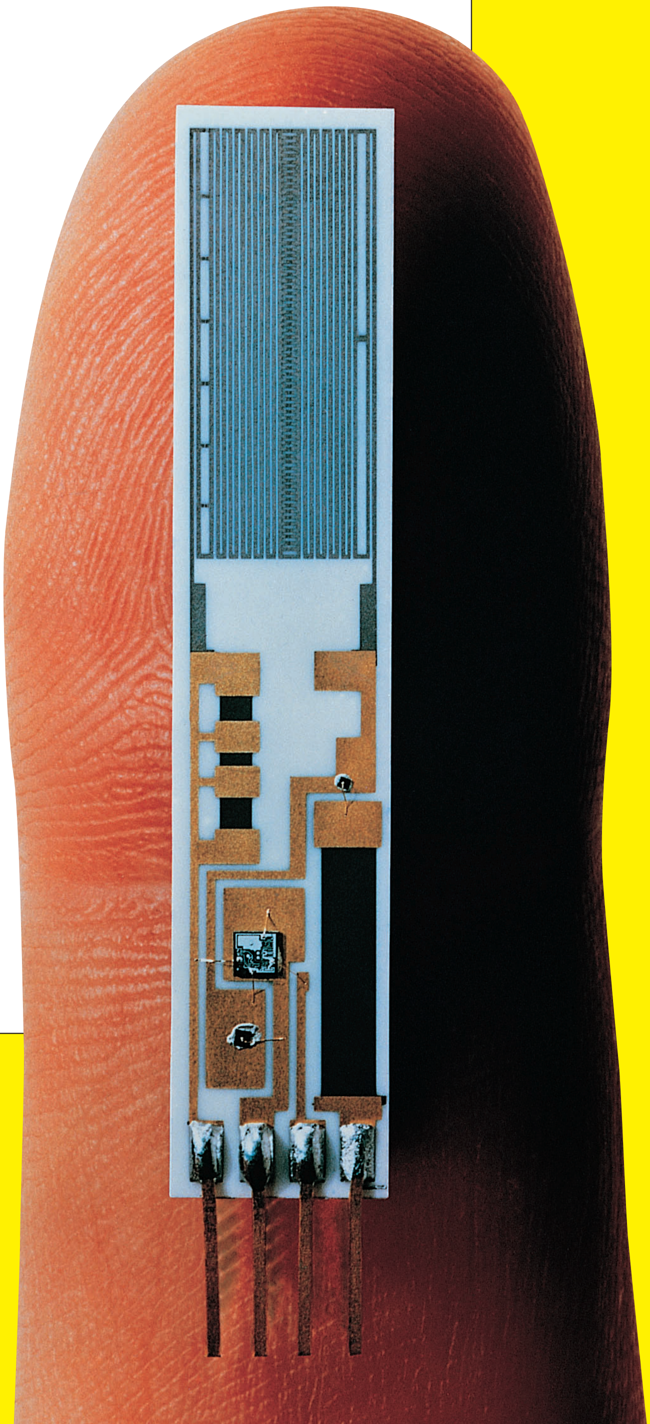
The Bosch Yellow Jackets **Edition 2002** | Technical Instruction | Automotive Electrics and Electronics

Automotive Sensors

BOSCH

Automotive Technology

- Classification, main technical requirements
- Measured variables, measuring principles, signal processing
- More than 50 examples of sensors and evaluation IC



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Editor-in-Chief:
Dipl.-Ing. (FH) Horst Bauer.

Editors:
Dipl.-Ing. (BA) Jürgen Crepin,
Dipl.-Ing. Karl-Heinz Dietsche.

Authors:
Dipl.-Ing. Erich Zabler
(Overall text on sensors in the vehicle, characteristics, measured variables, measuring principles, sensor examples),
Dipl.-Ing. Joachim Berger
(Various sensors for diesel-engine management),
Dipl.-Ing. Andreas Herforth
(Fuel-level sensor),
Dr. Michael Harder
(Axle sensors),
Dipl.-Ing. (FH) Herbert Arnold
(Ultrasonic sensors),
Dr.rer.nat Hermann Winner
(Ranging radar (ACC)),
Dipl.-Ing. Jürgen Töpfer,
(Hall-effect gearbox sensors),
Dipl.-Ing. (FH) Rüdiger Giesel
(OC sensor mat),
Dr.rer.nat Volkmar Denner
(Data processing in the vehicle).

in cooperation with the responsible departments of Robert Bosch GmbH.

Translation:
Peter Girling

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Automotive sensors

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Contents

In the automotive sector, electronic equipment is continuing to gain in importance. Here, the sensors represent the vehicle's sensory organs for registering distance travelled, movement, angle, rpm, speed, acceleration, vibration, pressure, throughflow, gas concentration, temperature, and a whole range of other influencing variables. The output signals from these sensors have in the meantime become indispensable for implementing a wide variety of engine and chassis management systems, as well as for safety, comfort and convenience. Thanks to electronic data processing, the above variables can be evaluated at very high speed, and the sensor signals conditioned to make them suitable for use with the particular vehicle function.
This manual deals with the measured variables and the measuring principles behind the various sensor groups. In each case, examples are presented of sensors that have gone into production.

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Automotive sensors

Today's state-of-the-art vehicle is equipped with a large number of sensors. These can be regarded as the vehicle's "sensory organs", and from their physical or chemical inputs they generate the electrical output signals needed by the vehicle's ECUs for implementing the closed and open-loop control functions used in its engine-management systems, and in its safety, comfort, and convenience systems.

Basics

Terms and definitions

The terms sensor, probe and pickup are synonymous. This manual uses the term "sensor". Taking into account disturbances Y_i, the sensor converts a physical or chemical (usually non-electrical) input quantity Φ into an electrical output quantity E. This often takes place with the help of non-electrical intermediate stages. The electrical sensor outputs are not only in the form of current and voltage alone, but are also available as current or voltage amplitudes, frequency, phases, pulse durations, and cycles or periods of an electrical oscillation, or as the electrical parameters "Resistance", "Capacitance", and "Inductance" (Figs. 1 and 2).

A sensor can be defined using the following equation:
1. Sensor output signal
$$E = f(\Phi, Y_1, Y_2, ..) \qquad (1)$$
2. Required measured variable
$$\Phi = g(E, Y_1, Y_2, ..) \qquad (2)$$

If functions f or g are known, these equations represent a "sensor model" with which the required measured variable can also be derived mathematically and practically without error using the output signal E and the disturbance Y_i (refer to "Intelligent sensors").

There are no specific rulings on whether the sensor can contain part of the signal-processing or not.

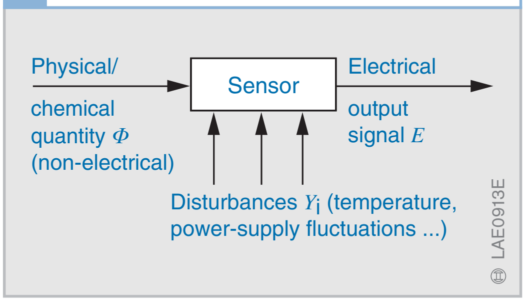
Applications in the vehicle

As part of the vehicle's periphery, the sensors and actuators form the vehicle's interface to its complex drive, braking, chassis, and bodywork functions, as well as to the vehicle guidance and navigation functions and the (usually digital) ECUs which operate as the processing units. As a rule, a matching circuit (refer to "Signal processing") adapts the sensor signals to the standard form required by the ECUs (measuring chain, measured-value acquisition, Fig. 3).

These matching circuits are tailor-made for specific sensors and are adapted to the particular vehicle. They are available in integrated design and in a wide variety of versions. They are a highly essential and worthwhile complementary device for the sensors described below, but due to lack of space are not gone into in detail. It would be impossible to use sensors in practice without these matching circuits. To be precise, definition of the sensor's measuring quality applies to the sensor and the matching circuit.

The vehicle can be regarded as a highly complex process, or control loop, which can be influenced by the sensor information from other processing units (ECU), as well as from the driver using his/her controls. Display units keep the driver infomed about the status and the process as a whole. Fig. 4 provides an overview of the abundance of electronic vehicle systems which are already on the market. Undoubtedly, this number will increase immensely in the years to come.

1 Basic sensor function



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Classification

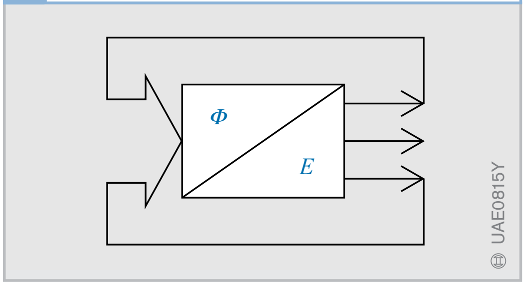
Automotive sensors can be divided into three categories:

Assignment and application

Here, sensors can be allocated to two different groups:

- Functional sensors mainly used for open and closed-loop control assignments,
- Sensors for safety and safeguarding (theft-deterrent) assignments, and
- Sensors for vehicle monitoring (On-Board Diagnostics (OBD)), fuel-consumption and wear parameters) and for driver/passenger information.

2 Sensor symbol



3 Sensors in the vehicle

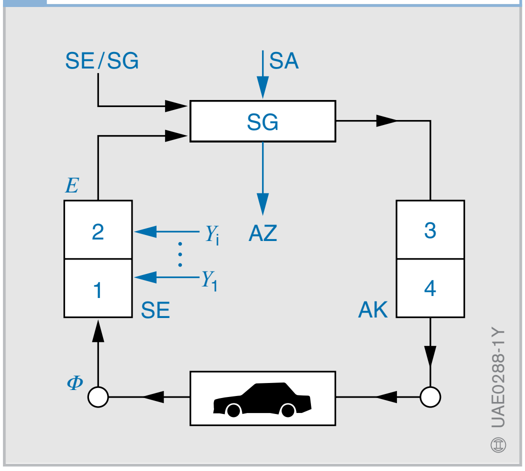
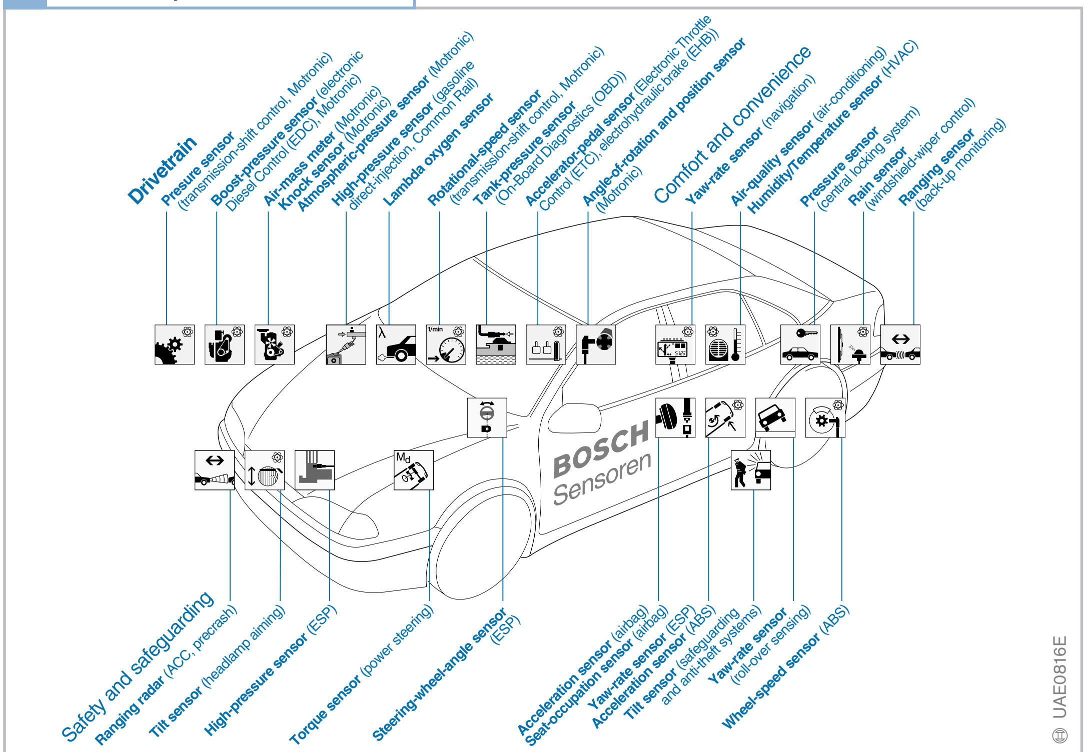


Fig. 3
1 Measuring sensor
2 Matching circuit
3 Driver
4 Actuators
AK Actuator
AZ Display
SA Switch
SE Sensor(s)
SG ECU
Φ Physical quantity
E Electrical quantity
$Y_{1...i}$ Disturbances

4 Automotive systems and their sensors



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Curve types

In order to perform their various monitoring and closed and open-loop control assignments, sensors must feature a variety of different characteristic curves (Fig. 5):

Continuous, linear curves
Such curves are used mainly for control assignments covering a wide measuring range. Linear curves are also distinguished by uncomplicated testing and calibration.

