characteristic line of deflecting arm force sensor in quarter-bridge circuit

Part exercise b)

To determine a force from the diagram

To do this, a line (x) is drawn parallel to the force axis from point A of the signal axis. From the intersection point (S) a line (y) is drawn parallel to the signal axis (V). The resulting intersection point (W) with the force axis gives the value of the force to be determined.

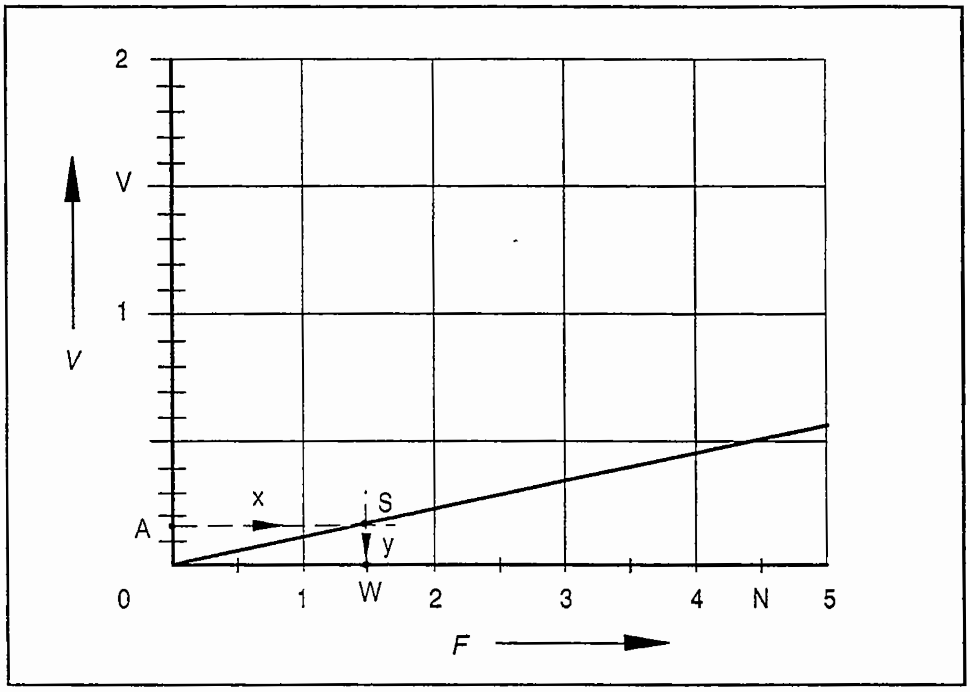


Fig. 4/6: Procedure for determining force

Voltage (V)	Force (N)	Mass (g)
0.15	1.5	150

Table 4/4: Example for determining the force of a given mass

Part exercise b)

Depending on the deflecting arm force sensor used and the measuring bridge amplifier, the results in this sample solution may vary slightly from the measured values determined by you.

Mass (g)	Force (N)	Voltage (V)
20	0.2	0.04
50	0.5	0.11
100	1.0	0.22
200	2.0	0.45
500	5.0	1.14

Table 5/3: Table of values for the characteristic line of the sensor

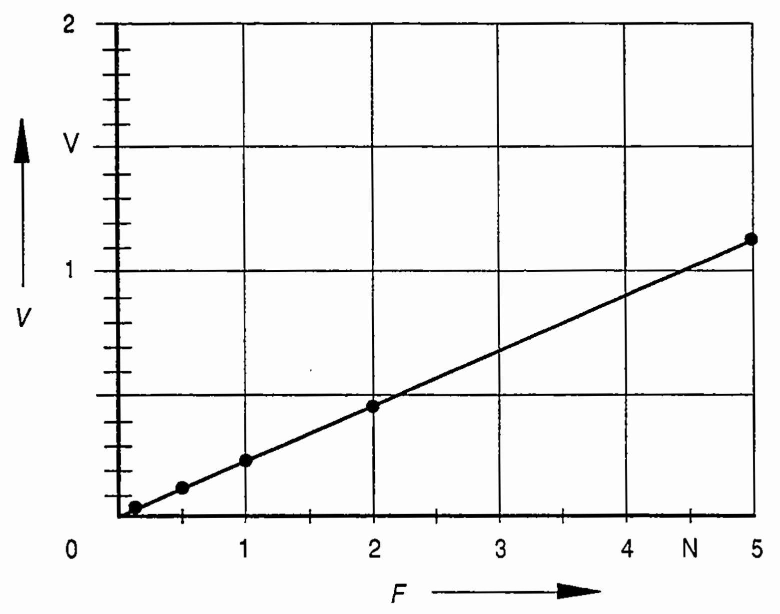


Fig. 5/5: Characteristic curve of deflecting arm force sensor in half-bridge circuit

Note

By using the deflecting arm force sensor with a half-bridge circuit, double the signal strength of a quarter-bridge circuit is generated with the same load. Thus the deformation of the second strain gauge ensures that the detuning of the Wheatstone bridge circuit is twice as strong.

If you have used the same weight for the force measurement as in exercise 4, you will detect a doubling of the signal.

Answer

The resistance changes of the two strain gauges oppose each other and are of the same magnitude. Due to the half-bridge circuit, the signal is doubled compared to the quarter-bridge circuit. Because the characteristic curve of the half-bridge circuit is twice as steep as the characteristic curve of the quarter-bridge circuit, this results in a doubling of the signal resolution.

Part exercise c)

To determine a force from the diagram

To do this, a line (x) is drawn parallel to the force axis from point A of the signal axis. From the intersection point (S) a line (y) is drawn parallel to the signal axis (V). The resulting intersection point (W) with the force axis gives the value of the force to be determined.

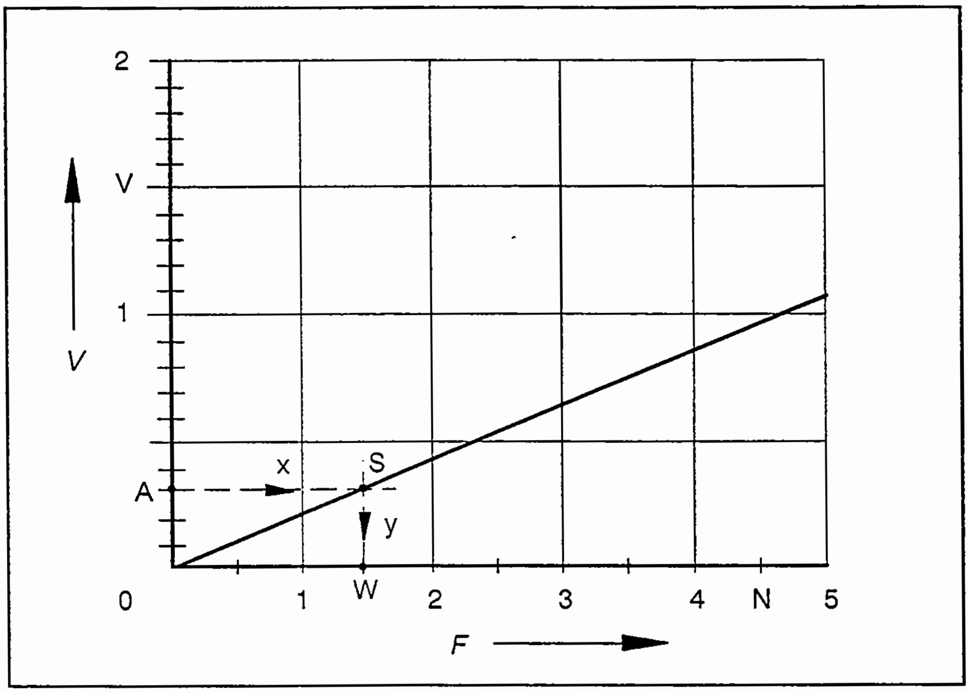


Fig. 5/6: Procedure for determining the force

Voltage (V)	Force (N)	Mass (g)
0.3	1.5	150

Table 5/4: Example for determining the weight of a particular mass

Answer

The half-bridge circuit generates double the signal strength for a given force on the deflecting beam. This is why double the signal strength is recorded while using the same weight as in exercise 4.

Part exercise b)

Depending on the force sensor used, the results in this sample solution may deviate slightly from the measured values determined by you.

Mass (kg)	Force (N)	Voltage (V)
0	0	0.00
1	10	0.12
2	20	0.24
3	30	0.36
4	40	0.48
5	50	0.60
6	60	0.72
7	70	0.84
8	80	0.96
9	90	1.08
10	100	1.20

Table 6/3: Table of values for characteristic line of the sensor

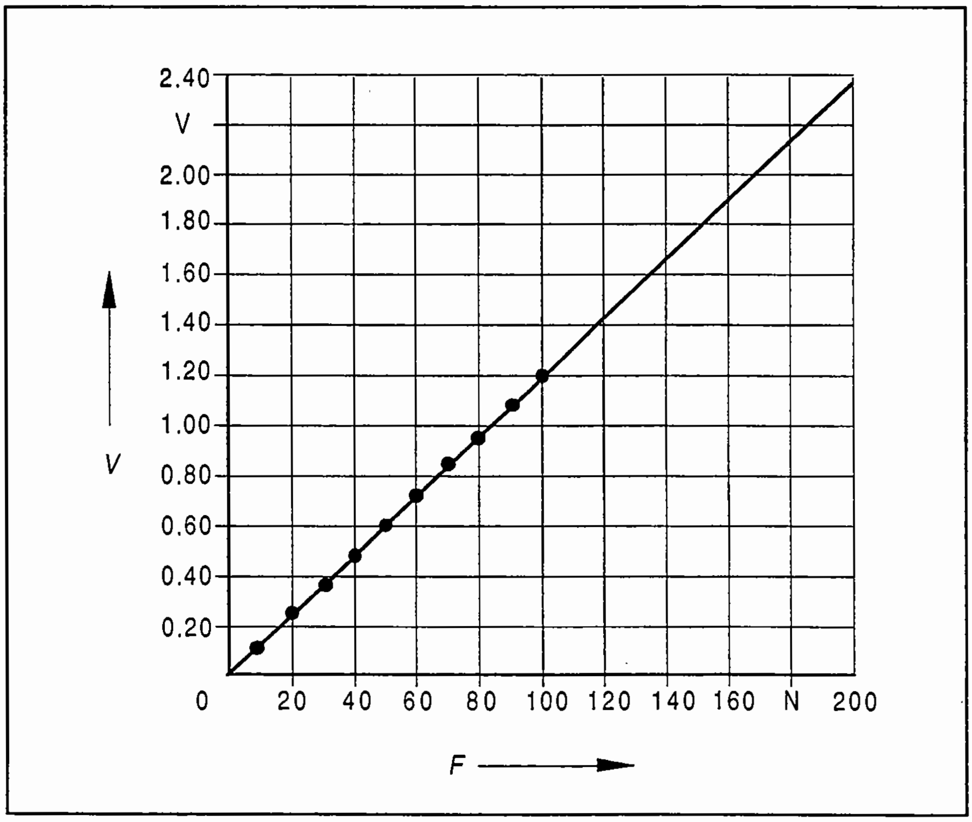


Fig. 6/5: Characteristic line of force sensor

Part exercise b, c)

The measuring values depend on the actual cylinder and force sensor used. The values in the following table solution may therefore vary from your measurements.

Pressure (bar)	$F_{(theor)}$ (N)	Voltage (V)	F_{actual} (N)	F_R (N)
1.0	49.1	0.50	41.7	7.4
2.0	98.2	1.06	88.3	9.9
3.0	147.3	1.63	135.8	11.5
4.0	196.3	2.20	183.3	13.0

Table 7/3: Table for determining the cylinder force

Part exercise d)

To determine a force from the diagram

To do this, a line (x) is drawn parallel to the force axis from point A of the signal axis. From the intersection point (S) a line (y) is drawn parallel to the signal axis (V). The resulting intersection point (W) with the force axis gives the value of the force to be determined.

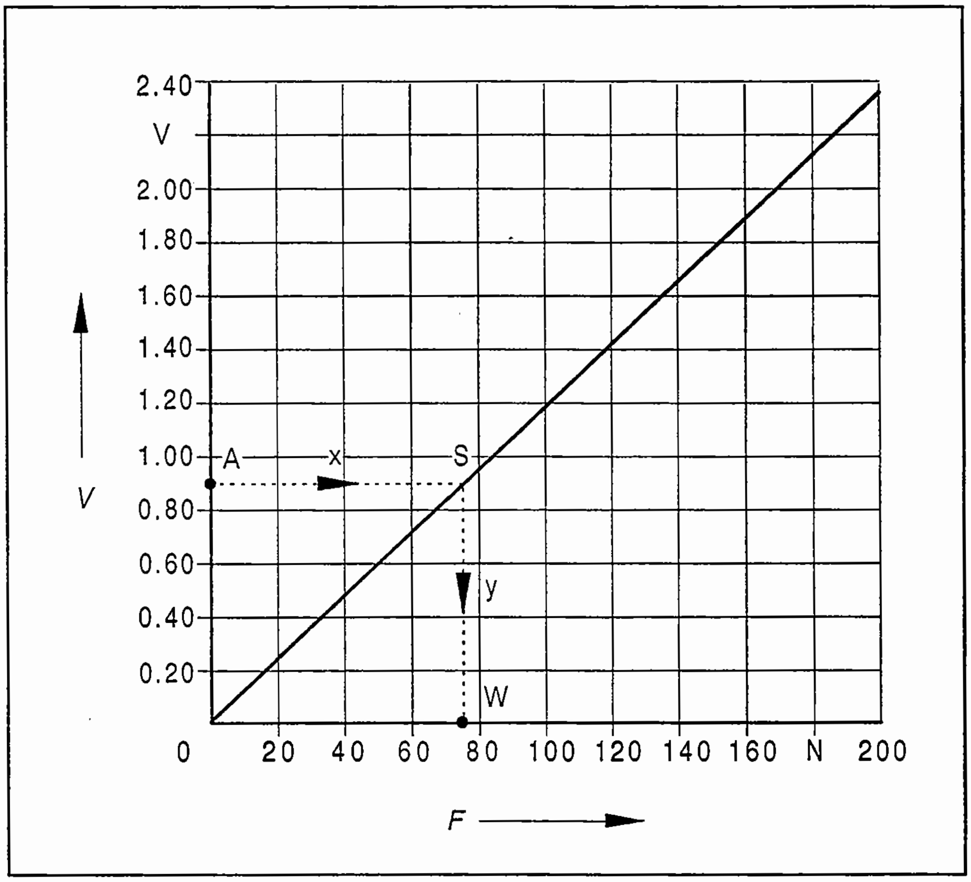


Fig. 7/6: Procedure for determining force

Voltage (V)	Force (N)
0.9	75

Tabelle 7/4: Example of force calculation

Part exercise a)

Connection	Plug colour
+ 24 V	red
0 V	blue
Voltage signal	black
Current signal	white

Table 8/3: Plug colours

A reliable wiring colour identification code enables the user to carry out the assembly of an analogue pressure sensor correctly.