Continuous, non-linear curves
Such curves are often used for the closed-loop control of a measured variable across a very restricted measuring range (e.g. exhaust-gas control to $\lambda = 1$, vehicle spring-deflection level). When, for instance, the permissible deviation relative to the measured value is demanded throughout the complete measuring range (air-mass meter), curves which feature both pronounced non-linearity and a special shape (e.g. logarithmic) are at an advantage.

Discontinuous, two-step curves
Such two-step curves (possibly even featuring hysteresis) are used for limit-value monitoring in such cases where remedial measures are easy to apply when the limits are reached. If remedial measures are more difficult, then multiple-step curves can be used for an earlier warning.

5 Characteristic curves

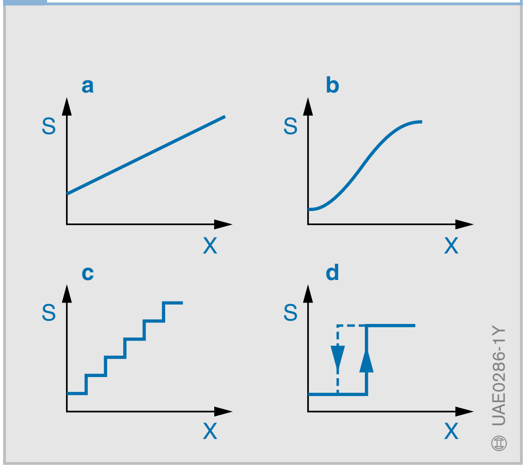


Fig. 5
S Output signal
X Measured variable
a Continuous linear
b Continuous non-linear
c Discontinuous multi-step
d Discontinuous two-step

Type of output signal

Sensors also differ with respect to their output signals (Fig. 6):

Output signals analog to:
- Current/voltage or a corresponding amplitude,
- Frequency/period and,
- Pulse duration/pulse duty factor.

Discrete output signal:
- Two-step (binary coded),
- Multi-step, with irregular steps (analog coded), or
- Multi-step, with equidistant steps, that is with uniform spacing (analog or digital coded).

Furthermore, the sensors differ in their output signal being continuously available or only at discrete instants in time (continuous and discontinuous respectively). For instance, the signal is bound to be discontinuous if it is digital and outputted in bit-serial form.

6 Signal shapes (Examples)

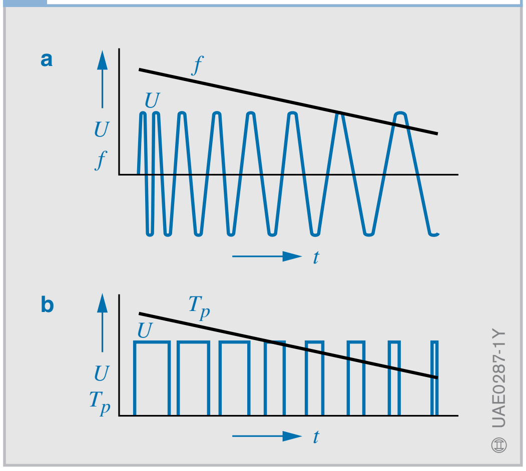


Fig. 6
a Output signal U
Frequency f
b Output signal U
Pulse duration T_p

Main requirements, trends

In contrast to the everyday universal-application sensors available on the market, automotive sensors are tailor-made to comply with the requirements of the vehicle's special electronic systems. The research and development departments are responsible for ensuring that they satisfy the five major demands as listed in Fig. 7. These requirements are also reflected in the most important trends in sensor engineering.

High reliability

In accordance with their assignments, automotive sensors are sub-divided into the following reliability classes, given in descending order of severity:

- Steering, brakes, passenger protection,
- Engine/drivetrain, chassis/tires,
- Comfort and convenience, OBD, information, and theft-deterrence.

In automotive engineering, the specifications for the highest reliability class correspond to those for aviation and astronautics, and in some cases necessitate similar measures being taken.

Development trends:
Appropriate design measures guarantee built-in reliability. For instance, this necessitates the use of reliable, top-quality components and materials, coupled with rugged and well-proven techniques and engineering. Plug-in connections are a potential source of trouble, and to avoid them system integration takes place as far as possible. This is also the aim of "radio-scanned sensors" based on the antenna-coupled SAW[1]) elements which do without wiring completely. Safety considerations can dictate that redundant sensor systems are used. That is, sensor systems connected in parallel which perform identical measuring functions.

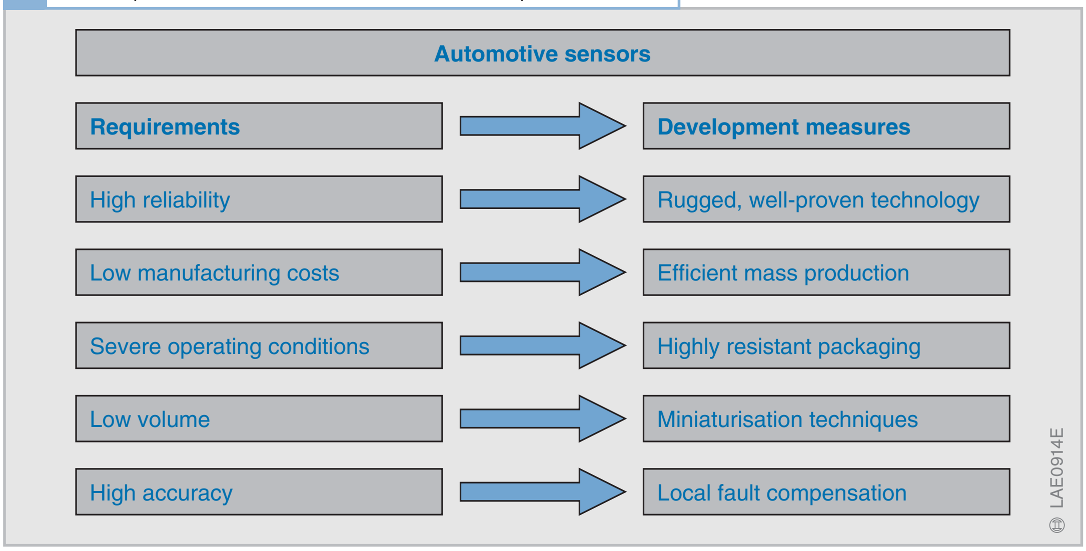
Low manufacturing costs

On board a modern-day, state-of-the-art vehicle, there can easily be as many as 60 to 70 sensors. Compared to other sectors of sensor application, this is a very large number and is only possible as long as low manufacturing costs are achieved. Typically, target costs are in the range between 2 and 50 DM (1 to 25 €), and are often 100 times lower than those of conventional sensors with the same performance, whereby when an innovative technology is introduced costs start at a high level, and then usually drop in the course of time.

Development trends
For the most part, sensor manufacture uses highly efficient automated production methods. For example, semiconductor sen-

[1]) SAW **S**urface **A**coustic **W**ave

7 Main requirements for automotive sensors and development measures



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sors are manufactured using "batch processing" in which there are typically 100 to 1000 sensors on a single Si wafer.

On the other hand, such manufacturing equipment is only an economic proposition when correspondingly large numbers of sensors are produced. These quantities sometimes exceed an automotive-industry supplier's own in-house requirements, and can commonly be between 1 and 10 million per year. Here, the high numbers of sensors needed by the automobile industry played an unprecedented and revolutionary role, and set completely new standards.

Severe operating conditions

Sensors are installed at particularly exposed positions on the vehicle. Accordingly, they are subjected to particularly severe loading and must be able to withstand a wide variety of different stresses:

- Mechanical (vibration, shock),
- Climatic (temperature, dampness),
- Chemical (e.g. splashwater, saline fog, fuel, lube-oil, battery acid),
- Electromagnetic (irradiation, wire-conducted spurious pulses, excess voltages, polarity reversal).

Due to the inherent advantages involved, sensors are preferably installed directly at the measuring point. This tendency though has led to a considerable increase in the severity of the requirements made on the sensor.

Development trends:
Protective measures must be introduced to cope with the above loading. This necessitates a very high know-how level in the field of sensor "Packaging". Among other things, this includes:

- Passivation and connecting techniques,
- Sealing and joining techniques,
- EMC measures [2]),
- Low-vibration installation,
- Service-life, test, and simulation methods,
- Use of highly resistant materials together with detailed knowledge of the loading to which the sensor will be subjected at the particular installation point. Total competence in the selection and implementation of suitable protective measures is the decisive factor for sensor quality. Such measures often account for a far greater share of the overall sensor costs than the actual measuring element itself.

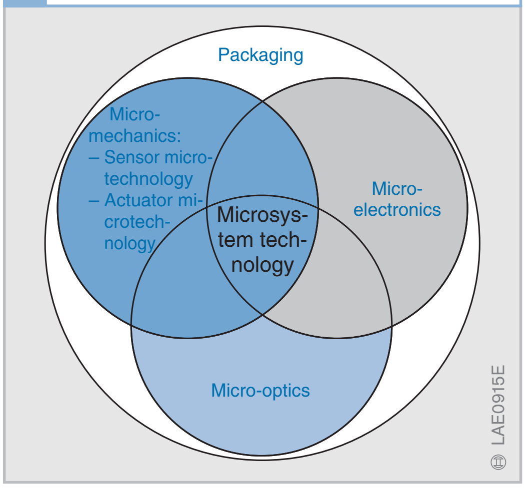
Fiber-optic sensors
In such sensors, the light flowing in the optical fiber (glass, plastic) can be modified as a function of the measured variable. Up to the point where the optical signal is converted back to an electrical signal, these sensors are regarded as being particularly immune to electromagnetic disturbances. Insofar as they are applied at all in the future, this will necessitate extensive development work on low-priced measuring elements and the accompanying technologies.

Low-volume design

On the one side the number of electronic systems in the vehicle continues to climb steadily. On the other, today's vehicles are becoming more and more compact. These facts, together with the need to retain the high level of passenger-compartment comfort forces development to concentrate on an extremely low-volume design. Furthermore, the increasing demand for further improvements

[2]) EMC **E**lectro**m**agnetic **C**ompatibility

8 Microsystems



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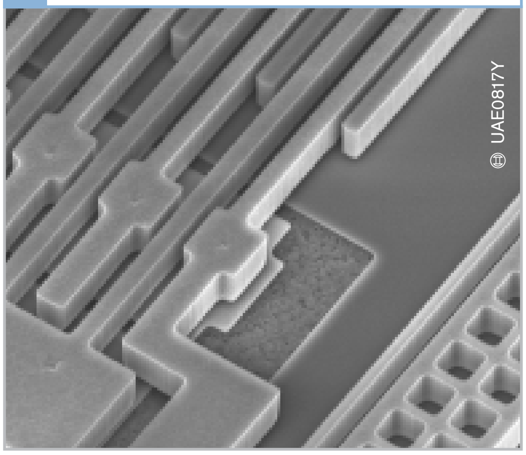
in fuel economy mean that minimization of the vehicle's weight is of prime importance.