Part exercise b)

Depending on the accuracy of the measuring device and the analogue pressure sensor used, the results below may vary slightly from the measured values determined by you.

p (bar)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Voltage (V)	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0

Table 9/3: Table of values for determining the voltage characteristic line

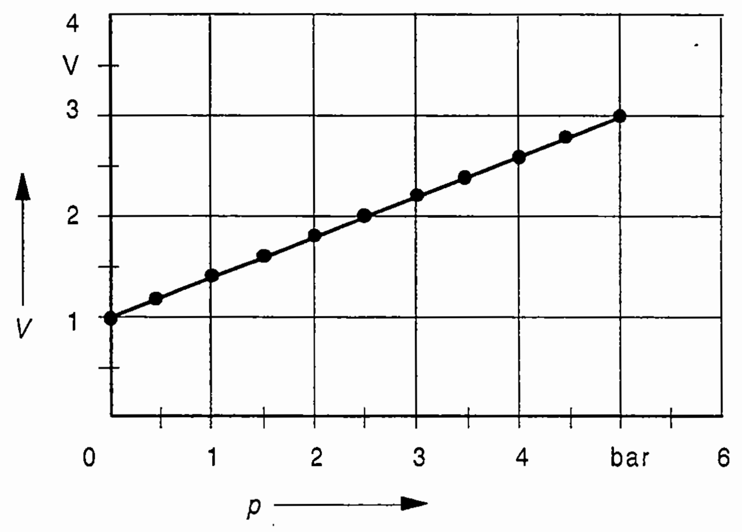


Fig. 9/7: The voltage characteristic line

Part exercise c)

p (bar)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Current (mA)	4.0	4.8	5.6	6.4	7.2	8.0	8.8	9.6	10.4	11.2	12.0

Table 9/4: Table of values for determining the current characteristic line

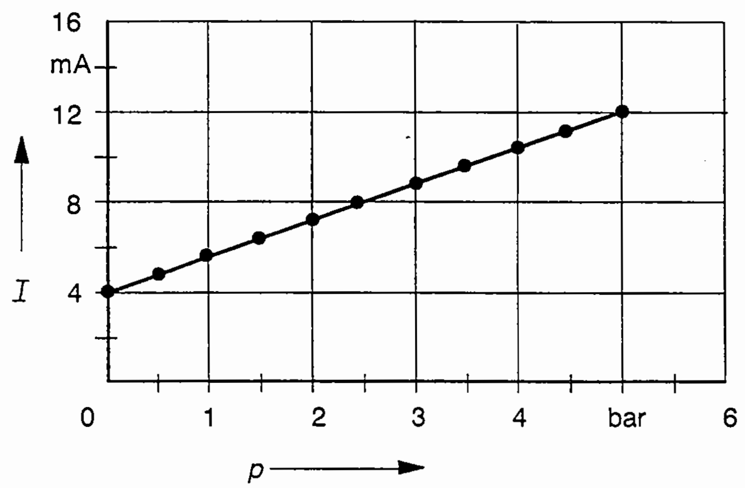


Fig. 9/8: The current characteristic line

To determine a pressure value from the characteristic line

Part exercise d)

To do this, a line (x) is drawn parallel to the force axis from point A of the signal axis. From the intersection point (S) a line (y) is drawn parallel to the signal axis (V) resulting intersection point (W) with the force axis gives the value of the force to be determined.

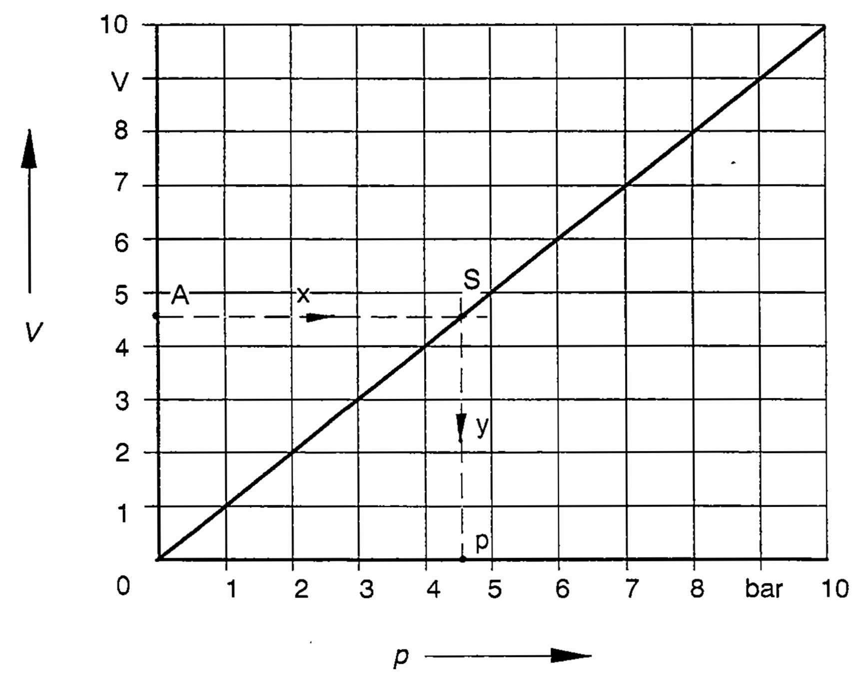


Fig. 9/9: Procedure for determining pressure

Measuring device	Voltage (V)	Current (mA)	p (bar)
Pressure gauge	———	———	3.60
SDE-10-10V/20mA	3.75	———	3.75
SDE-10-5V/20mA	2.50	———	3.75
SDE-10-5V/20mA	———	10.0	3.75

Table 9/5: Example of pressure measurement

Note

With different evaluation units (PLC, display, etc.), it is often advantagous to use sensors with different characteristic curves. If the evaluation unit can record the entire signal range of the sensor, then the resolution increases.

Part exercise b)

Measurement	Response pressure (bar)
1	The results of your measurements depend on the setting of the adjustment screw.
2	
3	
4	

Table 10/3: Table of values for determining response pressure

Part exercise d)

The measured values depend on the setting of the hysteresis adjustment screw. The values below may therefore differ from your measurements.

p_o (bar)	p_u (bar)	Hysteresis (bar)
3.00	2.07	0.93

Table 10/4: Table of values for determining hysteresis

Part exercise e)

p_o (bar)	p_u (bar)	Hysteresis (bar)
1.00	0.48	0.52
2.00	1.29	0.71
3.00	2.07	0.93
4.00	2.96	1.04

Table 10/5: Hysteresis for various switching states

Part exercise b)

Measurement	Response pressure (bar)
1	The results of your measurements depend on the setting of the adjustment screw.
2	
3	
4	

Table 11/3: Table of values for determining response pressure

Part exercise d)

The hysteresis of individual pressure switches depends on their mechanical construction. The values of the results below may therefore differ from your measurements.

p_o (bar)	p_u (bar)	Hysteresis (bar)
3.00	2.87	0.13

Table 11/4: Table of values for determining hysteresis

Part exercise e)

p_o (bar)	p_u (bar)	Hysteresis (bar)
1.00	0.96	0.04
2.00	1.93	0.07
3.00	2.87	0.13
4.00	3.83	0.17

Table 11/5: Hysteresis for various switching states

Part exercise d)

The hysteresis of individual pressure switches depends on their mechanical construction. The values of the results below may therefore differ from your measurements.

$p_{Difference}$ (bar)	p_o (bar)	p_u (bar)	Hysteresis (bar)
1.00	4.00	3.96	0.04

Table 12/3: Table of values for determining hysteresis

Part exercise e)

$p_{Difference}$ (bar)	p_o (bar)	p_u (bar)	Hysteresis (bar)
1.00	4.00	3.96	0.04
2.00	4.00	3.93	0.07
3.00	4.00	3.87	0.13

Table 12/4: Table of values for determining hysteresis

Answer

If the differential pressure is increased, there is a higher degree of contamination; if reduced, then the contamination is less.

Part exercise c)

p_o (bar)	p_u (bar)	Hysteresis (bar)
3.45	2.50	0.95

Table 13/3: Table of values for determining hysteresis

Part exercise e)

t (s)	0	10	20	30	40	50	60
p (bar)	4.0	3.2	2.5	2.1	1.7	1.4	1.2
t (s)	70	80	90	100	110	120	
p (bar)	0.9	0.7	0.6	0.5	0.4	0.3	

Table 13/4: Table of values for pressure drop

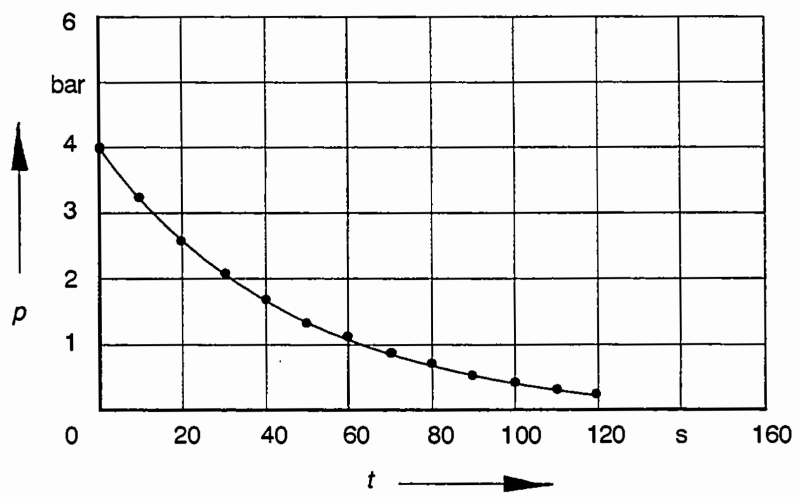


Fig. 13/7: Diagram showing time-related pressure drop

Answer

When filling the compressed air receiver, care should be taken that the filling pressure is greater than the reset point plus the hysteresis of the pressure switch. Only an actuated pressure switch can produce a signal at the reset point.

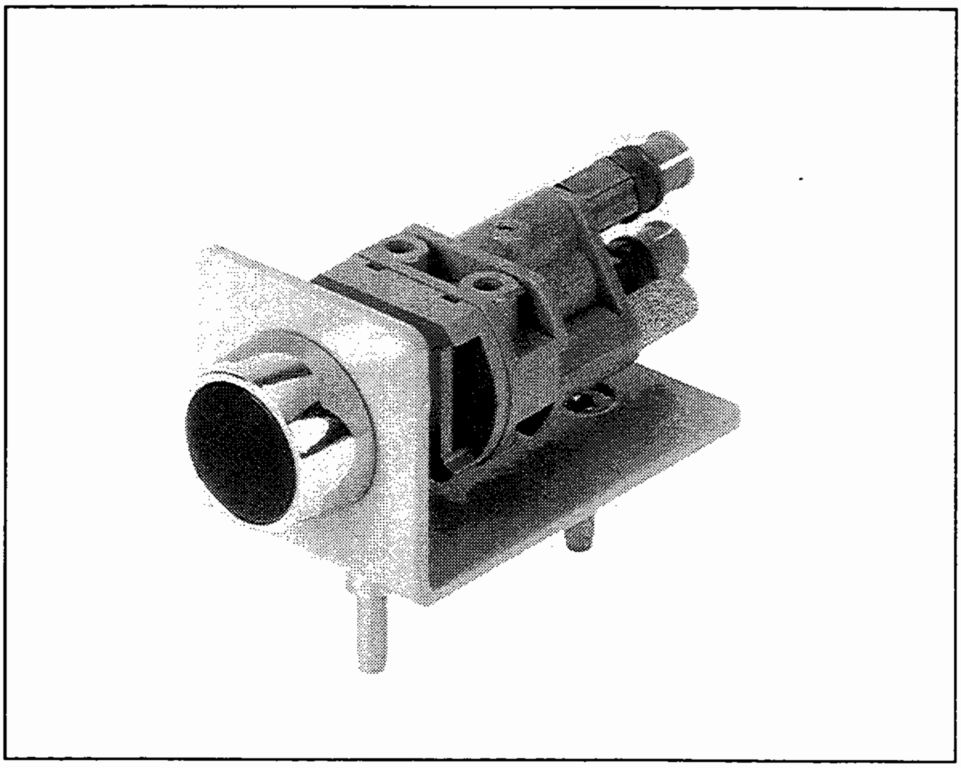
Answer

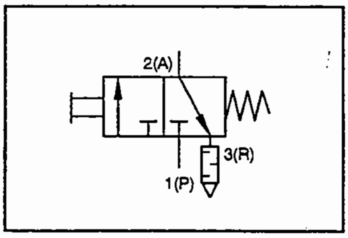
A further possibility of application for back pressure switches in the field of domestic appliances is monitoring the filling level in dish washers.

Appendix

Data sheets

3/2-way panel mounted valve	Description
D.ER-SV-3-M5	Designation
011422	Order No.





Symbol

Assembly

This component consists of a 3/2-way panel mounted valve with quick push-pull connectors and a silencer mounted on a plug-in plate. A black push-button actuating head is attached to the valve via a quick-latching device.

Function

By pressing the push-button, the valve is actuated. On release of the push-button, the valve is exhausted via a reset spring.

Note

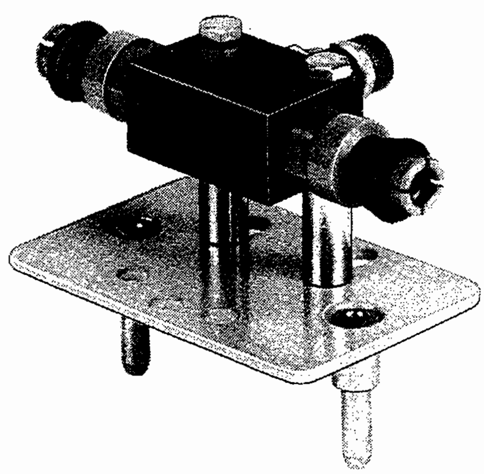
The valve positions are designated by numbers (to ISO draft standard 5599/II) or by letters:

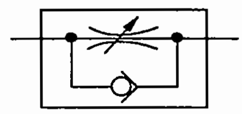
1 (P) = Supply port
2 (A) = Output port
3 (R) = Exhaust

Technical data

Medium	Compressed air, filtered (lubricated or unlubricated. Alternative: Vacuum; connection at 1 (P)).
Design	Poppet valve, unilateral direct actuation, returned via reset spring
Actuator	Push-button
Pressure range	-95 to 800 kPa (-0.95 to 8 bar)
Standard nominal pressure flow 1 (P) - 2 (A)	65 l/min
Actuating force at 6 bar	10 N
Connection	M5; PK-4 for plastic tubing PU-4

Description	One-way flow control valve
Designation	D.ER-GR-1/8 B
Order No.	011700





Symbol

Assembly

The component consists of an adjustable one-way flow control valve with quick push-pull connectors mounted on a plug-in plate.