Development trends
Widespread use is made of the familiar technologies applied in circuit engineering for the miniaturisation of electronic components (Fig. 8):
- Film and hybrid technologies (deformation-dependent resistors, thermistors, and magnetoresistors,
- Semiconductor techniques (Hall-effect and temperature sensors),
- Surface and bulk micromechanical techniques (silicon pressure and acceleration sensors, Fig. 9),
- *Microsystem technologies* (combinations of two and more microtechnologies such as microelectronics and micromechanics).

9 Micromechanical measuring element (structure)



Often, the indispensable mechanical part belonging to the function with which the sensor is associated is used to accomodate the sensor, and acts as its "housing". This combination of electronics and mechanics is known as *mechatronics* and is coming more and more to the forefront in the search for cost and space savings. In the foreseeable future, practically all systems will operate on this basis.

High accuracy
In comparison to the probes and sensors used for instance in the processing industry, with only a few exceptions (e.g. the air-mass meter) the demands on automotive-sensor accuracy are relatively modest. Generally, the permissible deviations are ≥1 % of the measuring-range final value. This applies in particular when considering the unavoidable effects of ageing. The permissible deviations are normally achieved by the application of complex techniques to compensate for manufacturing tolerances, and to balance the effective compensation measures used against interference. Particularly since the above-mentioned requirements have for the most part been satisfied, continually more demanding and sophisticated systems are imposing higher and higher demands in this sector.

10 Sensor integration level

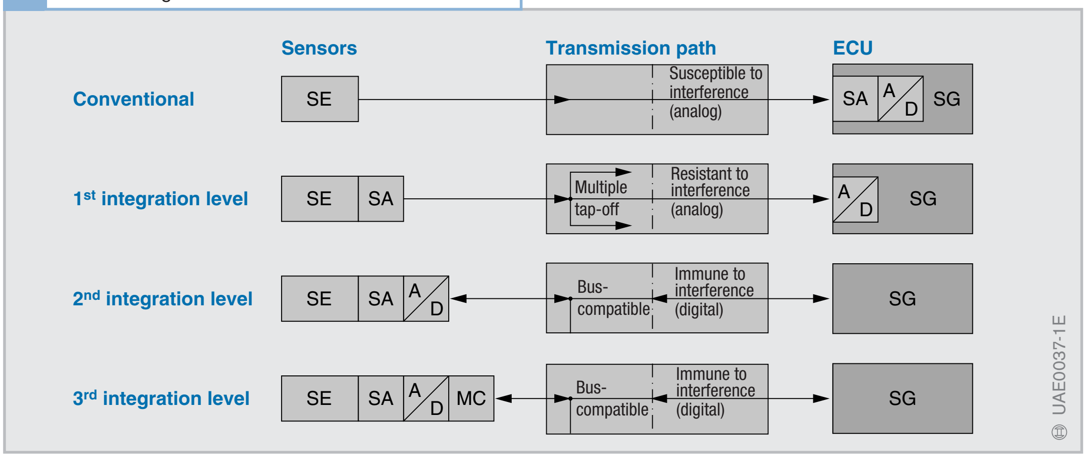


Fig. 10
SE Sensors
SA Signal conditioning (analog)
A/D Analog-digital converter
SG Electronic control unit (digital)
MC Microcomputer

Development trends
Initially, a tightening up of the tolerances in manufacture, and refinement of the calibration and compensation techniques help to guarantee a high level of accuracy. An important step forward here is the hybrid or monolithic integration of the sensor and signal electronics directly at the measuring point, up to complex digital circuits such as analog/digital converters and microcomputers (Fig. 10).

Such microsystems are also known as "intelligent sensors". They take full advantage of the sensor's inherent accuracy, and offer the following features:

- Reduce the ECU's working load
- Uniform, flexible, and BUS-compatible interface
- Sensors can be used for a number of different functions
- Due to local amplification and demodulation, it is possible to utilise low-output and high-frequency measuring effects
- The correction of sensor deviations at the measuring point, and the mutual calibration and compensation of both sensor and electronics, is simplified and improved by storing the individual correction information in a PROM.

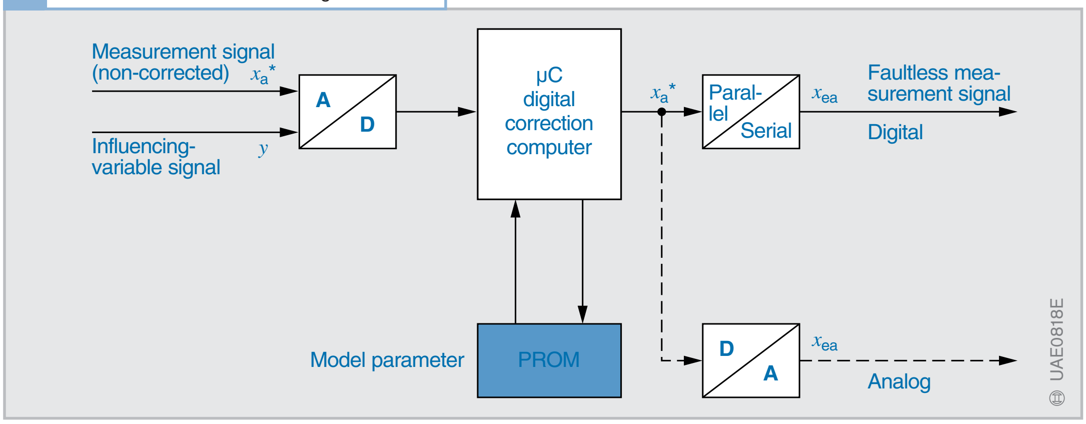
While simultaneously detecting and digitising disturbances, "intelligent sensors" can almost perfectly calculate the required measured variable by applying the mathematical sensor model given in the Paragraph "Terms, Definitions" (with Equations 1 and 2). Here, the item-specific model parameters (individual sensor samples are used in calculating a model auxiliary quantity) are defined in a preceding process which is equivalent to the calibration as previously performed, and stored in a PROM integrated with the sensor (Fig. 11, correction module).

In this manner, it is possible to considerably improve the sensor's static and dynamic characteristics (evaluation of the differential equation which defines the dynamic performance).

Local electronic circuitry (in other words directly at the measuring point), necessitates the use of *multi-sensor structures* which use a number of identical sensors, or a number of different sensors, to register a variety of highly complex facts and reduce these to their basic information content. This latter process can also take place locally. This applies in particular to *image sensors* which in future will play an every increasing role in registering the situation inside and outside the vehicle.

With a number of integrated *pressure sensors*, it is possible to not only increase the reliability of the measurement, but also to reduce the ageing drift (deviation due to ageing) by applying mean-value generation. If the individual sensor elements are designed for differing measuring ranges – and at the same time feature high overload capabilities (e.g. capacitive) – such a sensor can be used to considerably extend the high-acccuracy measuring range.

11 Correction module of an intelligent sensor



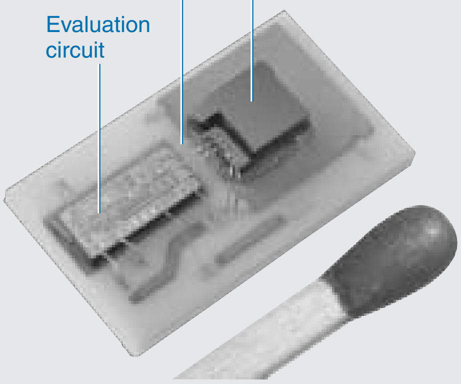
Miniaturization

Thanks to micromechanics it has become possible to locate sensor functions in the smallest possible space. Typically, the mechanical dimensions are in the micrometer range. Silicon, with its characteristics has proved to be a highly suitable material for the production of the very small, and often very intricate mechanical structures. With its elasticity and electrical properties, silicon is practically ideal for the production of sensors. Using processes derived from the field of semiconductor engineering, mechanical and electronic functions can be integrated with each other on a single chip or using other methods.

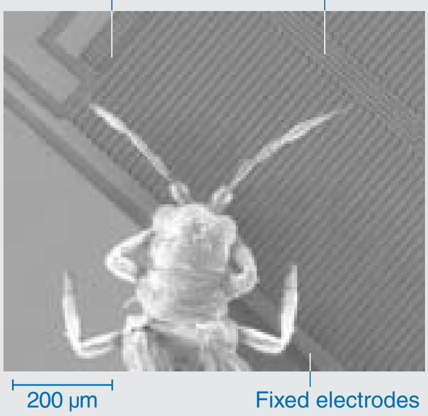
Bosch was the first to introduce a product with a micromechanical measuring element for automotive applications. This was an intake-pressure sensor for measuring load, and went into series production in 1994. Micromechanical acceleration and yaw-rate sensors are more recent developments in the field of miniaturisation, and are used in driving-safety systems for occupant protection and vehicle dynamics control (Electronic Stability Program ESP). The illustrations below show quite clearly just how small such components really are.

Micromechanical acceleration sensor

Electric circuit



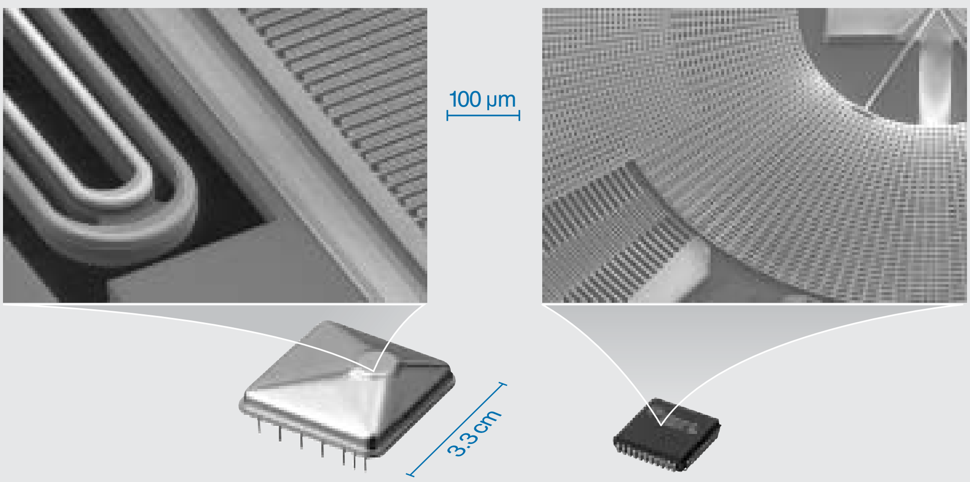
Comb-like structure compared to an insect's head



Micromechanical yaw-rate sensor

DRS-MM1 vehicle-dynamics control (ESP)

DRS-MM2 roll-over sensing, navigation



Position sensors (travel/angle)

Characteristics

Position sensors register the most varied forms of travel and angular position, and are certainly the most common sensor in the vehicle. In this sector of applications, activities have long since been directed at changing over to *proximity* or *non-contacting* sensor principles. Such sensors are wear-free and thus have a longer service life as well as being more reliable. The costs involved though, often force vehicle manufacturers to retain the "wiper-type" sensor principle, and such sensors still perform efficiently enough at a number of points in the vehicle.

Table 1

Position sensors are often referred to as so-called *"extensive sensors"*. Here, sensor size and measured quantity are always interrelated, although with regard to wave-propagation sensors, this only applies to a limited degree. In the classification method used here, sensor and measuring principles which only measure extremely minute shifts/movements (a few μm, for instance in the case of expansion) are allocated to other measured variables such as force, torque, and acceleration. Only those position sensors will be dealt with which are used for measuring larger distances (≥1 mm) and angles (≥1°).

Table 2

Measured variables: Overview

In this sector there are a large number of applications in which position represents the actual measured variable. This is shown by the Table on the right.

1 Travel/angular position as the direct measured variable

Measured variable	Measuring range
Throttle-valve setting on the spark-ignition engine	90°
Accelerator-pedal/ brake-pedal position	30°
Seat, headlamp, rear-view mirror position	
Control-rack travel and position for diesel in-line fuel-injection pumps	21 mm
Angular setting of the injected-fuel-quantity actuator on the diesel distributor pump	60°
Fuel level in the fuel tank	20 ... 50 cm
Clutch-actuator travel	50 mm
Distance from vehicle to vehicle or between vehicle and obstacle	150 m
Steering-wheel angle	$\pm 2 \cdot 360°$ (± 2 revolutions)
Angle of inclination (tilt)	15°
Angle of vehicle travel	360°

In other cases, the measured position or angle represents a different measured variable (Table 2).

2 Travel/angular position as the indirect measured variable

Measured variable	Measuring range
Spring-deflection travel (headlamp range, vehicle inclination or tilt)	25 cm
Torsion angle (torque)	1 ... 4°
Deflection of a sensor plate (throughflow)	30 ... 90°
Deflection of a spring-mass system (acceleration)	0.5 ... 1 mm

In practice, *"incremental sensor systems"* are also often referred to as angular-position (or angle-of-rotation) sensors, even when they are used for measuring rotational speed. Since the increments (steps with which a given quantity increases) which have to be measured with these sensors in order to measure the deflection angle must be counted with the correct preceding sign (in other words, added), these sensors are in reality not angular-position (or angle-of-rotation) sensors. Due to the danger of the counter being falsified due to spurious pulses, such angular-position measuring systems are only in limited use. Fixed, directly locatable reference marks only provide very little help in this dilemma. Another disadvantage of such angular-position measuring systems is the fact that the absolute position is lost when the power supply is switched off. Here, it is no use storing the final position in a non-volatile memory, since most angular positions can change mechanically. This also applies when power has been removed.

Measuring principles

Potentiometer-type sensors

For measuring purposes, the wiper-type potentiometer (Fig. 1) uses the correspondence between the length of a wire or film resistor (Cermet or conductive plastic) and its resistance. At present, this is the lowest-priced travel/angle sensor. Voltage is usually applied to the measurement track through low-resistance series resistors R_V (these can also used for calibration of zero point and curve-slope). The shape of the curve is influenced by shaping the measuring track (or only sections of it). Wiper connection is usually through a second contact conductor track with an identical surface applied over a low-resistance conductor track.

Wear and falsification of measured values can be kept to a minimum by keeping the electrical loading of the pick-off as low as possible (I_A <1 mA) and by dust-proof encapsulation. One of the prerequisites for low wear is the optimal friction pairing between the wiper and the conductor track. To this end, wipers can be of "spoon" or "scraper-shape" design, and one or more can be mounted. Brush-shaped wipers are also in use.

A whole range of clear advantages are faced by a considerable number of serious disadvantages:

Advantages of the potentiometer-type sensors

- Simple design
- Very extensive measuring effect (measurement range ≅ supply voltage)
- No electronic circuitry required
- High level of interference immunity
- Broad temperature range (up to 250°C)
- High precision (better than 1% of full range)
- Wide measuring range (almost 360° is possible)
- No difficulty with redundant design
- Calibration possible (Laser etc.)
- Flexible characteristic curve (variable conductor-track width)
- Flexible assembly (on curved as well as on flat surfaces)
- Wide range of manufacturers
- Samples can be supplied quickly.

Disadvantages of potentiometer-type sensors

- Mechanical wear, abrasion
- Measuring errors due to abraded particles
- Problematic regarding operation in fluids
- Variation in contact resistance between wiper and measurement track
- Strong acceleration or vibration can result in wiper lift-off
- Testing is costly
- Limited possibilities of miniaturization
- Noise.

Examples of potentiometer-type sensors

- Sensor-plate potentiometer (KE- and L-Jetronic)
- Throttle-valve angular-position sensor (M-Motronic)
- Accelerator-pedal sensor, accelerator-pedal module
- Fuel-level sensor.

1 Wiper-type potentiometer

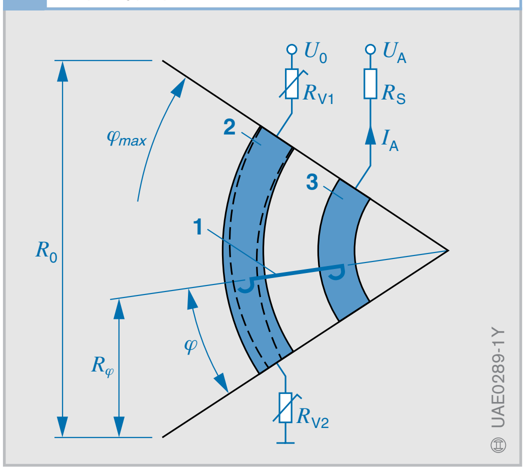


Fig. 1
1 Wiper
2 Resistance track
3 Contact conductor track
I_A Wiper current
U_0 Supply voltage
U_A Measurement voltage
R Resistance
φ_{max} Maximum angle of rotation
φ Measured angle

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Magnetically inductive sensors

Of all the sensors using proximity and non-contacting principles for position measurement, the magnetic sensors have proved to be the most rugged and most insensitive to interference. This applies in particular to those principles relying on alternating current, in other words magnetically inductive principles. Compared with a micromechanical sensor though, the coil configuration needed here requires far more space. This means therefore that there is no favorable possibility of redundant (parallel measurement) design. Furthermore, coil contacting is less favorable from the costs and reliability viewpoint. Although there are a multitude of different principles in use for this form of sensor, only two have come to the forefront for automotive applications. Regarding their operating concepts, these are very similar to each other.

Eddy-current sensors

When an electrically conductive flat or curved (damping) disc (for instance Al or Cu) approaches a coil (usually ironless) to which high-frequency AC has been applied, it has an effect upon the coil's equivalent resistance and its inductance. This is the result of the eddy currents generated in the disc (otherwise known as a spoiler) due to the increasing magnetic coupling. The disc's position represents the measured travel (Fig. 2).

Although this principle functions satisfactorily in the kHz range, for detection of rapid movements it is recommended that a higher operating frequency in the MHz range is applied. This also uses less current. On the other hand, this generally means that the electronics must be in or on the sensor. In order to convert the measuring effect into an electrical output signal, either the damping-effect (equivalent resistance) or field-displacement (inductance) principles can be applied. In the first (damping effect) case, a variable-amplitude oscillator can be used, and in the second a variable-frequency oscillator or a constantly supplied inductive voltage divider (differential configuration).

There are many ways to adapt the eddy-current principle to the measuring assignment. It is just as suitable for the measurement of large travels and angles as it is for smaller quantities. Sensors applying this principle have low temperature sensitivity.

Short-circuiting-ring sensors

In contrast to eddy-current sensors, the coil of a short-circuiting-ring sensor has a straight or curved U or E-shaped soft-magnetic, (usually) laminated iron core (Fig. 3). The coil, or short-circuiting-ring ("spoiler"), is of highly conductive material (Cu or Al), and is located around one (or all) of the core limbs. Thanks to the iron core, such sensors have a far larger inductance than eddy-cur-

2 HF damping or eddy-current principle

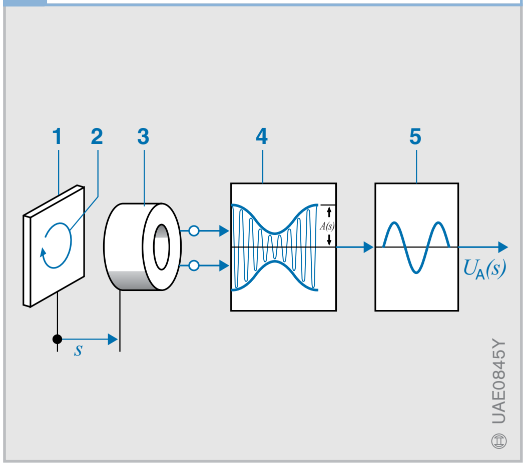

Fig. 2
1 Spoiler
2 Eddy currents
3 Air-core inductor
4 Variable-damping oscillator
5 Demodulator
s Measured travel
$A(s)$ Oscillator voltage
$U_A(s)$ Output voltage

3 Short-circuiting-ring sensor

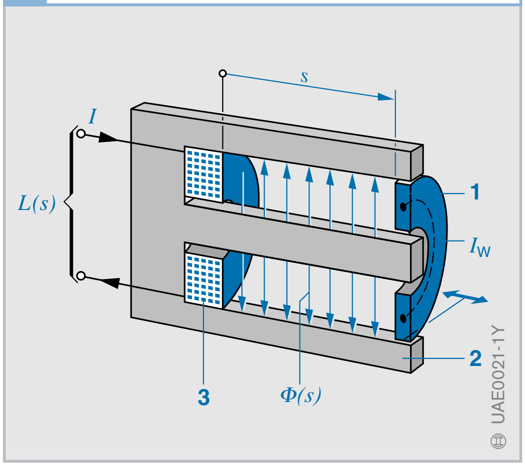

Fig. 3
1 Short-circuiting ring
2 Soft-magnetic core
3 Coil
I Current
I_W Eddy current
$L(s)$ Inductance and
$\Phi(s)$ Magnetic flux for measured travel s

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rent sensors. This means that they operate well at low frequencies, and do not necessarily require their signal electronics locally, that is directly on the sensor itself.

The alternating field generated in and around the Fe core by the coil current *I* is unable to pass through the short-circuiting ring, since the eddy currents in the ring reduce it practically to zero. In other words, therefore, the eddy currents in the short-circuiting ring limit the extension of the magnetic flux to the space between the coil and the ring. The ring's position thus has a practically linear effect upon the inductance throughout a wide range. Practically the whole length of the sensor can be utilised for measurement.

The mass of the moving short-circuiting ring is very low. Shaping the gap between coil and limb has an effect upon the shape of the curve: Reducing the gap towards the end of the measuring range further improves the already good linearity. Depending upon material and design, operation is mostly in the 5...50 kHz range. This sensor can also be used in very severe conditions, for instance on diesel injection pumps.

This (short-circuiting ring) measuring principle is also highly adaptable to the particular measurement assignment and is available in a very wide variety of different versions (Figs. 4 and 5).

The "half-differential sensor" is very precise. It has two short-circuiting rings, the movable ring being for measurement and the fixed ring serving for reference purposes. It is applied as follows:

- As an inductive voltage divider (evaluation of the inductances L_1/L_2 or $[L_1 - L_2]/[L_1 + L_2]$), or as
- The frequency-determining component of an oscillatory circuit for generaton of a frequency-analog signal (highly resistant to interference, easy to digitize).