Function

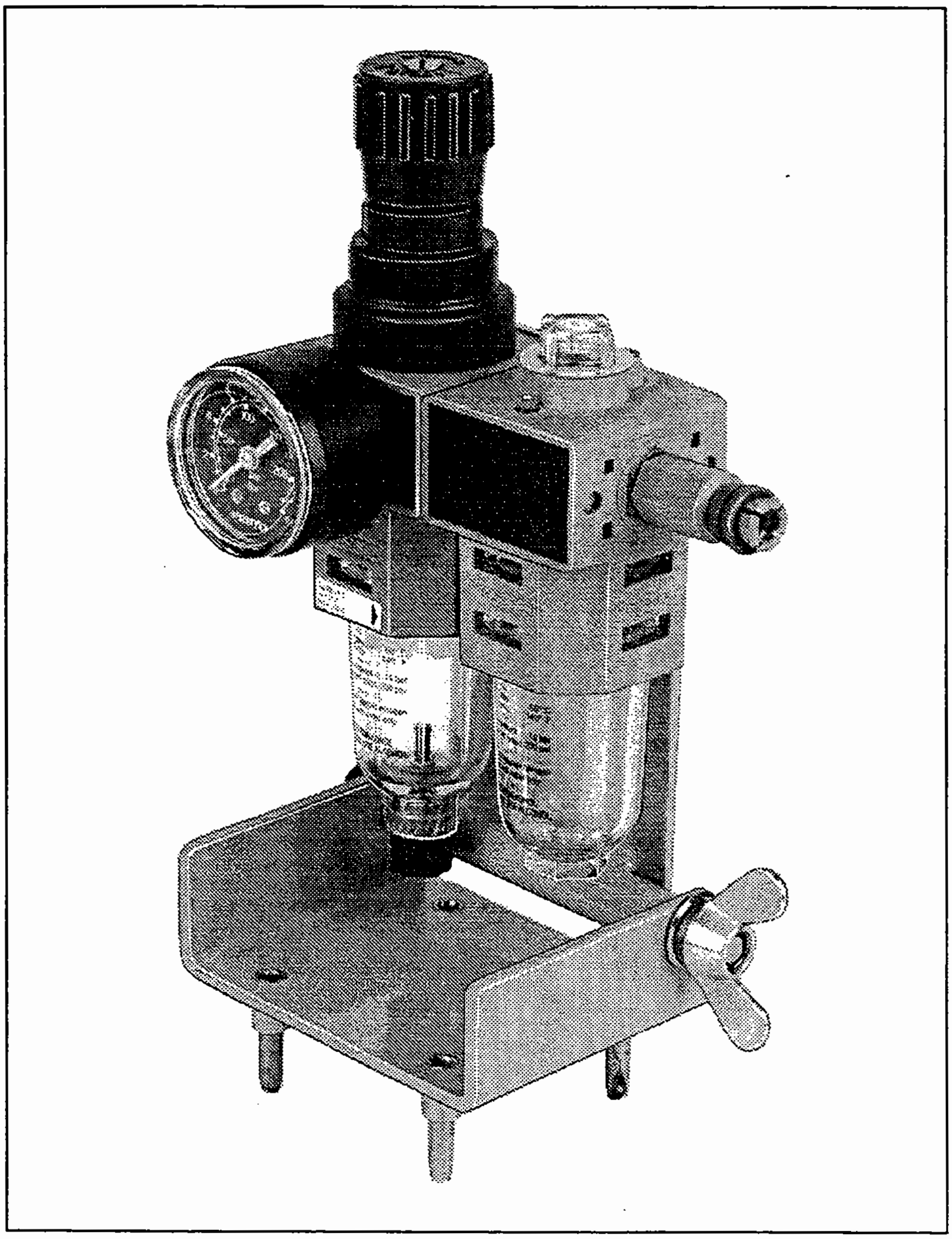
The one-way flow function is achieved by the combination of a flow control valve and a non-return valve.

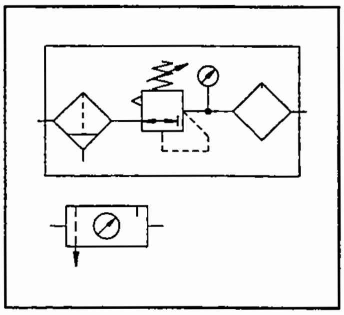
The non-return valve blocks the flow of air in one direction, so that the air must flow through the flow control valve. The throttle cross section can be adjusted by means of an adjusting screw. The direction of flow control is indicated by an arrow on the housing. In the reverse direction, the air flows freely via the non-return valve.

Technical data

Medium	Compressed air, filtered, (lubricated or unlubricated)
Design	One-way flow control valve
Pressure range	0.5 to 10 bar (50 to 1000 kPa)
Standard nominal flow rate	
in direction of flow control	0 to 100 l/min
against direction of flow control	150 l/min
Connection	G 1/8; PK-4 for plastic tubing PU-4

Description	**Service unit**
Designation	**D.ER-FRC-1/8-S**
Order no.	**011758**





Symbol

Design

This element consists of a swivel-mounted service unit comprising of a filter, pressure regulator, pressure gauge, lubricator, quick coupling connection and quick push-pull connector, mounted on a plug-in plate.

Function

The **filter** includes a water separator and cleans the compressed air of dirt, pipe scale, rust and condensation.

The **regulator** regulates the incoming compressed air to the set working pressure and evens out fluctuations in pressure. The direction of flow is indicated by an arrow on the body of the valve.

The **lubricator** mixes a certain amount of oil mist into the air after it has been cleaned. The mist injection is proportional to the throughput of air.

The **pressure gauge** indicates the pressure in the pneumatic control system.

Note

When building circuits make sure that the service unit is in an upright position when installed.

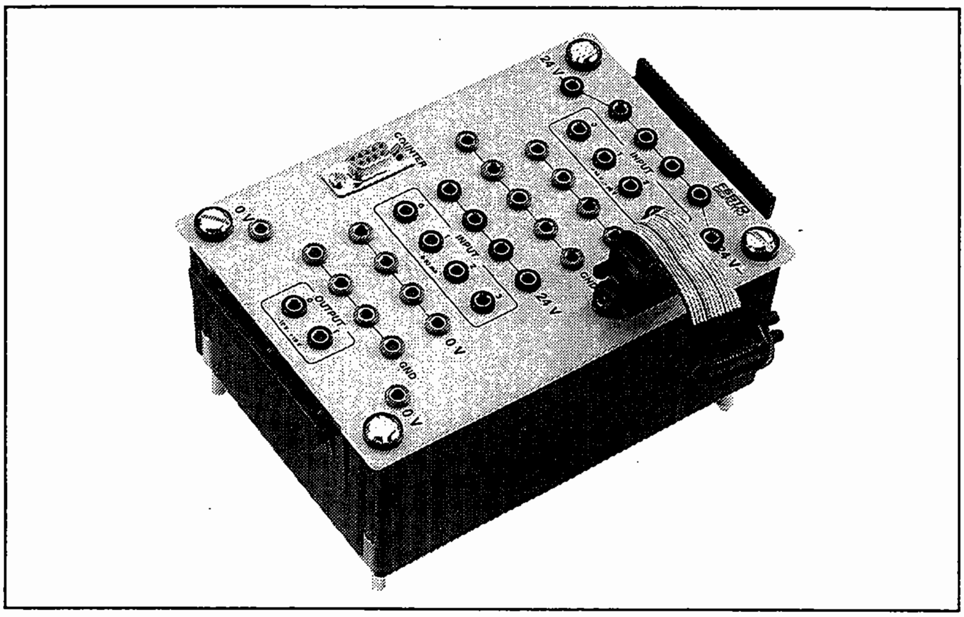
The pressure regulator can be locked by means of the regulator head. If the head is pulled upwards, it is unlocked; the required pressure can be set by turning. In order to lock the head, it is pushed downwards (audible engagement).

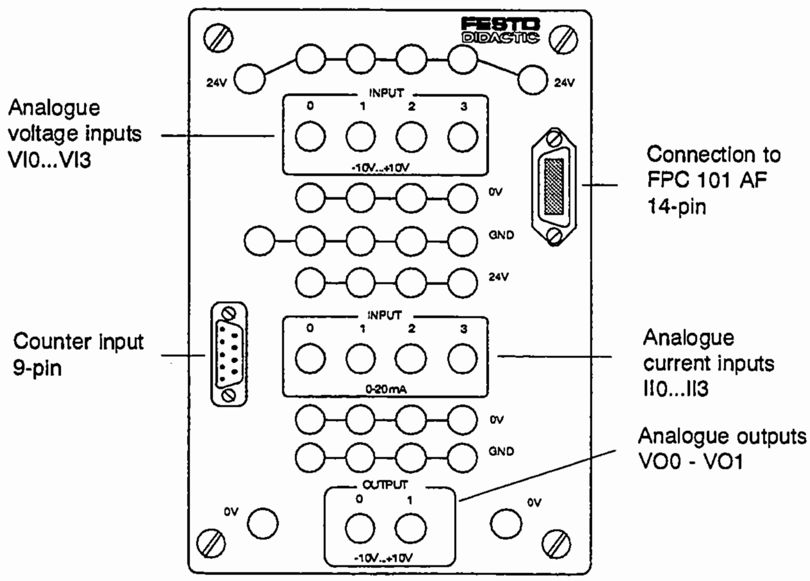
Technical Data

Medium	compressed air
Design	sintered filter with water separator, piston-type relieving regulator, direct proportional lubricator
Standard nominal flow rate*	550 l/min
Upstream pressure	max. 1400 kPa (14 bar)
Operating pressure	max. 1200 kPa (12 bar)
Min. flow for lubricator	from 2.4 l/min
Filter rating	0.04 mm average pore size
Condensate capacity	10 cm^3
Connection	R 1/8 PK-4 for plastic tubing PU-4 KS1/8 for coupling plug KD-1/8N

* Upstream pressure 1000 kPa (10 bar)
Working pressure 600 kPa (6 bar)
Differential pressure 100 kPa (1 bar)

Connection unit 101AF	Description
D.ER-AE-101AF	Designation
014595	Order No.





Assembly

The connection unit 101AF is mounted in a single housing with connector sockets for assembly on a panel or assembly board.

The connection unit is supplied with a flat ribbon cable with 14 pin sub-miniature plug (Order No. 327594) for linking to a 101CPU connection unit (Order No. 14593). The analogue inputs and outputs are accessible via 4 mm sockets.

A shaft encoder can be connected via the 9-pin SUB-D socket.

Function

The 101AF connection unit permits the connection of a Festo FPC 101AF programmable logic controller via 4 mm sockets. The connection unit can also be used as a signal distributor without the programmable logic controller.

The Festo Didactic power pack provides a 24 V power supply for the 101CPU and the 101AF connection units.

The analogue current inputs of the FPC 101AF programmable logic controller (II0...II3), the analogue voltage inputs (VI0...VI03), the analogue voltage outputs (VO0,VO1) and the analogue ground signal (GND) are all accessible via 4 mm sockets.

The counter inputs of the FPC 101AF controller (A+, B+, I+) can be connected to a shaft encoder via the 9-pin SUB-D socket.

All inputs and outputs (4 mm sockets) of the 101AF connection unit are designed with a protective circuit against reverse polarity, whereby the 24 Volt power supply (max. 27 V) can be connected to the analogue voltage and current inputs without damaging the inputs of the FPC 101AF controller.

If the 24 V socket is connected with the sockets for the analogue voltage output, this may damage the fuses built into the 101AF connection unit. In this case, open the 101AF connection unit and replace the damaged fuse with a new fuse (Order No. 331612).

The analogue voltage outputs (VO0, VO1) are short-circuit proof which means that the built-in fuses cannot be damaged!

Note

The FPC 101AF controller connected via the connection unit is protected against reverse polarity and short-circuit.
If 2, 3 or 4 sensors are connected to the current inputs (II0...II3), GND must be connected to 0 V, otherwise the currents add up.

Technical data

All data applies in connection with the FPC 101AF programmable logic controller	
Permissible operating voltage	24 V D.C.
Perm. voltage fluctuations	22 V D.C. ... 27 V
Analogue voltage inputs	
Range	–10 V ... +10 V to GND (max. ± 30 V)
Input resistance	200 kΩ
Analogue current inputs	
Range	0 ... 20 mA to GND (max. –4 ... +24 mA)
Input voltage	max. ± 30 V
Analogue voltage outputs	
Range	–10 V ... +10 V to GND Short circuit protected max. ± 30 V
Additional data	see FPC 101AF manual*

* *Festo FPC 101 programmable logic controller, operator manual (Order No. 81446)*

Counter

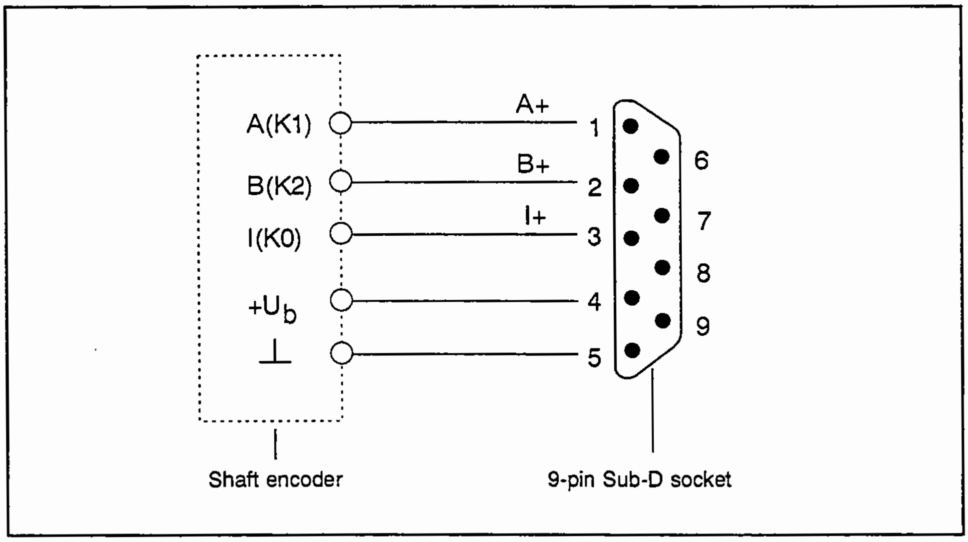
You have the facility to expand the FPC 101AF programmable logic controller functions by additionally fitting a counter chip (E.CIC-101-AF, Order No. 14609).

This enables you to:

- realise counter functions, whereby pulses of a high clock-pulse rate need to be detected (fast counter) or
- solve simple positioning tasks by using a 2-channel shaft encoder with/without zero or index pulse (incremental/decremental counter).