4 Short-circuiting-ring angular-position sensors

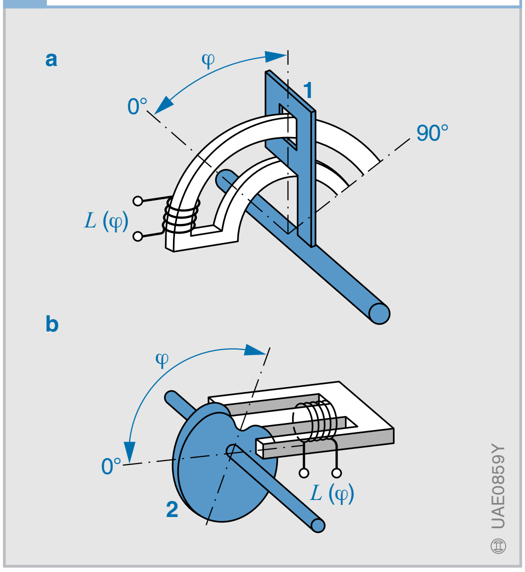

Fig. 4
a Short-circuiting-ring sensor
b Short-circuiting-disc sensor
1 Short-circuiting ring
2 Short-circuiting disc
$L(\alpha)$ Inductance
φ Measured angle

5 Short-circuiting-ring travel sensor

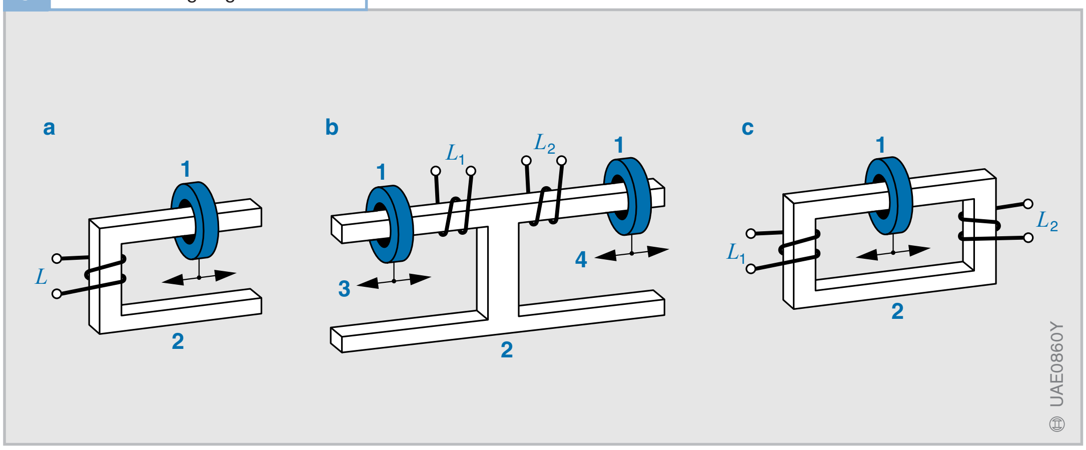

Fig. 5
a Single type
b Half-differential type
c Full-differential type
1 Short-circuiting ring
2 Core
3 Measuring system
4 Reference system (calibration)
L Inductance

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Fig. 7
1 Multiple-cavity coil
2 Ferrite core
3 Plastic extrusion coating with sliding guide
4 Rotating shaft with guide pin
$L(s)$ Inductance at measured travel s
φ Measured angle

Fig. 6
1 Short-circuiting reference ring, fixed
2 Reference coil
3 Short-circuiting measuring ring, movable
4 Coupling flux
5 Measuring coil
6 ECU
s Control-rack travel
SA Signal conditioning
A/DA/D converter

The short-circuiting-ring sensors feature a relatively pronounced measuring effect which is typically $L_{max}/L_{min} = 4$. There are a number of simulation programs on the market for calculating the electromagnetic behaviour of a short-circuiting-ring sensor. Results are very realistic and three-dimensional (Fig. 6).

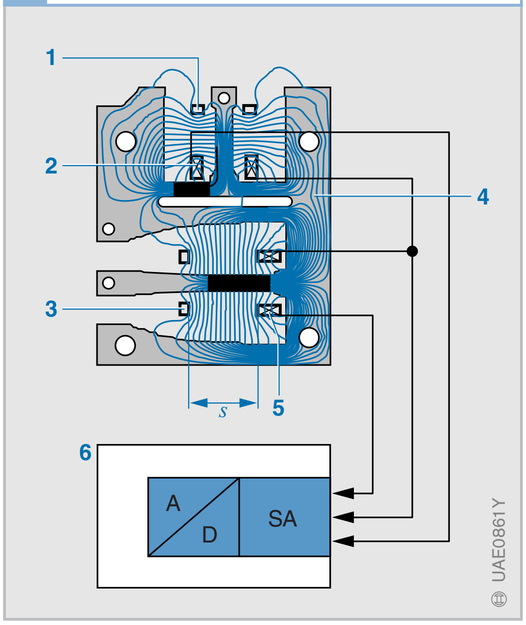
Short-circuiting ring sensors: Examples

- Rack-travel sensors for in-line injection pumps (attached-type load sensor, EDC sensor),
- Angular-position sensor for distributor injection pumps.

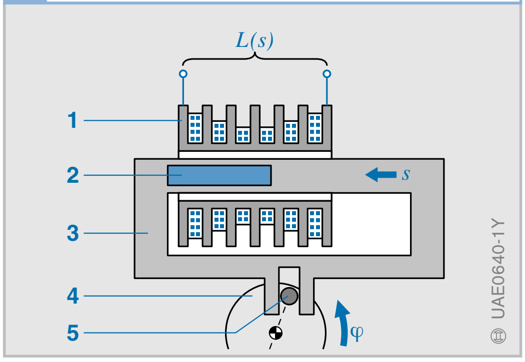
Solenoid-plunger sensors

Solenoid-plunger sensors (Fig. 7) utilise the fact that a coil's inductance can be varied by means of a movable core. This core can be manufactured from solid iron (wire), rolled Fe sheet, or ferrite, and must be precisely guided (sliding contact). The inherent nonlinearity of these sensors can be reduced by using special signal-conditioning circuitry. It is often the case that sensor length considerably exceeds the measured travel.

6 Magnetic lines of force in a half-differential short-circuiting-ring travel sensor used in an electronically controlled diesel in-line pump



7 Solenoid-plunger travel sensor



Dividing the winding into uneven cavities (Fig. 7) avoids these disadvantages.

The addition of a second plunger coil extends the measuring concept to provide a "differential throttling sensor" which, connected as an AC voltage divider, features better linearity and zero-point stability. If both coils, whose values change in opposite directions, are then not supplied directly but rather from a magnetically coupled, symmetrical-configuration primary coil, it is possible to avoid the negative effects of the copper losses in the coils. This measuring concept is not suitable for angular measurement since the angle of rotation must first of all be mechanically converted to travel, and this is a source of further errors.

Solenoid-plunger sensors: Examples

- Accelerator-pedal sensor (electric vehicles (EV))
- Position proportioning valves

Magnetostatic sensors

Magnetostatic sensors measure a DC magnetic field. In contrast to the magnetically inductive (coil) sensors they are far more suitable for miniaturisation and can be manufactured at reasonable cost using microsystem techniques. Above all, galvanomagnetic effects (Hall and Gaussian effects, Fig. 8) are used, as well as anisotropic magnetoresistive (AMR) metallic thin-film elements.

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Galvanomagnetic sensors

Above all, thin semiconductor wafers are used in such sensors for the evaluation of the *Hall effect*. If current flows through such a wafer which is permeated vertically by a magnetic induction B, a voltage U_H, which is proportional to the field strength, can be picked-off at right angles to the direction of current (Hall effect). At the same time the wafer resistance increases along a roughly parabolic curve (Gaussian effect, magnetoresistor). When silicon is used as the basic material, a signal-conditioning circuit can be integrated on the wafer. Sensors using these principles are very cheap to produce, whereby silicon is by far not the most favorable semiconductor material for Hall-effect sensors. For instance, such "III-V semiconductors" as gallium arsenide (GaAs) or indium antimonide have far better characteristics.

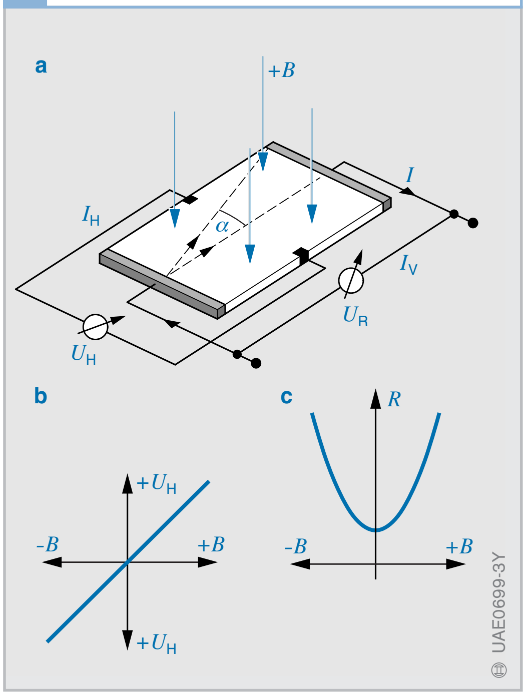
Hall-effect switch

In the most simple case, the Hall voltage is applied to an electronic threshold circuit (Schmitt trigger) which then outputs a digital signal. If the magnetic induction B applied at the sensor is below a given minimum threshold level, the Schmitt trigger's output value corresponds to a logical "0" (release status); if it exceeds a given upper threshold the output value corresponds to a logical "1" (operate status). Since this behaviour is guaranteed across the complete operating-temperature range and for all sensors of a given type, the two threshold values are relatively far apart (approx. 50 mT). In other words, it takes a considerable induction jump (ΔB) to trigger the Hall-effect switch.

Sensors using the "spinning-current" princciple

Up to now, the sensor's sensitivity to the unavoidable mechanical strain resulting from the packaging was a disadvantage, and led to unfavorable temperature sensitivity of the offset. It became possible to overcome this by the application of the "spinning-current" principle (Fig. 9). For the first time, Hall ICs were now suitable for analog sensor applications. By means of high-speed, electronically controlled rotation (spinning) of the electrodes

8 Galvanomagnetic effect



9 Hall-effect sensor using the "spinning-current" principle

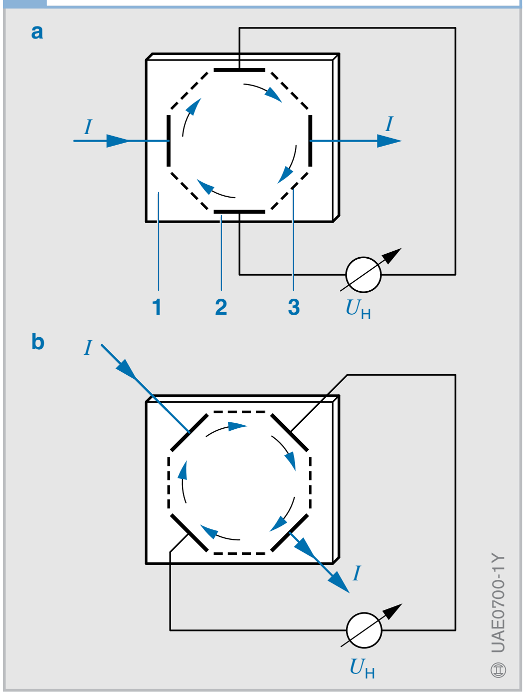


Fig. 8
- a Circuit
- b Curve of Hall voltage U_H
- c Increase of wafer resistance R (Gaussian effect)
- B Magnetic induction
- I Wafer current
- I_H Hall current
- I_V Supply current
- U_R Longitudinal voltage
- α Deviation of the electrons due to the magnetic field

Fig. 9
- a Rotary phase φ_1
- b Rotary phase $\varphi_2 = \varphi_1 + 45°$
- 1 Semiconductor wafer
- 2 Active electrode
- 3 Passive electrode
- I Supply current
- U_H Hall voltage

trodes, or their cyclic reversal, and output-signal averaging, it was possible to suppress the mechanical interference effects (piezoresistive effects). These measures though did not result in a reduction of the considerable effects of temperature on the sensor's measurement sensitivity.

Such Hall ICs are suitable above all for the measurement of small travel distances (refer to "Acceleration sensors"), in which they register the fluctuating field strength of a permanent magnet as it approaches.

Differential Hall-effect sensors
For a number of years now, there have been fully integrated duplicate Hall-effect sensors ("Differential Hall sensor configurations", Fig. 10) on the market. Here, two complete Hall systems are located on a single chip at a defined distance from each other. The appropriate electronic circuitry evaluates the difference between the two Hall voltages. The advantage of such sensors lies in the fact that their output signal is for the most part independent of the absolute value of the magnetic-field strength, and as differential sensors they only register the magnetic induction's change in space, in other words the field gradient (thus the common designation "Gradient sensor").