Technical data
Counter

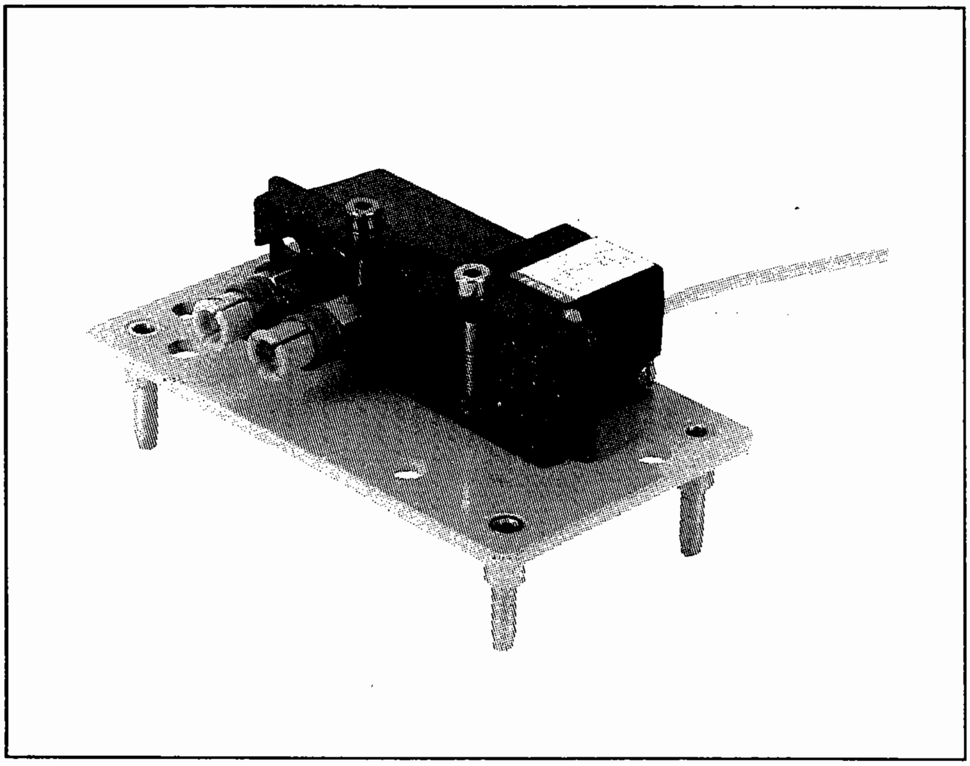
Input voltage	24 V D.C.
Max. input voltage	27 V D.C.
Max. frequency	Shaft encoder max. 25 kHz Single-level evaluation max. 100 kHz
Phase displacement	$90^o \pm 20^o$
Resolution	24 Bit
Response time	0.65 ms to 35 ms depending on processor load and type of reaction required (see FPC 101AF manual)*
Input resistance	1.2 kOhm
Input current	max. 20 mA

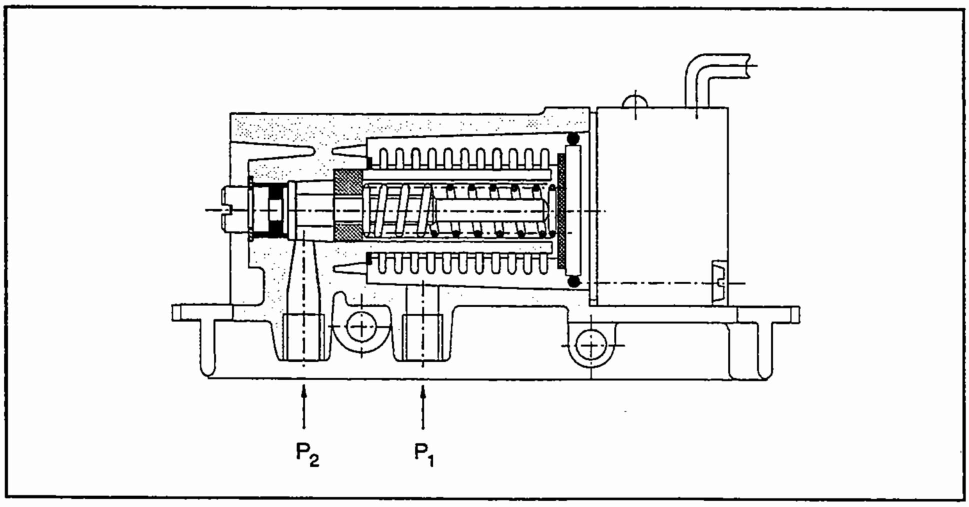


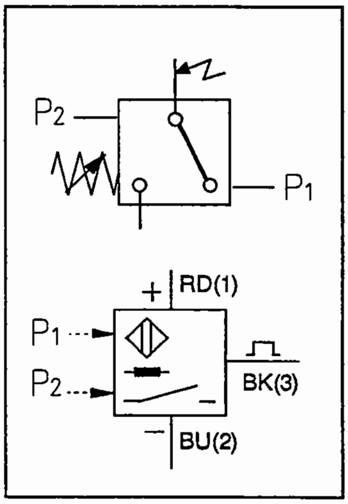
Connection of a shaft encoder

* *Festo programmable logic controller FPC 101, Operator Manual (Order No. 81446)*

Pneumatic-electronic switch	**Description**
D.ER-PEN-M5	**Designation**
032188	**Order no.**







Pneumatic and electrical symbol

Design

This element consists of a pneumatic-electrical signal converter, mounted on a plug-in plate.

Function

The spring pressure, which presses the metal bellows against the stop face, can be adjusted by an adjusting screw. The metal bellows is then situated within the active area of the initiator. When the metal bellows is moved by a pneumatic signal, the initiator is activated and produces an output signal, which can switch loads up to max. 400 mA.

The pneumatic-electrical signal converter has 3 functions: Pressure switch, vacuum switch, differential pressure switch.

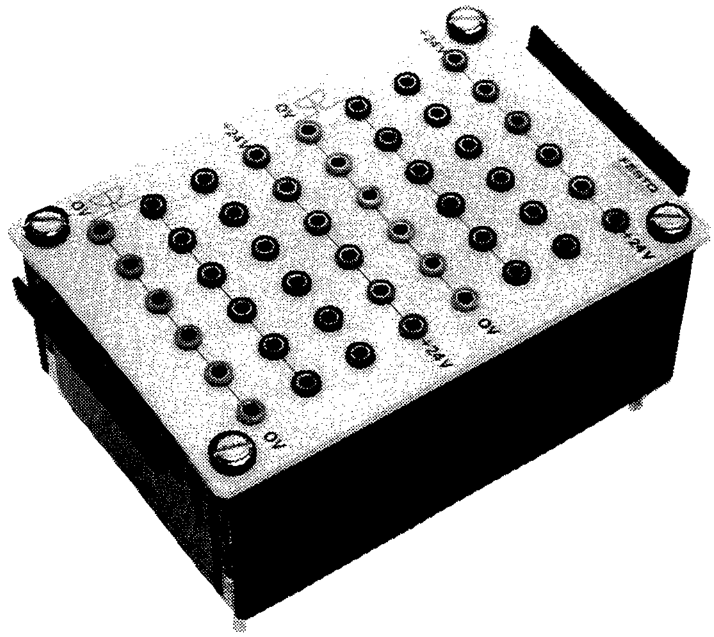
The plugs of the connection cable are marked as follows:

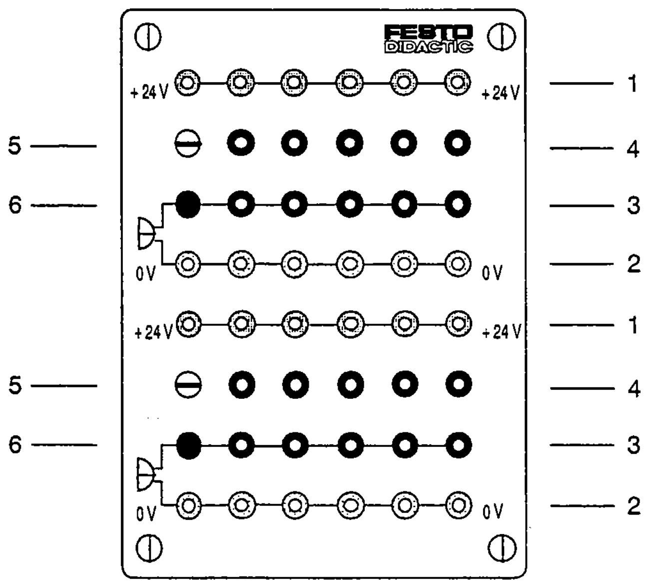
+ 24 V	red	(RD)
0V	blue	(BU)
Switch output	black	(BK)

Technical Data

Pneumatic operation	
Medium	Compressed air, filtered, lubricated or unlubricated
Design	Metal bellows pre-loaded and initiator
Pressure range	
Pressure switch	
Connection P1	Adjustable for pressure ranges between 25 and 800 kPa (0.25 to 8 bar)
Vacuum switch	
Connection P2	Adjustable for pressure ranges between -20 and -70 kPa (-0.2 bis -0.7 bar)
Hysteresis	max. 25 kPa (0.25 bar)
Pressure range	
Differential pressure switch	
Connection P1, P2	Adjustable for differential pressure ranges between 20 and 780 kPa (0.2 to 7.8 bar)
Connection	For plastic tubing PU-4
Electrical operation	
Voltage	24 V DC
Current on contact	400 mA
Connection	4 mm plug

Distribution unit	Description
D.ER-VERT-SENSOR	Designation
034080	Order No.





1 +24V
2 0V
3 Buzzer sockets
4 Vacant sockets
5 Potentiometer for sound level setting
6 Light emitting diode

Assembly

The unit has four rows of sockets for supply voltage, two rows of sockets for connecting the proximity sensor signal outputs, two audible indicators (buzzers) and two vacant rows of sockets. The electrical connections to these various sockets is established by means of 4 mm plugs. The unit is retained via four locating pins.

Attachment of this unit to the profile plate requires four plug-in adapters (Part No. 035651).

Function

The distribution plate connects the sensor units with the voltage supply. Operating voltage is supplied through the sockets of rows 1 (+24 V) and rows 2 (0 V). The switching outputs of the proximity sensors are plugged into rows 3 (fig. 1, row 3). These sockets are decoupled via diodes. If a certain sensor switches, it is signalled acoustically via a built-in buzzer and optically via a built-in light emitting diode. The volume of the buzzer can be adjusted via the potentiometers. With sensor designs which have normally open, as well as normally closed outputs, the plug not in use at that time is pushed into one of the vacant sockets of rows 4.

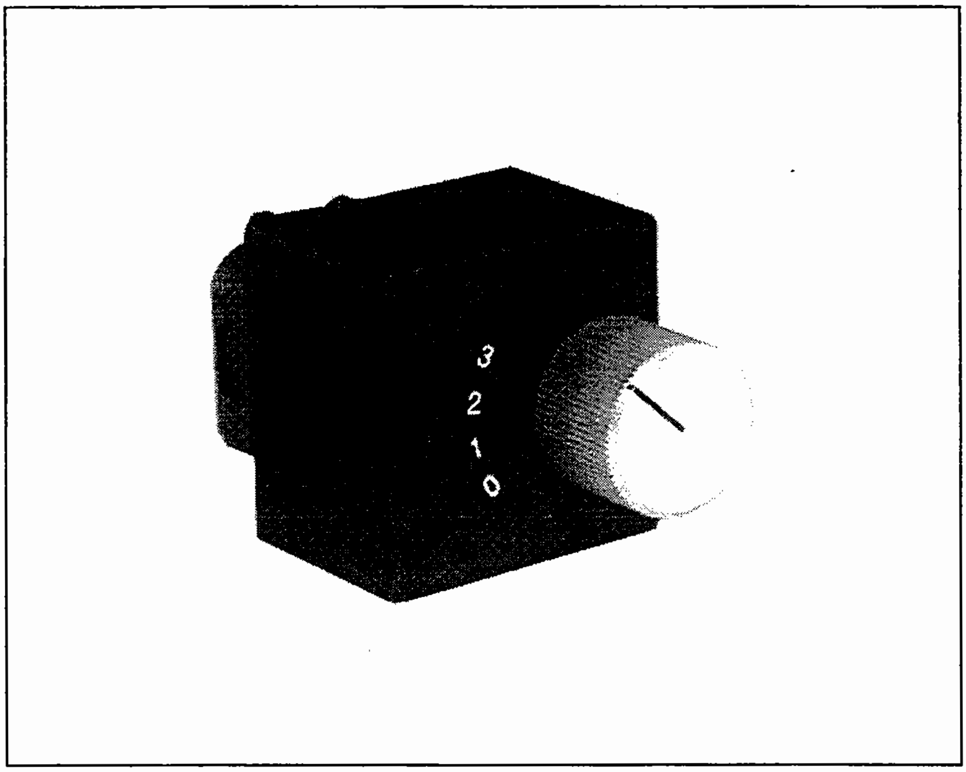
Note

In order to avoid disturbing other working groups by the buzzer sound, its volume can be adjusted to zero via the potentiometers. The switching status display then takes place solely via the light emitting diode (LED), which is built into the sensor (LED).

Technical data

Voltage	24 V D.C.
Contact set	10 signal inputs
Power consumption (Audible indicator)	1.2 W
Material	Surface panel Al, housing plastic
Weight	0.50 kg
Connection	for 4 mm plugs

Signal switching unit	Description
D.AS-SUAE-101	Designation
150538	Order No.

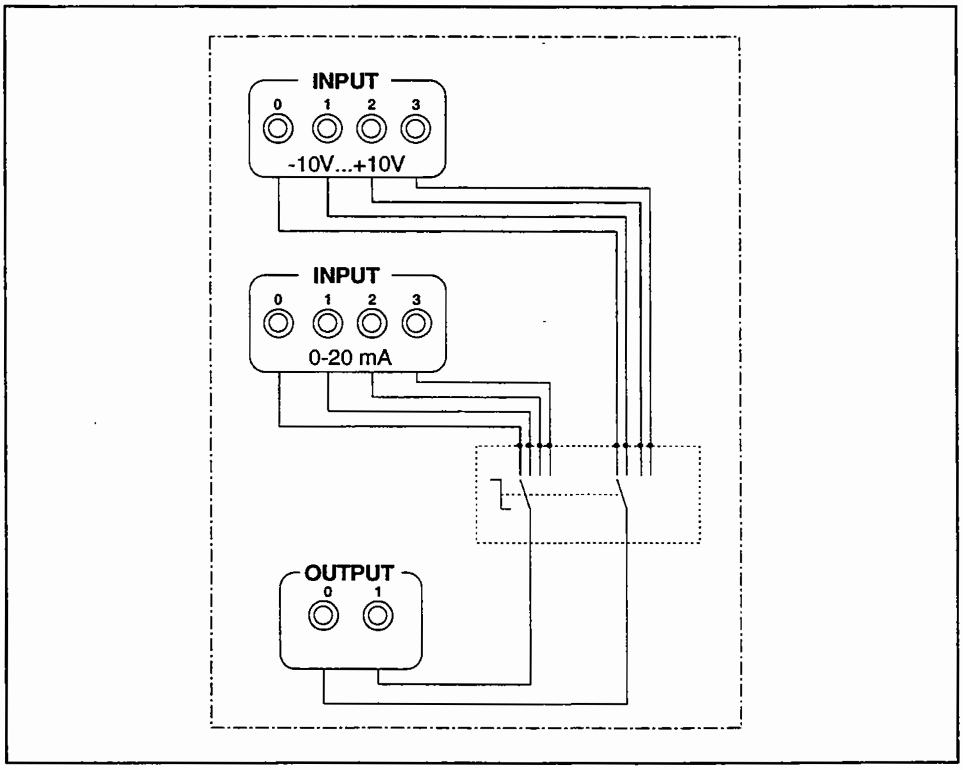


Design

This signal switching unit consists of a rotary switch and a micro-ribbon connection plug moulded into a plastic housing. It can only be used in conjunction with connection unit 101AF (Order No. 014595).

Function

The signal switching unit is plugged into the 14-pin micro-ribbon socket of the connection unit 101AF. The connection unit 101AF is used as a signal distributor without connection to a programmable logic controller.
The signal switching unit consists of a 2-pin rotary switch with 4 switching positions. The signals of analogue voltage inputs 0 to 3 of the connection unit 101AF are connected to OUTPUT 0 via the signal switching unit. The signals of the analogue current inputs 0 to 3 of the connection unit 101AF are connected to OUTPUT 1 via the switching unit. By means of the changeover function, the signal of the two inputs bearing the same number, e.g. VI0 and II0, are switched to the corresponding outputs for each switching position. The respective output signals can be detected by means of a measuring device.



Block circuit diagram for the switching unit and connection unit 101AF

Note

The signal ranges indicated in the OUTPUT field of connection unit 101AF (-10V...+10V) apply only if a programmable logic controller FPC 101AF is used.

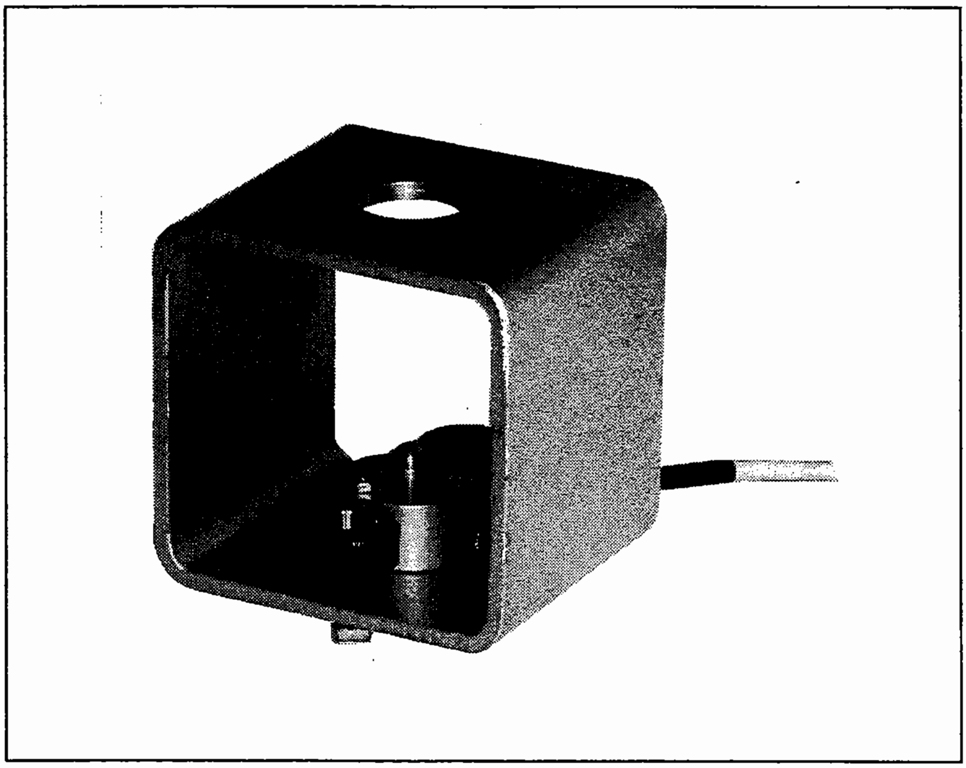
Switch setting	Inputs	Outputs
0	INPUT 0, voltage INPUT 0, current	OUTPUT 0 OUTPUT 1
1	INPUT 1, voltage INPUT 1, current	OUTPUT 0 OUTPUT 1
2	INPUT 2, voltage INPUT 2, current	OUTPUT 0 OUTPUT 1
3	INPUT 3, voltage INPUT 3, current	OUTPUT 0 OUTPUT 1

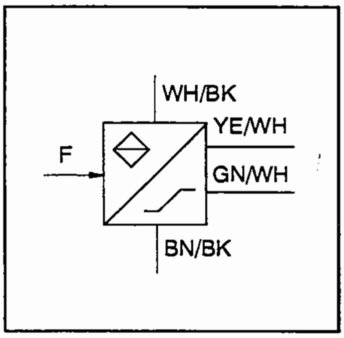
Allocation of switch settings of the signal switching unit to the inputs of the connection unit 101AF

Technical data

Switching capacity	max 0.4 VA
Switching voltage	max 28 V
Service life, electrical	10^4 cycles
Conductance	< 50 mΩ
Insulation resistance	> 100 mΩ
Voltage requirement	> 500 V~
Ambient operating temperature	-25 °C...+85 °C
Connection	Micro-ribbon connector, 14-pin
Weight	58 g

Force sensor	**Description**
D.ER-KS-FP1130	**Designation**
150541	**Order No.**





Symbol

Assembly

The force sensor is fitted with a short rounded stem to enable the load to be applied centrally. The sensor is mounted in a hollow box profile made of steel. There is a hole in the hollow profile opposite the force sensor, through which a force can be introduced in the form of a calibration device D.AS-SGA, or a pneumatic cylinder. The hollow profile can be mounted on to the profile plate by means of a knurled screw or a T-head nut.

The weight support is used for calibrating and consists of a metal rod with screwed-on disk, on to which the circular weights of the set D.AS-S-GWS-FP1130 can be placed.

Function

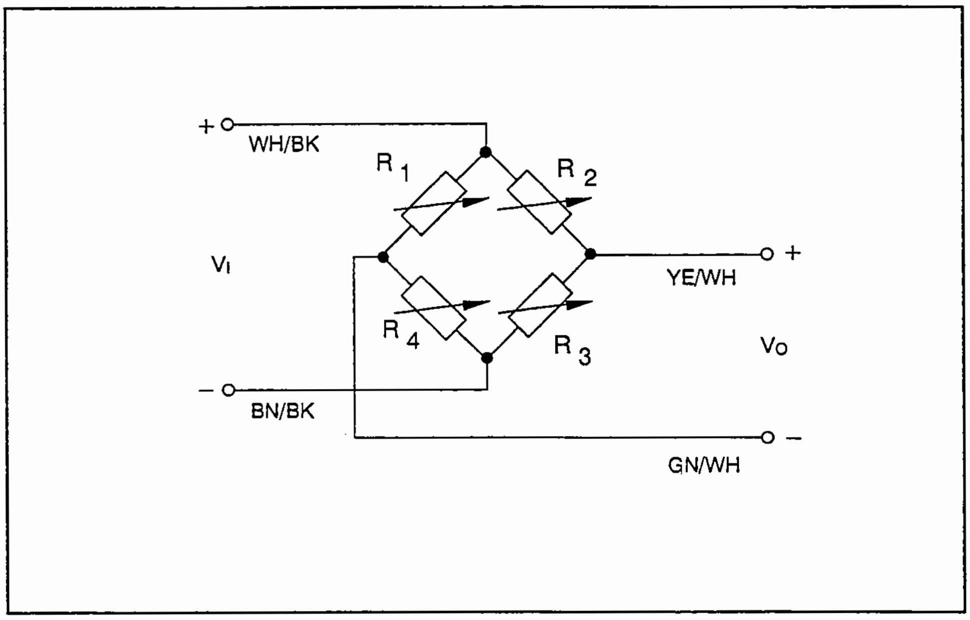
The force sensor is a strain gauge diaphragm sensor. The strain gauges are fitted to the strain gauge diaphragm in the form of a full-bridge. Under load, the diaphragm becomes deformed, resulting in the strain gauge full-bridge becoming unbalanced. The resulting signal which is in the millivolt range can be amplified and evaluated.

Wire and plug colours

The wires and plugs of the connection cable are colour coded as follows:

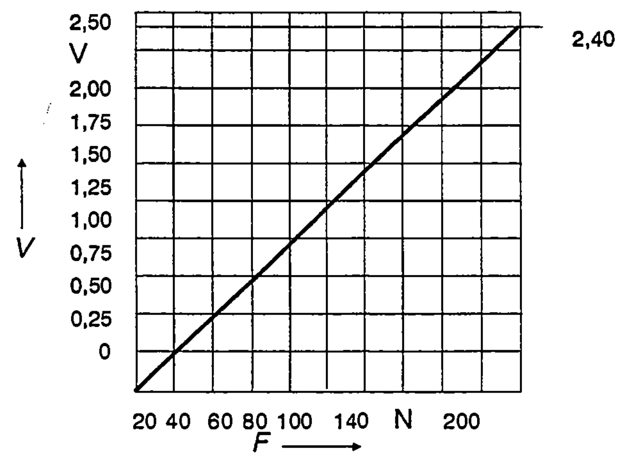
	Wire	**Plug**
Positive supply voltage	white (WH)	black (BK)
Negative supply voltage	brown (BN)	black (BK)
Positive signal output	yellow (YE)	white (WH)
Negative signal output	green (GN)	white (WH)

Electrical circuit diagram



Characteristic curve

In the characteristic curve below, the sensor signal, balanced and amplified by the measuring bridge amplifier D.ER-BV-FP1130, is plotted against the force.

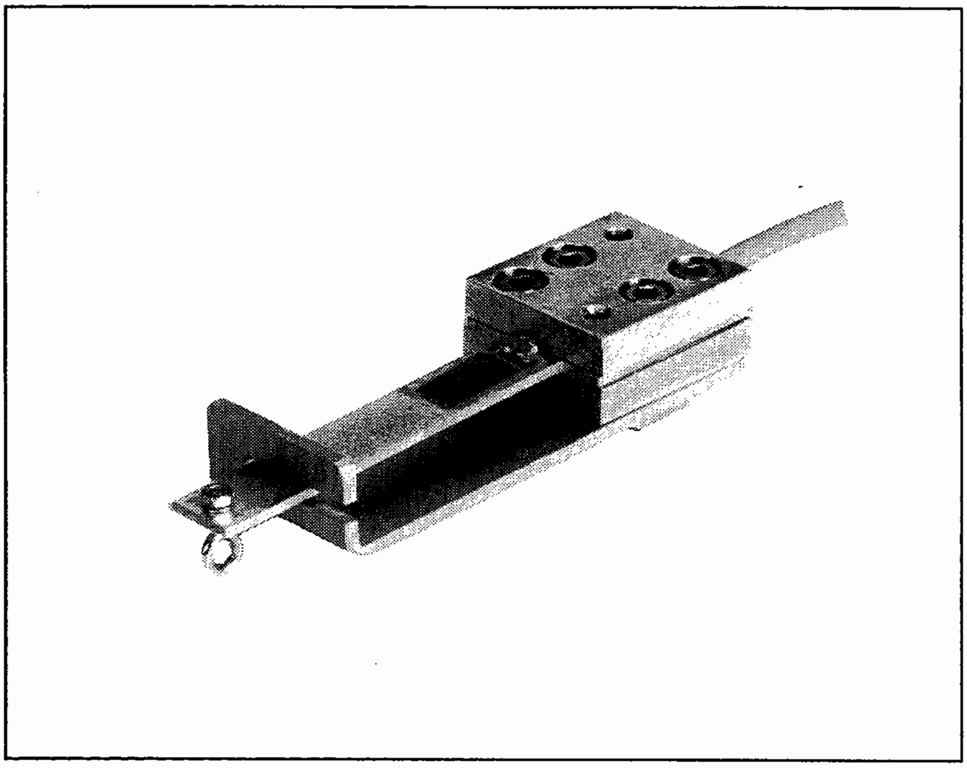


Technical data

Measuring range	0 ... ± 200 N
Measuring error*	≤ 1 % of final value
Sensitivity [nominal]	1 mV/V
Mechanical values	
Overload	130% of measuring range
Breaking load	≥ 200% of measuring range
Distance moved under nominal load (Pressure direction)	0.1 mm max.
Dyn. load rating recommended	50% of measuring range
permitted	170% of measuring range
Material	Force sensor: Al Hollow profile: Steel, galvanized
Weight	750 g
Environmental conditions	
Operating temperature range	-30C to +70C
Compensated temperature range	0C to +70C
Thermal zero point shift	± 0.04% of final value/K
Therm. sensitivity change	+0.07% of scale value/K
Protection class to DIN 40 050	IP 54
Electrical value	
Bridge resistance (Full bridge)	350 Ω (nominal)
Supply voltage permissible	3 to 10 V = or ≈
recommended	5 V
Isolation resistance	>10 M Ω
Electrical connection	shielded, 4-core cable, highly flexible, 2 m long
Bending radius of connection cable	≥ 15 mm
Connection	4 mm plugs

* The measuring error is defined as the sum of the errors for non-linearity, hysteresis and reproducibility.
$1N = 1\ kg\ m\ s^{-2} = 0.1019\ kp = 0.2248\ lbf$

Description	Deflecting arm force sensor
Designation	D.ER-BB-KS-FP1130
Order No.	150542



Assembly

The deflecting arm force sensor consists of an aluminium strip with two attached strain gauges (SG). The strain gauges are covered with a transparent silicone layer to prevent damage. The deflecting arm is clamped between two plates for mounting on to the MPS profile. A force is applied at the opposite end of the strip via an eyelet screw.

A mechanical stop fitted between the MPS profile and the deflecting arm ensures that plastic deformation of the sensor does not occur due to excessive loading.

The deflecting arm force sensor is calibrated by means of attaching weights from the set D.AS-GWS.

Function

When a force is applied via the eyelet, the deflecting arm is deflected downwards. The attached strain gauges undergo the same deformation as the deflecting arm, whereby their electrical resistance changes. This effect is transformed into a voltage signal of just a few millivolts via a wheatstone bridge circuit. The signal can be amplified with the measuring bridge amplifier D.ER-BV-FP1130 and transmitted to an evaluating device.