Since the polarity of their output signal is independent of the air gap between rotor and sensor, these sensors are mostly used for rotational-speed measurement. Usually, in order to achieve as high an output signal as possible, the two sensors are each located on the edge of the (elongated) chip, the distance between them corresponding to about half the rotor tooth interval.

The signal maximum is very wide and covers a broad range of variation of the increment spacing. More pronounced variations in the spacing necessitate a highly complex redesign of the sensor.

A gradient sensor must be precisely aligned to the rotor's direction of rotation.

10 Differential Hall-effect sensor (Double Hall-effect sensor)

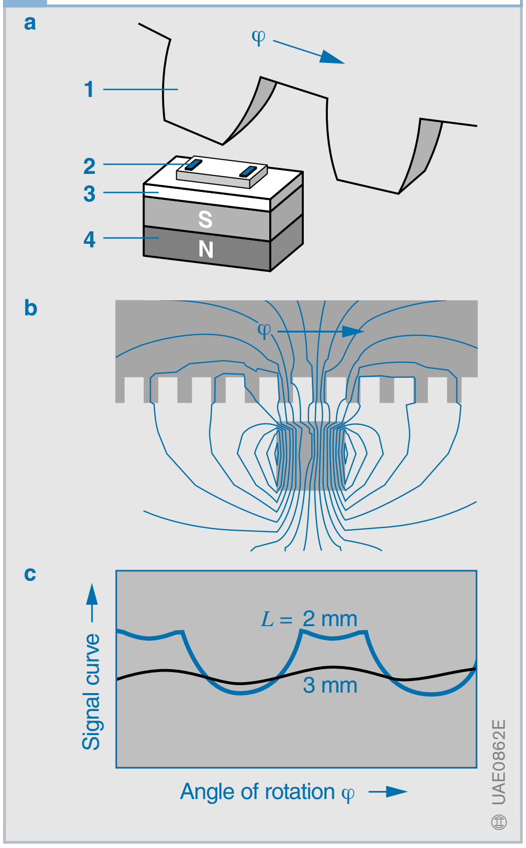


Fig. 10
a Design and construction
b Field-strength distribution (1.5 times increment spacing)
c Signal curve for air-gap widths L
1 Rotor
2 Differential Hall-effect IC
3 Homogenizing wafer (soft iron)
4 Permanent magnet

11 Analogue Hall-effect angle-of-rotation sensor ("movable magnet") with linear characteristic curve for angles up to 180°

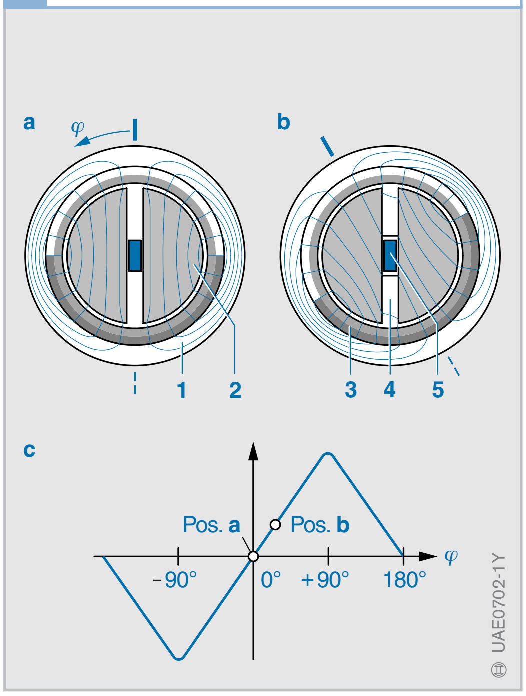


Fig. 11
a Position a
b Position b
c Output signal
1 Magnetic yoke
2 Stator (1,2 soft iron)
3 Rotor
4 Air gap
5 Hall-effect sensor
φ Angle of rotation

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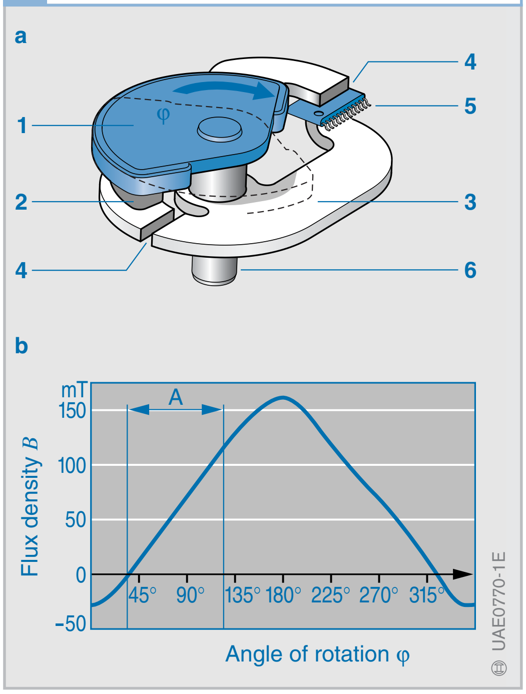
Angle-of-rotation sensors in the range up to 180°:
Using a rotatable magnetic ring ("movable magnet"), together with a number of fixed soft-magnetic conductive elements, a linear output signal can be generated for a larger angular range without conversion being necessary (Fig. 11). Here, the movable magnet's bipolar field is directed through a Hall-effect sensor located between semicircular conductive elements. The effective magnetic flux flowing through the Hall-effect sensor is a function of the angle of rotation φ.

The Type ARS1 Hall-effect angle-of-rotation sensor with a measuring range of approx 90° (Fig. 12) is derived from the basic "movable magnet" principle. The magnetic flux from a practically semicircular permanent-magnet disc is returned to the magnet through a pole-shoe, two additional conductive elements each of which contains a Hall-effect sensor in its magnetic path, and the shaft which is also ferromagnetic. Depending upon the angular setting, the flux is led through the two conductive elements to a greater or lesser degree. Using this principle, it is possible to achieve a practically linear characteristic.

The Type ARS2 is a simplified version which does without conductive elements (Fig. 13). In this version, the magnet moves around the Hall-effect sensor in a circular arc. Only a relatively small section of the resulting sinusoidal characteristic curve features good linearity. If the Hall-effect sensor is located slightly outside the center of the circular arc, the characteristic curve increasingly deviates from the sinusoidal, and now features a short measuring range of almost 90°, and a longer measuring range of more than 180° with good linearity.

A great disadvantage though is the low level of shielding against external fields, as well as the remaining dependence on the geometric tolerances of the magnetic circuit, and the fluctuations in magnetic flux density of the permanent magnet as a function of temperature and age. On the other hand, mechanically it is an easy matter to integrate these sensors in an accelerator-pedal module.

12 Hall-effect angle-of-rotation sensor ASR1 ("movable magnet") with linear characteristic for angles up to 90°



13 Hall-effect angle-of-rotation sensor ASR2 ("movable magnet") for angles >180°

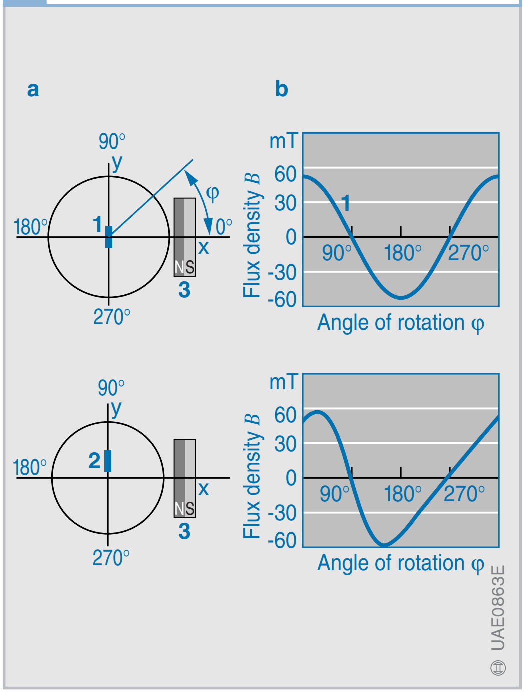


Fig. 12
- a Design and construction
- b Characteristic curve with working range A
- 1 Rotor disc (permanent magnet)
- 2 Pole shoe
- 3 Conductive element
- 4 Air gap
- 5 Hall-effect sensor
- 6 Shaft (soft magnetic)

Fig. 13
- a Principle of operation
- b Characteristic curve
- 1 Hall-IC positioned in the mid-point of the circular path
- 2 Hall-IC located outside the mid-point (linearization)
- 3 Magnet

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14 Digital Hall-effect angle-of-rotation sensor for angles up to 360° using a circular, arrangement of simple Hall-effect switches located equidistantly from each other

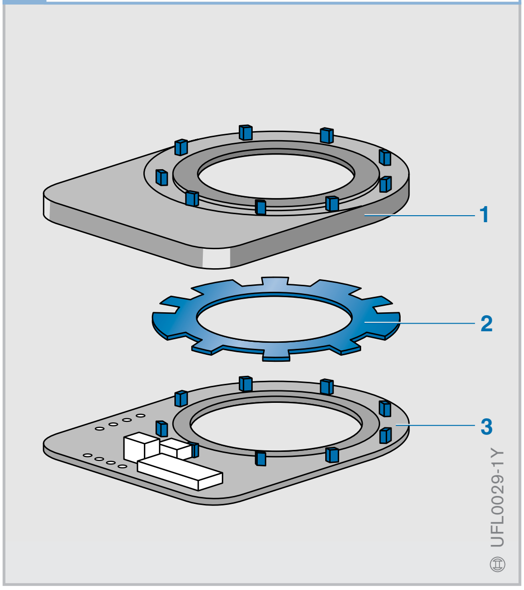

Fig. 14
1 Case cover with permanent magnets
2 Code disc
3 pcb with Hall-effect switches

15 Analog Hall-effect sensor for angles up to 360°

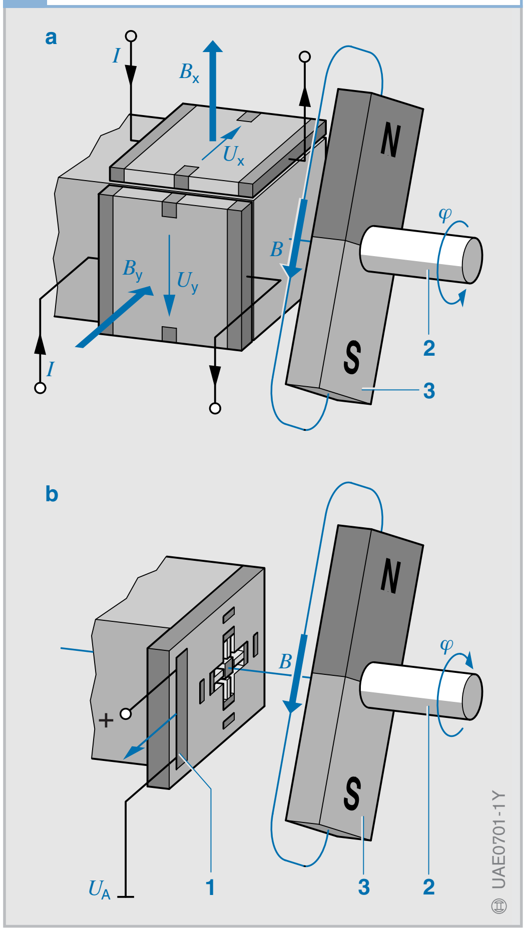

Fig. 15
a Constructed from discrete Hall ICs
b Constructed from planar integrated Hall ICs
1 Signal electronics
2 Camshaft
3 Control magnet
B Induction
I Current
U Voltage
U_A Output voltage
φ Angle of rotation

Angle-of-rotation sensors in the range above 180°

Type LWS3 steering-angle sensors are simple Hall ICs ("Hall-effect switches"), similar to those also used for rotational-speed measurement. In conjunction with small working-point magnets, they can be used as digital angle-of-rotation sensors for angles up to 360°. Here, in order to obtain an *n*-bit resolution, *n* Hall-effect switches are arranged in a circle at equal distances from each other (Fig. 14). Depending upon its position, a rotatable soft-magnetic code disc blocks the magnetic field of the individual permanent magnets located above each Hall-effect switch, or opens it when it rotates further so that one after another the Hall-effect switches generate *n* different code words. To prevent errors in intermediate settings of the code disc, it is expedient to apply the Gray code (cyclic binary code).

For the practical implementation of a steering-angle sensor, the code disc is connected to the steering shaft for instance, and the sensor's non-moving parts to the vehicle body.

In order to measure a number of complete rotations, an additional 3-bit configuration can be used in which the code disc is rotated by a step-down gearing. Such configurations though usually have a resolution of not better than 2.5°.

Fig. 15 shows an analog Hall-effect angle-of rotation sensor with a measuring range of up to 360°. As shown, a permanent magnet rotates in front of 2 Hall-effect sensors arranged at right angles to each other and in parallel to the permanent magnet's rotary axis. When the field-strength vector B rotates past the sensors, therefore, they register its x and y components:

$U_{H1} = U_x = B \sin \varphi$

$U_{H2} = U_y = B \cos \varphi$

Using the trigonometrical relationship $\varphi = \arctan (U_{H1} / U_{H2})$, it is then an easy matter to use these signals for calculating the angle φ in a commercially available evaluation

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chip belonging to the sensor. Principally speaking, the planar integration of this Hall-effect sensor configuration with "VHD" (**V**ertical **H**all **D**evices) as shown in Fig. 15 is possible, so that the sensor-chip is vertical to the rotary axis. Monolithic integration also guarantees the high level of precision as required for the 90° arrangement of the two Hall systems.

Differential magnetoresistive sensors

The resistive or Gaussian effect with semiconductor wafers mentioned at the beginning is put to use in magnetoresistors which are manufactured from a "III-V-semiconductor" (crystalline indium antimonide (InSb)). In contrast to the Hall-effect sensors, the optimum wafer shape for a magnetoresistor tends to be shorter and squatter, and represents a very low resistance. In order to arrive at technically applicable resistance values in the kΩ range it is therefore necessary to connect a large number of these wafers in series. This problem is solved elegantly by adding microscopically fine, highly conductive nickel-antimonide needles to the semiconductor crystal. These are located obliquely to the direction of current flow. A further measure is to apply meander techniques to the semiconductor resistor (Figs. 16 and 17a).

Magnetoresistors are usually applied to a ferrite substrate so that the effective air gap can be kept to an absolute minimum when they are installed in a magnetic circuit. Since their temperature sensitivity has a pronounced effect upon their resistance (approx. 50% reduction for 100K), they are usually delivered only in the dual-configuration form in voltage-divider circuits (differential magnetoresistors). For the particular application, each of the two resistor sections must then be magnetically triggered (as far as possible with oppposite polarities). Notwithstanding the high temperature coefficient of the individual resistors, the voltage-divider circuit guarantees good stability of the working-point (that point at which both resistor sections have the same value).

16 Magnetic triggering of a differential magnetoresistive sensor used for gearwheel sensing (incremental angle-of-rotation measurement, rotational-speed sensing)

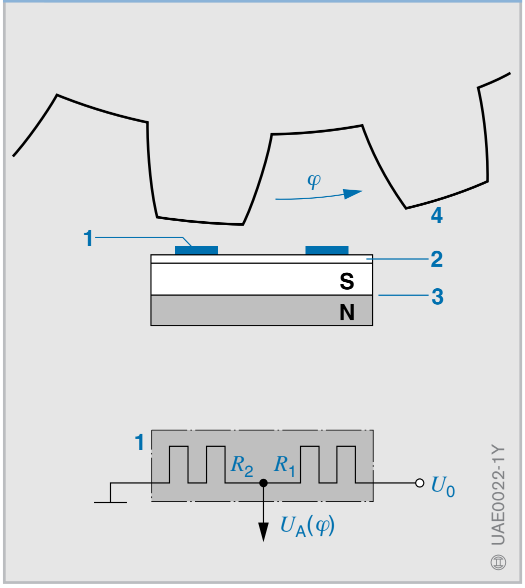


Fig. 16
1 Magnetoresistors R_1, R_2
2 Soft-magnetic substrate
3 Permanent magnet
4 Gearwheel
U_0 Supply voltage
U_A Output voltage for angle of rotation φ

17 Differential magnetoresistive sensor

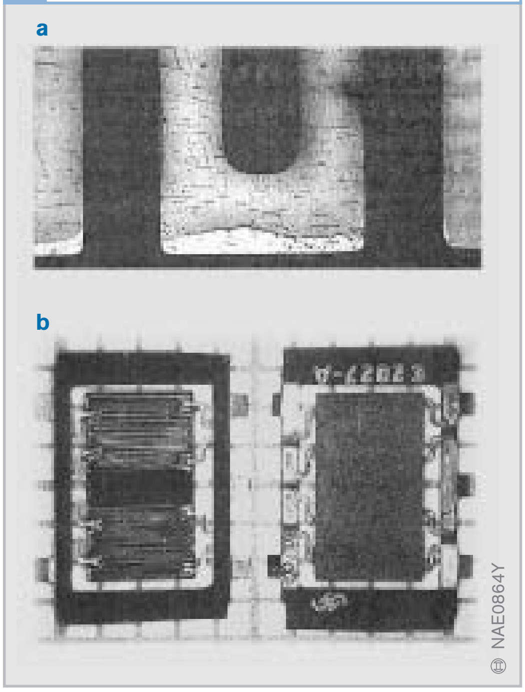


Fig. 17
a Microscopic section
b On ferrite substrate in Super-8 film carrier

Magnetoresistors are usually delivered at the production line in "Super-8 film packaging" (Fig. 17b). In this mode, a specially structured copper grid provides an effective connection from the internal semiconductor connection to the external assembly contact.

Taking into account their use in automotive applications, these sensors have operating-temperature limits of 160 °C sustained temperature and 200 °C short-time peak temperature. The dependence of the resistance on the magnetic flux density *B* follows a square-law function up to inductances of approx. 0.3 T, and above this point it is increasingly linear. There is no upper limit to the control range, and dynamic response can be regarded as practically free from lag.

In order to achieve good measurement sensitivity, it is best to operate the magnetoresistors at a magnetic working point between 0.1...0.3 T. Generally, the required magnetic bias is supplied by a small electromagnet the effects of which can be increased by using a small magnetic return plate. Without such a bias magnet, the sensor's measuring sensitivity would be practically zero. For measurement of displacement or angle, a small conductive element usually moves past the sensor configuration. At its symmetrical mid-point, this element triggers both sensor resistances equally, whereas when it is off-center it unbalances the voltage divider so that the output voltages feature good linearity and lead to high sensitivity. The magnetoresistor nevertheless still features pronounced temperature sensitivity so that it is used almost exclusively in incremental angle-of-rotation and displacement sensors, or in binary limit-value sensors (with switching characteristic).

The magnetoresistor's main advantage is its high signal level which is usually in the volts range. This means that amplification is unnecessary, as well as the local electronic circuitry and the associated protective measures which would otherwise be needed. Furthermore, in their role as passive, resistive components they are highly insensitive to electromagnetic interference and, as a result of their high bias voltage practically immune against external magnetic fields (for examples of application, refer to the Chapter "Speed and rpm sensors").

Magnetoresistive NiFe thin-film sensors

These sensors are otherwise known as AMR sensors (AMR = **A**nisotropic **M**agnetoresistive) and are formed from 30...50 nm thick NiFe films (also termed permalloy). They permit the design of highly compact, non-contacting angle-of-rotation sensors. In the AMR, the resistance of the printed conductor track is anisotropic, that is, in the direction of the magnetization vector it is several percent higher than at right angles to it.

Without an external control field being necessary, spontaneous magnetisation is generated in the longitudinal direction of the conductor (form anisotropy). In order to give this magnetisation a clearly defined direction – theoretically, it could be in the other direction – AMR sensors are often provided with weak bias magnets. If external influences are applied to turn the magnetizing vector through the angle φ, the resistance drops gradually until reaching its minimum at $\varphi = 90°$. Here, the resistance depends only on the angle φ which is enclosed by the magnetisation and the current. It has an approximate cosine shape as a function of φ. If the external field is much stronger than the spontaneous generated magnetisation, and this is usually the case when control magnets are used, the effective angle φ is *almost completely a function of the direction of the external field.* The field strength is now irrelevant, and in other words the sensor is now operating in the "saturated state"

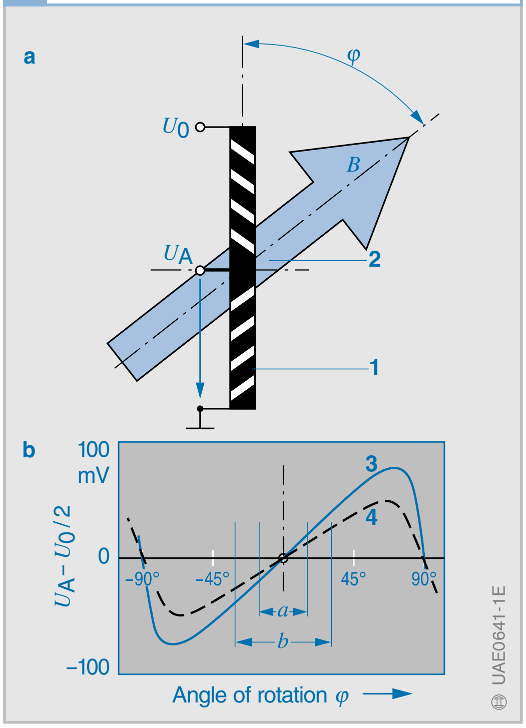
Highly-conductive short-circuiting strips (for instance of gold) on the AMR film force the current to flow at an angle of below 45° to the spontaneous magnetisation (longitudinal direction) without the application of an external field. As a result of this "trick", the sensor curve shifts by 45° compared to that of the simple resistor. This results in the so-called "Barber Pole" sensor. This means, therefore, that even with the external field strength at zero, the curve is at the point of maximum sensitivity. The *"striping of two resistors in opposite directions"* (Fig. 18) means that they change their resistances in opposite directions under the effects of the same field. In other words, one of the resistances increases while the other drops. In principle, the oxidized silicon wafers which serve as the substrate material can also incorporate the electronic circuitry for signal conditioning. At present, cost considerations dictate that sensor chip and electronics chip are for the most part manufactured separately, and then mounted for instance on a common "Leadframe" and packaged. The magnetic control field *B* is usually generated by magnets which rotate above the sensor.

"Barber Pole" AMR angle-of-rotation sensors with extremely limited accuracy and somewhat limited measuring range (max. ± 15°) rely on the unbalance of a magnetoresistive voltage divider comprising an elongated (possibly meander-shaped) permalloy resistor with highly conductive cross stripes of gold (Fig. 18). Although the zero point of such sensors is practically independent of the distance from magnet to sensor, this does not apply to the gradient of their characteristic curve.

Magnetoresistive angle-of-rotation sensors of the *"Pseudohall"* type utilise the practically 100% sinusoidal signal that is picked-off at the output terminals of the four-pole, sensor structure, whereby two complete periods of the electrical output signal correspond to a mechanical rotation of the magnets through 360°. Using a second element, which has been turned through 45°, a cosine signal is also generated (Fig. 19). By appling the arc-tangent function for instance, the relationship between the two signal voltages can be applied to determine the measured angle using a microcontroller or an ASIC. This applies throughout a range of 180°, and is for the most part independent of temperature changes and magnetic-field fluctuations (aging, spacing).