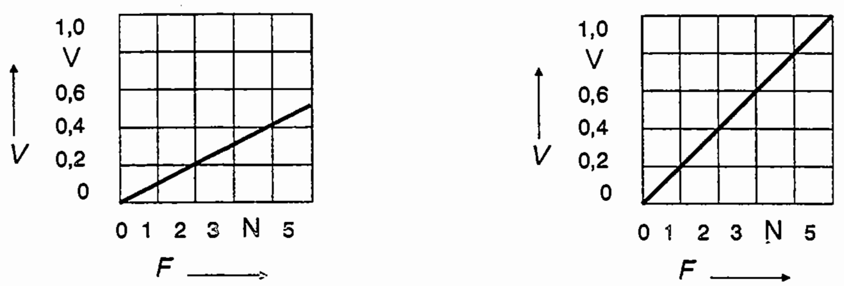
Plug colours

The plugs of the connection cable are colour coded as follows:

Upper SG	black (BK)
Lower SG	white (WH)

Characteristic curves

In the characteristic curve below, the sensor signal, balanced and amplified by the bridge amplifier D.ER-BV-FP1130, is plotted against the force.

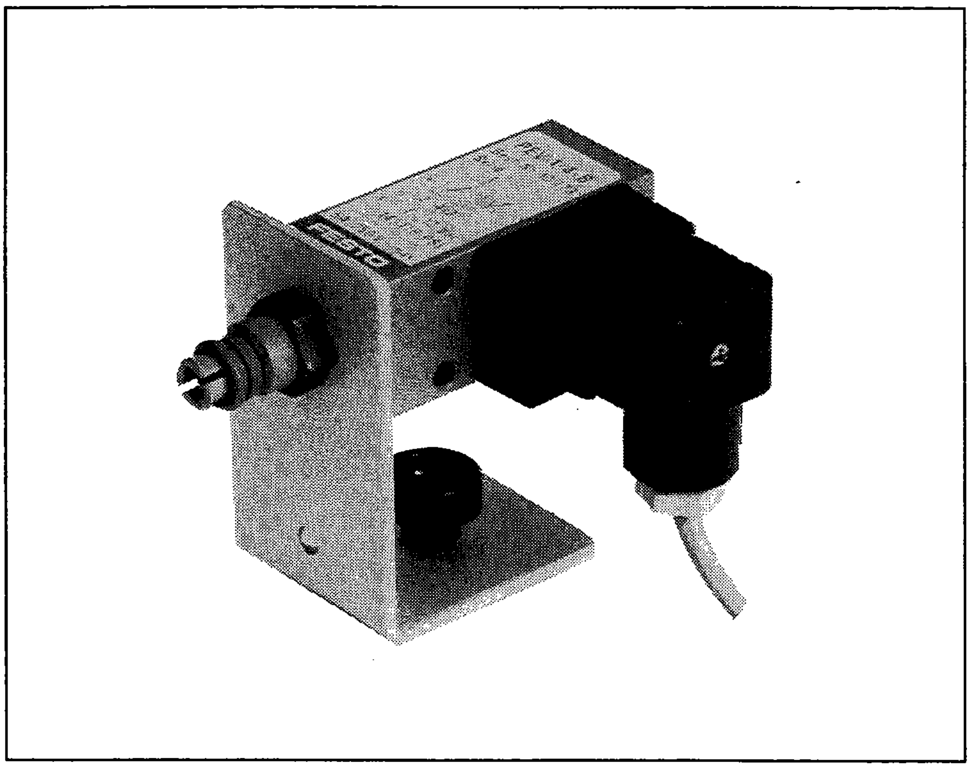


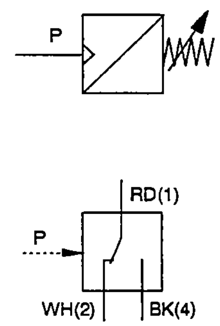
Quarter-bridge Half-bridge

Technical data

Measuring range	0 to 5 N
Overload	130% of measuring range
Operating temperature	-10 to +70C
SG type	Foil SG
SG resistance	350 Ω
Max. permissible supply voltage	10 V
Material	Stop galvanised steel Deflecting arm Al Clamping plate Al, anodised
Weight	200 g
Connection cable	4-wire, shielded, 2 m
Connection	4 mm plugs

Pressure switch	Description
D.ER-PEV-1/4-B	Designation
150554	Order No.





Pneumatic and electrical symbol

Assembly

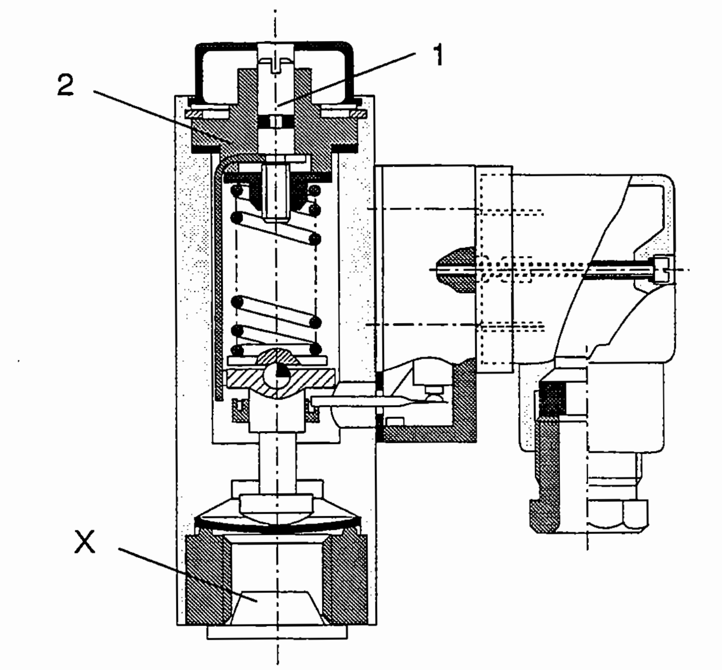
This component consists of a mechanical pressure switch with quick push-pull connector mounted on a support bracket. The support bracket can be attached to the profile plate by means of a knurled screw and a T-head nut.

Function

When the pressure at port X reaches a preset switching point, a diaphragm actuates a micro-switch thus triggering a connected electrical circuit. The switching point can be infinitely adjusted between 1 and 12 bar by means of an adjusting screw 1.

Depending on the switch-on pressure, the reset pressure can be set between 15 and 35% of the switch-on pressure by means of adjusting screw 2 under the plastic cap.

When delivered, the switch-on pressure is set at 6 bar and the reset pressure at 4.8 bar.



Plug colours

The plugs of the connection cable are colour coded as follows:

Signal voltage	red (RD)
Normally open contact	black (BK)
Normally closed contact	white (WH)

Technical data

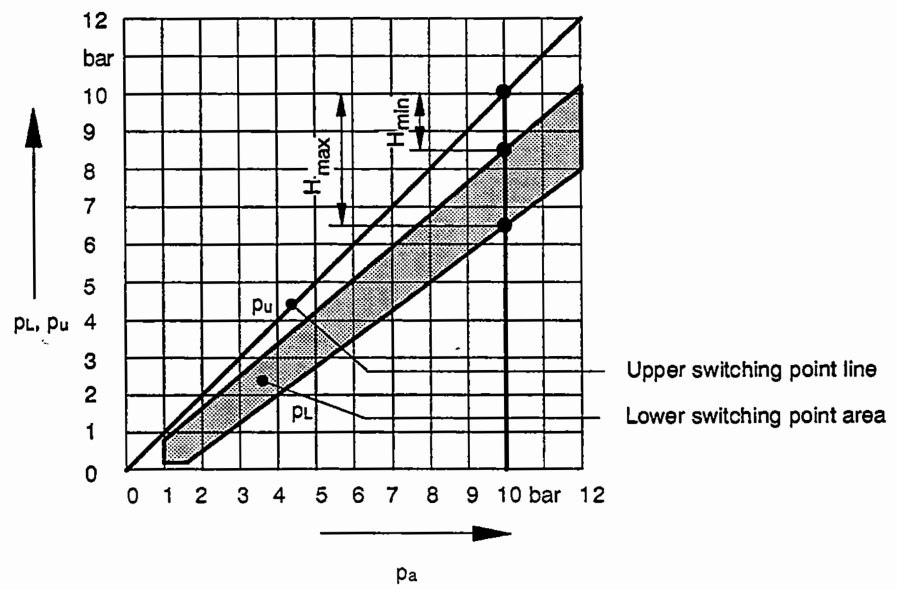
Medium	Compressed air, filtered (lubricated or unlubricated, non-aggressive gases and fluids)
Design	Pneumatic-electric signal converter
Assembly position	any
Connections	
pneumatic	Internal thread R 1/4
electrical	Appliance socket to DIN 43 650
Pressure range	1 to 12 bar (100 to 1200 kPa)
Overload pressure	Short-term max. 50 bar
Switching frequency	max. 3.3 Hz
Reproducibility of switching point	< ± 3%
Switching capacity*	
Direct current/DC	24 V : 6 A/220 V : 0.5 A
Alternating current/AC	220 V : 5 A
Strain relief	built into appliance socket
Protection class	IP 65
Temperature range	
Temperature of medium**	-20 to +80 °C
Ambient temperature	-20 to +80 °C
Materials	
Housing	AlMgSi
Diaphragm	Acrylonitrile-butadiene
Mounting bracket	Al, anodised
Weight	365 g
Connection cable	3-wire cable, 2 m
Connection	4 mm plugs

* The electrical life is reduced when used under maximum load.

** If temperatures are under +1 °C, the compressed air should not reach its dew point. With oil, the temperature of the medium to be measured should be high enough to prevent its sticking.

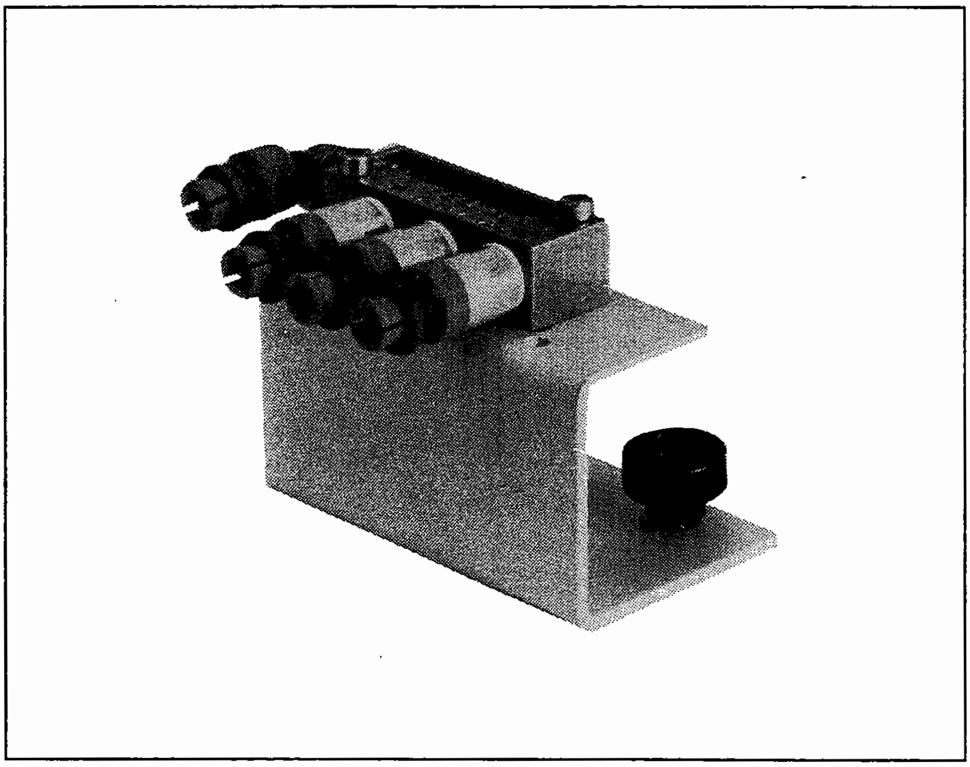
Characteristic curves

Adjustable hysteresis



p_a = applied pressure
p_u = pressure at upper switching point
p_L = pressure at lower switching point
$H_{max.}$ = max. adjustable hysteresis
$H_{min.}$ = min. adjustable hysteresis

Pressure manifold	Description
D.ER-FR-4-1/8-B	Designation
150555	Order No.



Assembly

The pressure manifold is screwed on to a mounting bracket. The mounting bracket can be attached to the profile plate by means of knurled screws and T-head nuts. The side connection of the pressure manifold is fitted with an elbow connector, the remaining connections have self-holding plug-in couplings.

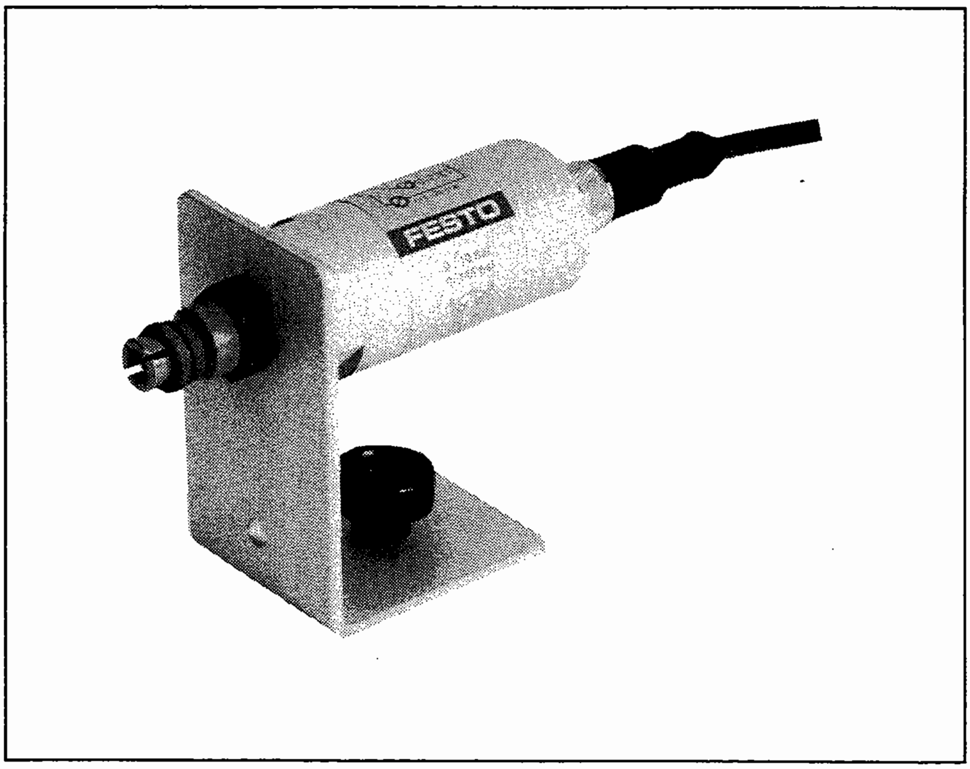
Function

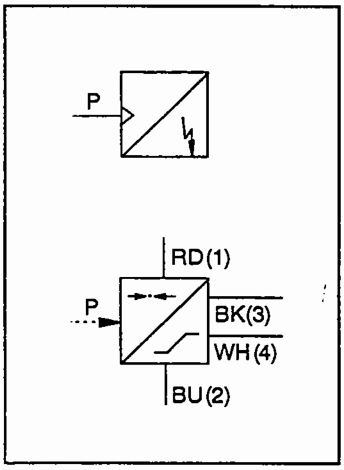
The manifold is connected to the compressed air supply via the elbow connector. Depending on requirement, pneumatic components can be connected to the pressure circuit via the straight connectors with the self-holding plug-in couplings. Unused plug-in couplings remain closed.

Technical data

Connection	G 1/8; LCS, KCS for plastic tubing PU-4
Pressure range	0 ... 16 bar (0...1600kPa)
Material	Al
Mounting bracket	Al, anodised
Weight	165 g

Analogue pressure sensor	Description
D.ER-SDE-10-10V/20mA	Designation
150556	Order No.





Pneumatic and electrical symbol

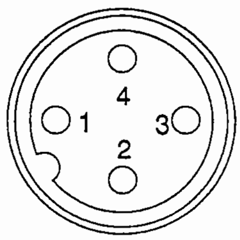
Assembly

This unit consists of a pressure sensor with quick push-pull connector fitted to a mounting bracket. The mounting bracket can be attached to the profile plate by means of a knurled screw and a T-head nut.

Function

The piezoresistive analogue pressure sensor with built-in amplifier and temperature compensator are fitted into a single aluminium housing. The pressure to be measured is transmitted to a piezoresistive element via a silicone layer. The signal thus generated is amplified and output as a current or voltage at the electrical connector. The output signal is calibrated, so that sensors may later be interchanged.

Pin assignment



1 Supply voltage +24V
2 Earth 0V
3 Voltage output
4 Current output

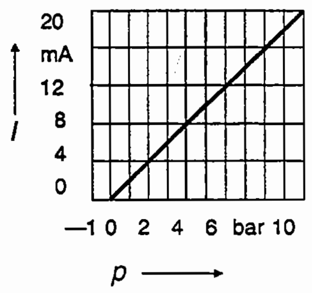
Plug colours

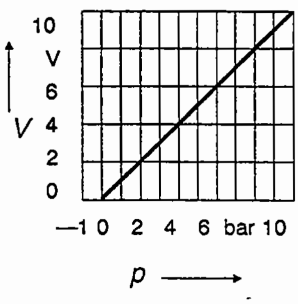
The plugs of the connection cable D.AS-SDE-K-4-GD are colour coded as follows:

+24 V	red	(RD)
0 V	blue	(BU)
Voltage output	black	(BK)
Current output	white	(WH)

Characteristic curves

D.ER-SDE-10-10V/20mA



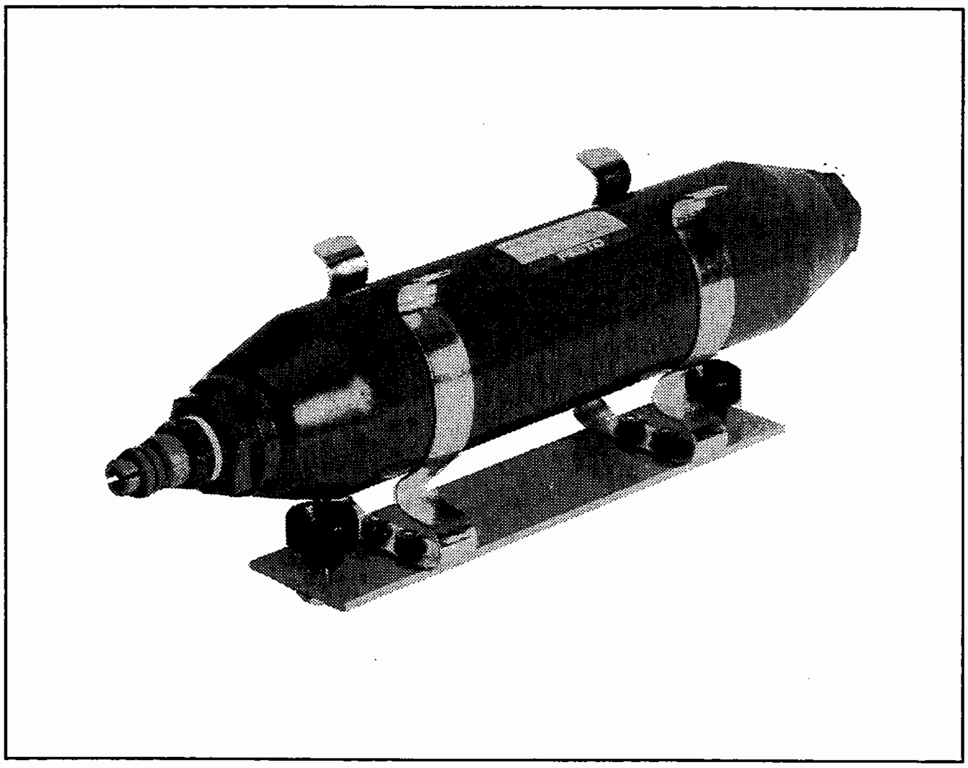


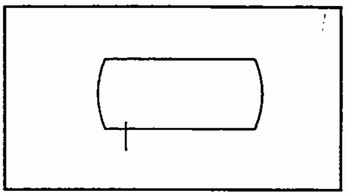
Technical data

Pressure range*	0 bar to +10 bar
Max. perm. pressure	14 bar (1400 kPa)
Supply voltage V_s	12 ... 30 V D.C.
Residual ripple of V_s	10% to DIN 41 755
Current consumption	With current output approx. 35 mA with voltage output approx. 15 mA
Load resistance	Current output: 300 Ω max. $R_L \leq (V_s - 3\ V)/30\ mA$ Voltage output: 4 kΩ min.
Total error	± 1% of final value
Temp. drift zero point	< 0.3% of final value/10 K
Temp. drift final value	< 0.3% of final value/10 K
Max. measuring frequency	100 Hz
Medium	Compressed air (lubricated or unlubricated)
Ambient operating temperature	0 °C to +85 °C
Compensation range	+10 °C to +70 °C
Storage temperature	-25 °C to +125 °C
Electrical protection	Short circuit proof, polarity-safe. Overvoltage-proof up to 50 V- (short-term)
Protection class	IP65
Material	Al, anodised; silicone
Weight	265 g
Connection cable	4-cable wire, 2 m
Electrical connection	4-pin socket, 4 mm plug
Pneumatic connection	Internal thread G1/4 with pneumatic plug-in coupling

* Sensor provides a signal even if pressure is < 0 bar.
Linearity and proportionality are not guaranteed in this case.

Compressed air reservoir	Description
D.ER-VZS-0.4	Designation
150557	Order No.





Symbol

Assembly

The compressed air reservoir is attached to the retaining plate by means of spring clips. The retaining plate can be mounted on a profile plate with knurled screws and T-head nuts. One connection of the compressed air reservoir is fitted with a pneumatic plug-in coupling and the other sealed with a blanking plug.

Function

The compressed air reservoir can be used for the following applications:

To generate static pressure with the help of a one-way flow control valve.

To create greater delay times in combination with time delay and flow control valves.

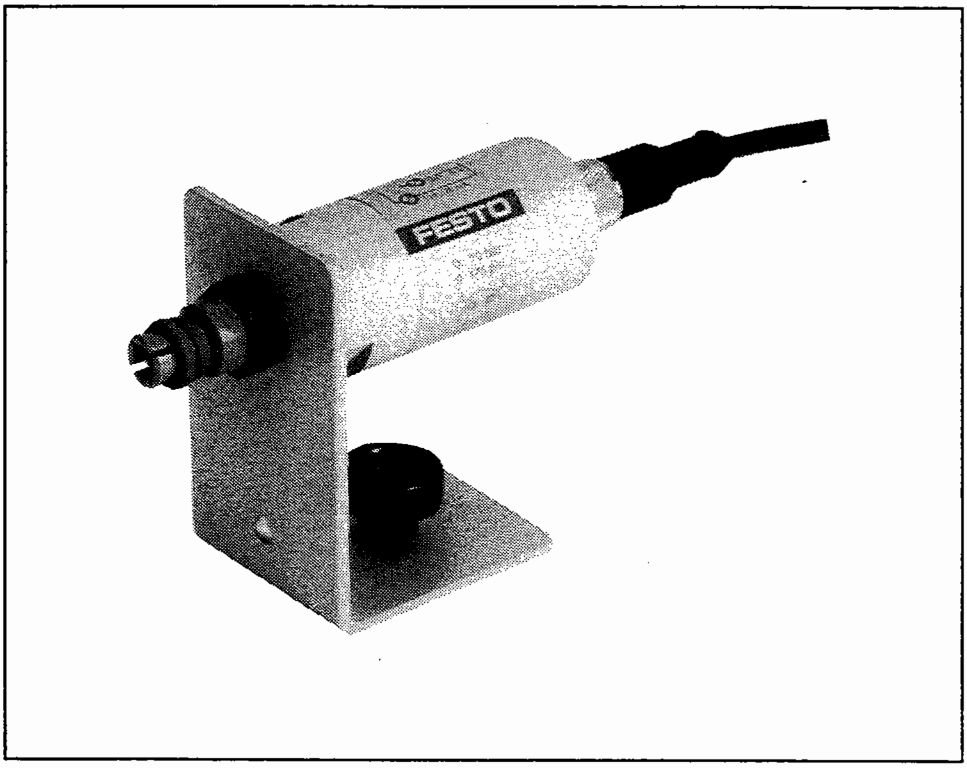
To compensate for pressure fluctuations.

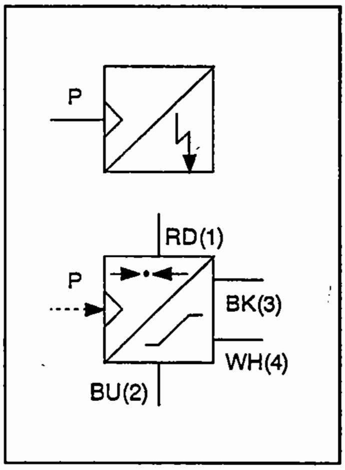
For use as a compressed air reservoir in a circuit subject to sudden pressure drop.

Technical data

Type	VZS-0,4
Medium	Compressed air, filtered (lubricated or unlubricated)
Design	Soldered container
Type of mounting	Spring clips, retaining plate
Connection	G 1/4; CS for plastic tubing PU-4
Volume	400 ml
Pressure range	0 to 16 bar (0 to 1600 kPa)
Temperature range	Depending on tube or pipe
Material	Brass, painted blue spring clips, retaining plate: steel
Weight	730 g

Analogue pressure sensor	**Description**
D.ER-SDE-10-5V/20mA	**Designation**
150558	**Order No.**





Pneumatic and electrical symbol

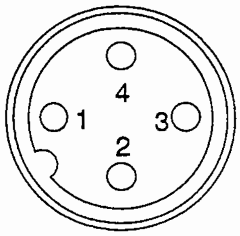
Assembly

This unit consists of a pressure sensor with quick push-pull connector fitted to a mounting bracket. The mounting bracket can be attached to the profile plate with a knurled screw and a T-head nut.

Function

The piezoresistive pressure sensor with built-in amplifier and temperature compensator are fitted into a single aluminium housing. The pressure to be measured is transmitted to a piezoresistive element via a silicone layer. The signal thus generated is amplified and output as a current or voltage at the electrical connector. The output signal is calibrated, so that sensors may later be exchanged.

Pin assignment



1 Supply voltage +24V
2 Earth 0V
3 Voltage output
4 Current output

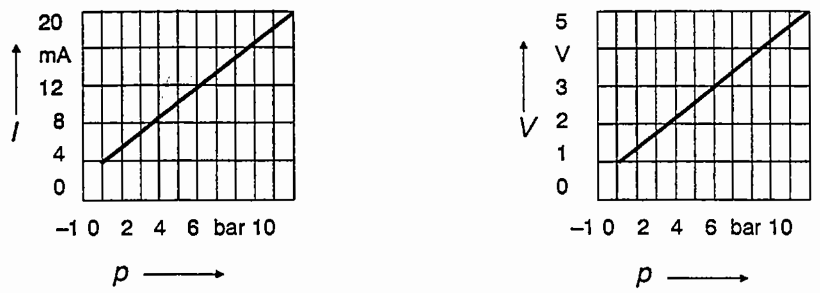
Plug colours

The plugs of the connection cable D.AS-SDE-K-4-GD are colour coded as follows:

+24 V	red	(RD)
0 V	blue	(BU)
Voltage output	black	(BK)
Current output	white	(WH)

Characteristic curves

D.ER-SDE-10-5V/20mA

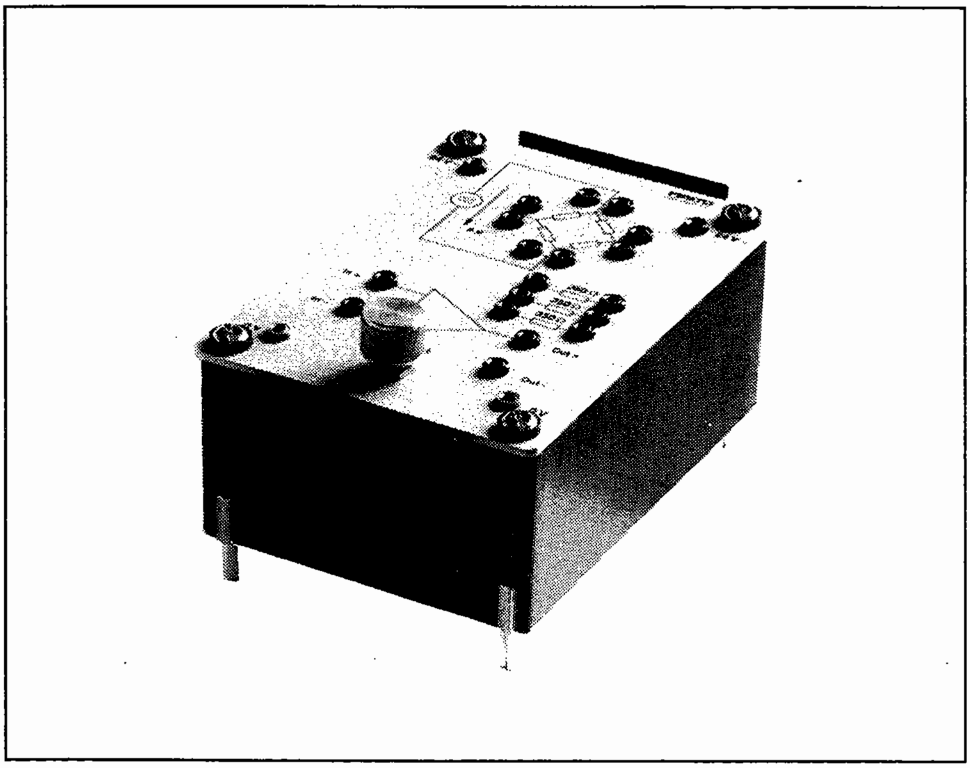


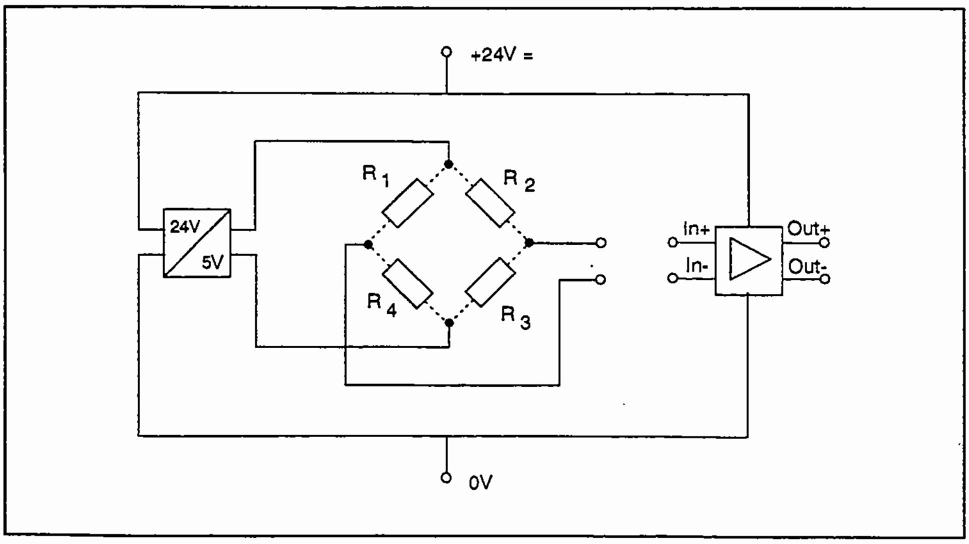
Technical data

Pressure range*	0 bar to +10 bar
Max. perm. pressure	14 bar (1400 kPa)
Supply voltage V_S	12 ... 30 V D.C.
Residual ripple of V_S	10% to DIN 41 755
Current consumption	With current output approx. 35 mA with voltage output approx. 15 mA
Load resistance	Current output: 300 Ω max. $R_L \leq (V_S - 3\ V)/30$ mA Voltage output: 4 kΩ min.
Total error	± 1% of final value
Temp. drift zero point	< 0.3% of final value/10 K
Temp. drift final value	< 0,3% of final value/10 K
Max. measuring frequency	100 Hz
Medium	Compressed air (lubricated or unlubricated)
Ambient operating temperature	0 °C to + 85 °C
Compensation range	+ 10 °C to + 70 °C
Storage temperature	-25 °C to +125 °C
Electrical protection	Short circuit proof, polarity-safe. Overvoltage-proof up to 50 V D.C. (short-term)
Protection class	IP65
Material	Al, anodised; silicone
Weight	265 g
Connection cable	4-cable cable, 2 m
Electrical connection	4-pin socket, 4 mm plug
Pneumatic connection	Internal thread G1/4 with pneumatic plug-in coupling

* Sensor provides a signal even if pressure is < 0 bar.
Linearity and proportionality cannot be guaranteed in this case.

Measuring bridge amplifier	**Description**
D.ER-BV-FP1130	**Designation**
150563	**Order No.**





Block circuit diagram

Assembly

The measuring bridge amplifier is built into a housing with four locating pins. The electrical connection for the operating voltage, signal inputs and outputs is established by means of 4 mm plugs.

Function

The bridge amplifier has an integral voltage supply to power strain gauges and force sensors. Various bridge circuits can be constructed with the complementary resistors provided. Very small electrical signals are further amplified for evaluation. The offset can be set within a wide range with the rotary knob. The amplified measured signal can be displayed or evaluated with the help of a multimeter or other equipment for measured data acquisition via the output sockets (Out +, Out-).

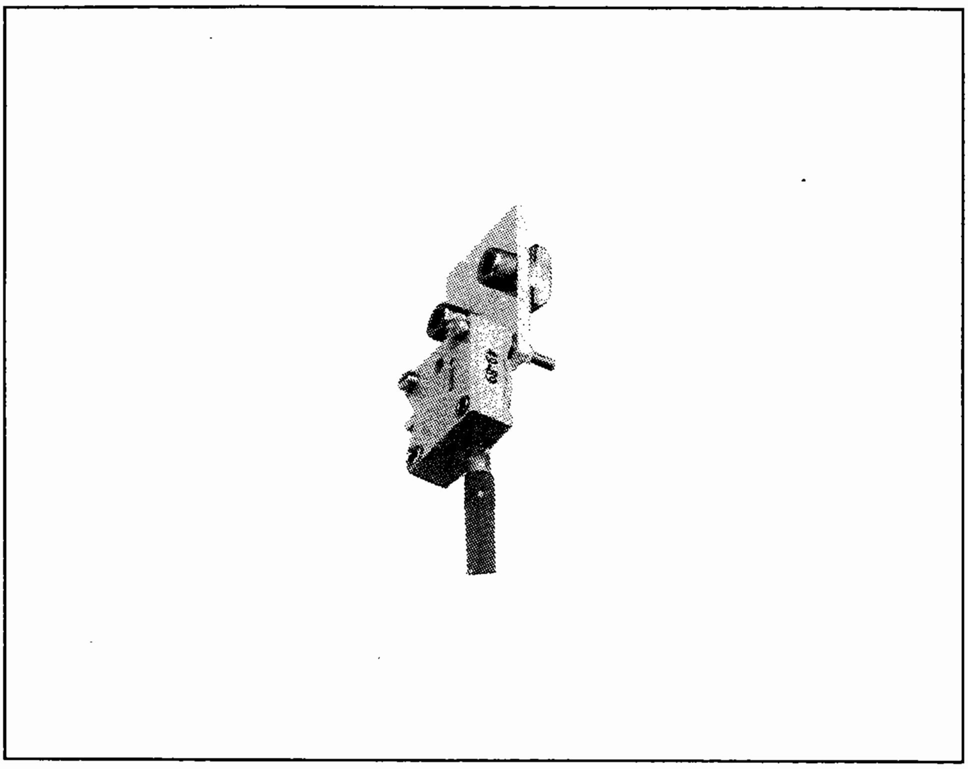
Note

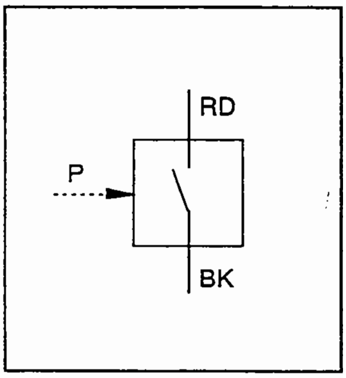
The measuring bridge amplifier reaches its operating temperature after approximately 5 minutes. After this point, zero-point drift does not occur. The output socket Out– is electrically isolated from connection 0 V.

Technical data

Supply voltage	24 V D.C.
Current consumption	50 mA
Complementary resistors	350 Ω
Bridge supply voltage	5 V D.C.
Amplifier input	Max. ± 10 mV
Amplifier output	Max. ± 5 V
Amplfication	Approx. 500
Weight	510 g

Description	Back pressure switch
Designation	D.ER-SDS
Order No.	150565





Symbol

Assembly

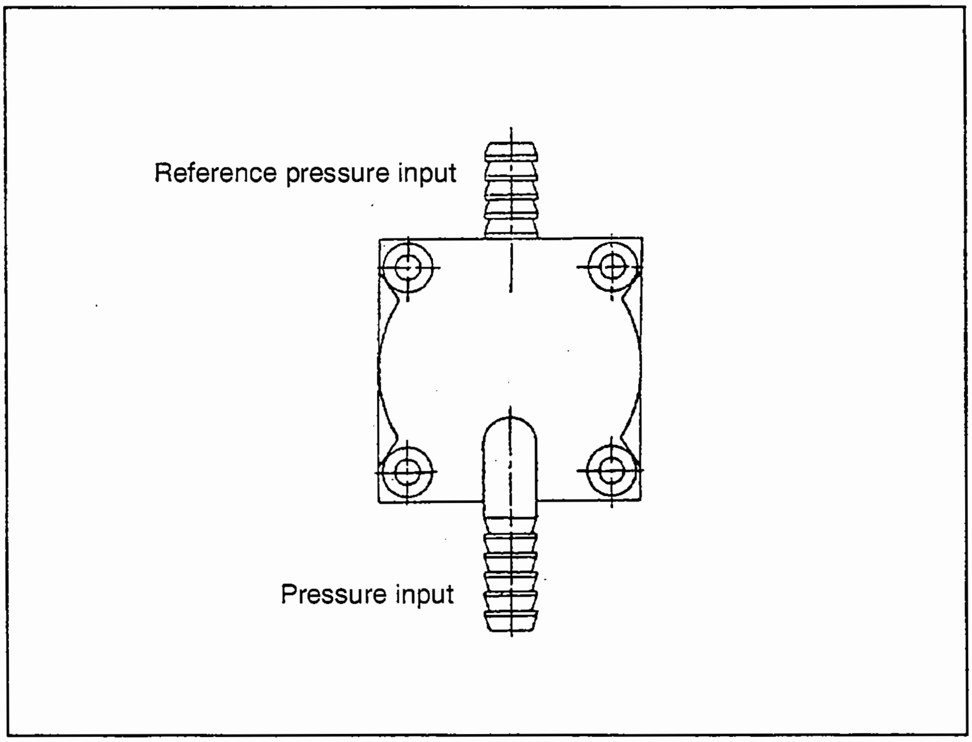
The back pressure switch can be fitted to an MPS profile rail (MPS = **M**odular **P**roduction **S**ystem by Festo Didactic) by means of a small metal plate with two Allen screws and two T-head nuts. The back pressure switch is actuated by a pressure signal, which is transmitted via tubing attached to the pressure input.

A voltage signal effected via a switching contact is passed on to an evaluation or display unit by means of the two-core cable D.AS-K-2 attached to the switch.

Function

The measuring principle of the back pressure switch is based on a reference pressure measurement. If the pressure at the pressure input is greater than that at the reference pressure input, then a diaphragm actuates the switching contact. The gold-plated switching contacts function as normally open contacts. They operate without spring effect practically almost hysteresis free.

The switching point can be adjusted within the measuring range by means of the adjusting screw.



Note

Avoid using the back pressure switch in conditions likely to cause short circuiting of the electrical contacts.

Plug colours

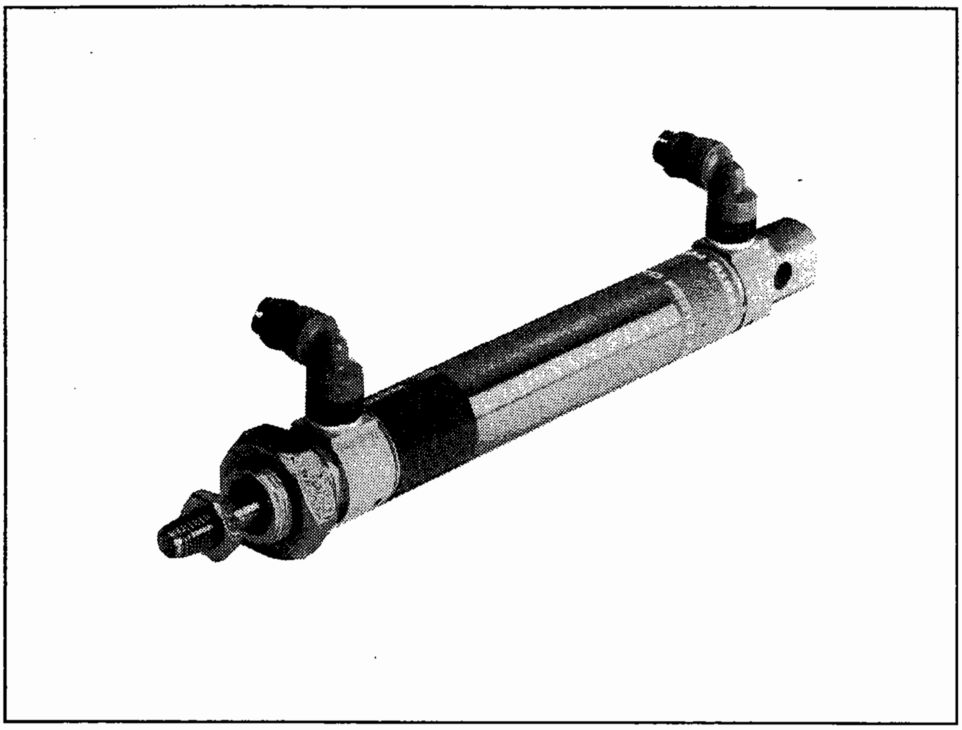
The plugs of the connection cable D.AS-K-2 are colour coded as follows:

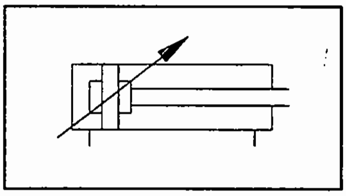
Voltage supply	red
Signal	black

Technical data

Materials	
Housing	Glass fibre reinforced polyester
Diaphragm	Polyurethane
Contacts	Gold-plated
Mounting plate	Steel, galvanised
Working temperature	Max. 120 °C
Bursting pressure	2 bar (200 kPa)
Switching frequency	Max. approx. 200 Hz
Mech. service life	> 10^8 switching cycles
Switching performance	Max. 50 mA for 24 V D.C.
Measuring range	1.2 ... 8 mbar (120...800 kPa)
Weight	35 g
Connection cable	2-cable wire, 2 m
Connection	Cable lug, 4 mm plug

Cylinder	Description
D.AS-DSN-PPV	Designation
150578	Order No.





Symbol

Assembly

The component consists of a double-acting cylinder with quick push-pull elbow connectors and adjustable end position cushioning.

Function

Piston rod motion of the double-acting cylinder is reversed by means of alternating the supply of compressed air. End position cushioning at both ends prevents hard impact on the cylinder housing. The end position cushioning can be adjusted by means of two adjusting screws.

Technical data

Medium	Compressed air, filtered, (lubricated or unlubricated)
Design	Piston cylinder
Operating pressure max.	10 bar (1000 kPa)
Stroke length max.	100 mm
Thrust at 6 bar	267 N
Return force min. at 6 bar	220 N
Connection	G 1/8; PK-4 for plastic tubing PU-4