The measurement sensitivity of this so-called Pseudohall Element can be considerably increased (without excessively falsifying the sinusoidal shape) by "hollowing out" the element from the inside so that only the "frame" remains. This modification converts

18 Magnetoresistive angle-of-rotation sensor ("barber-pole" version) for measuring ranges of up to ±15°



19 Magnetoresistive angle-of-rotation sensor ("Pseudo-hall" version) for measuring ranges up to 180°

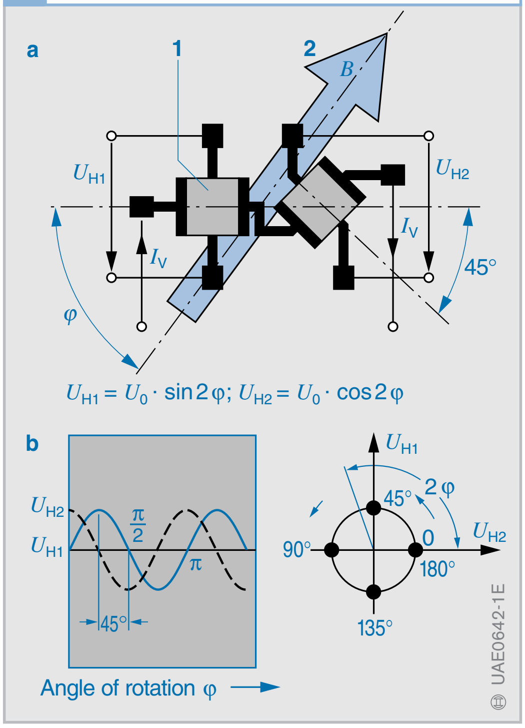


Fig. 18
a Measuring concept
1 Permalloy resistors
2 Rotatable permanent magnet with control induction *B*
b Characteristic curve
3 Lower operating temperature
4 Higher operating temperature
a Linear measuring range
b Effective measuring range
U_A Output voltage
U_0 Supply voltage (DC 5V)
φ Angle of rotation

Fig. 19
a Measuring concept
b Output signals
1 Thin NiFe film (AMR sensor)
2 Rotatable permanent magnet with control induction *B*
I_V Supply current
U_{H1}, U_{H2} Measurement voltages
φ Angle of rotation

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the pseudohall sensor to a full bridge consisting of four AMR resistors (Fig. 20). Even when the bridge resistors are meander-shaped, provided a given minimum conductor width is not dropped below, this still has negligible effect of the signal's sinusoidal shape.

A further prerequisite for the high accuracy of this sensor principle is that the field at both bridges is at least in the same direction (above a given magnitude, field strength is irrelevant). This can only be guaranteed when both bridges are directly above one another. A design was drawn up in which the two bridges, which are at 45° to each other, were interweaved so that they can be regarded as being at the same point and quasi "on top of one another" (Fig. 21). The *major advantage* of these Pseudohall-version sensors is the fact that in contrast to the corresponding "genuine" Hall-sensor versions, they are almost completely independent of the magnitude of the control field.

As soon as this has exceeded a given magnitude, the output signal is dependent solely upon the control-field angle.

The reason is that these sensors operate in the "saturation region" in which the angle of the spontaneous internal magnetism has switched almost completely to the direction imposed from outside. In other words, it is not necessary to have a constant control-field magnitude. At the measuring point, all that is required is a certain homogeneity of direction. With this sensor principle, neither the aging of the magnets and of the magnetic conductor elements, nor of the air-gap tolerances and fluctuations, plays an important role.

A dual-configuration "pseudohall angle-of-rotation" sensor can be used to measure a number of rotations of a rotating component (for instance, a steering shaft). The shaft's rotating member rotates the two permanent magnets through a step-up unit with a high transmission ratio. Since the two driven, smaller gearwheels differ from each other by one tooth, their respective phase position is a clear measure for the absolute angular position. Furthermore, each sensor's resolution of the angle of rotation is somewhat course. Using such a configuration, it is possible for instance to register the complete

20 Technically implemented full-bridge form of the "Pseudohall" sensor

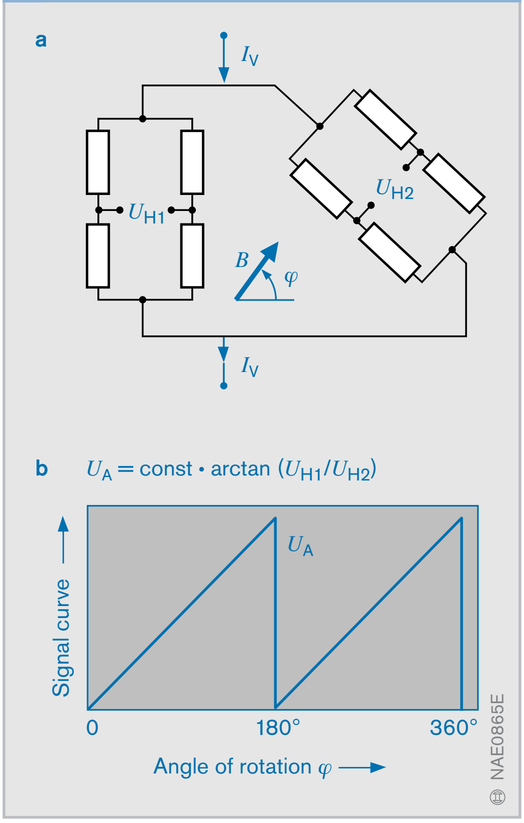
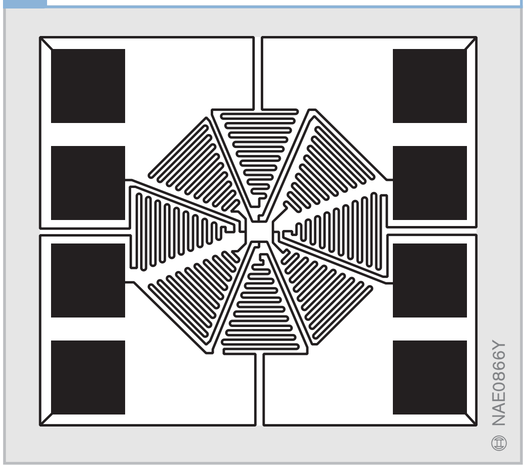


Fig. 20
- a Bridge circuit
- b Output signal U_A of the evaluation circuit
- B Control induction
- I_V Supply current
- U_{H1} Measurement
- U_{H2} voltages
- φ Angle of rotation

21 "Nested" design of two AMR bridges offset from each other by 45°



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steering-wheel range of four full rotations with a resolution of better than 1°.

GMR sensors

Just lately magnetoresistive (GMR) sensors have appeared on the market which use "nanotechnology" (GMR = **G**iant **M**agneto **R**esistive). These are composed of a number of thin layers applied one on top of the other. These layers have a thickness of only one or two atomic layers (Fig. 23). They are very similar to the AMR sensors, but have a far more pronounced measuring effect (Fig. 22). In contrast to the AMR sensors, the GMR sensor resistance (in the case of a Pseudohall configuration) depends solely upon the angle of rotation and not on the sinus of double the mechanical angle of rotation. This means that a full 360° angle of rotation can be measured.

Compass sensors (earth's-field sensors)

A completely novel type of angle-of-rotation sensor is required by vehicle navigation systems. At least at road junctions and crossings, these must be able to measure the angle steered by the vehicle ("Heading"). This must also be possible even when there is no steering-wheel-angle sensor installed in the vehicle. Until suitable inert sensors (time-integrated yaw-rate sensors) became available, magnetic-field sensors ("saturation core field sensors", Fig. 24) are used which use the geomagnetic field (compass) to determine the direction taken by the vehicle.

23 GMR single sensor (structure)

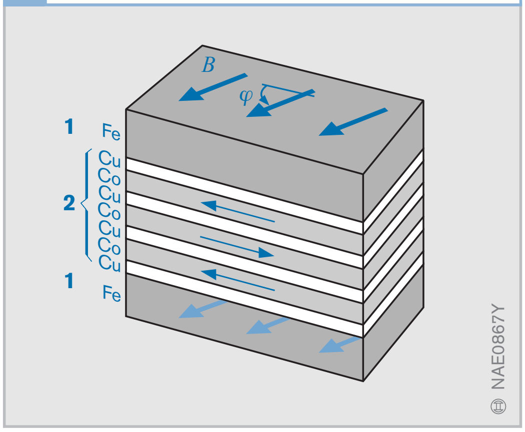


Fig. 23
1 Fe layers
2 Thin anti-ferromagnetic CuCo layers
B Control induction
φ Angle of rotation

24 Sensor core of the geomagnetic field sensor

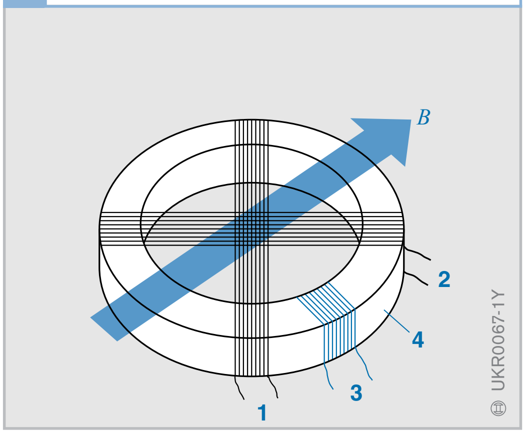
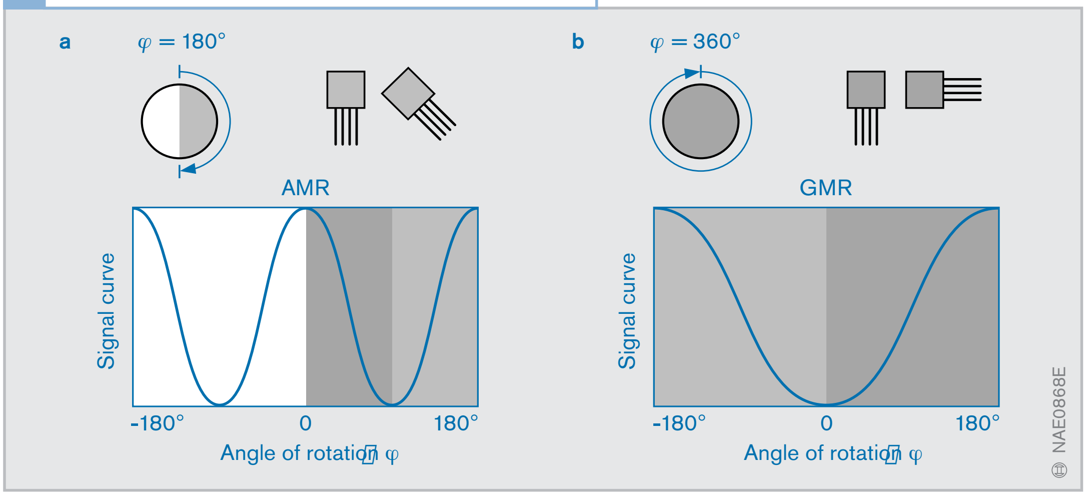


Fig. 24
1 Sensor coil (x-axis)
2 Sensor coil (y-axis)
3 Excitation winding
4 Toriodal core
B Measuring field (horizontal component of the geomagnetic field)

22 Comparison betwen AMR sensors (a) and GMR sensors (b)



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Wave-propagation sensors

For vehicle-spacing measurement, ultrasonic running-time methods (near range 0.5...5 m) are suitable, as are running-time or triangulation methods using light in the near-infrared range (Lidar, medium range up to 50 m), and electromagnetic radar (distance zone up to 150 m).

Acoustic sensors (ultrasonic)

Similar to the echo-sounding process, the sensors here transmit ultrasonic pulses with a frequency of around 40 kHz (Fig. 25), and register the time taken for the echo pulse to arrive after having been reflected back from an obstacle. The distance a to the next obstacle is calculated from the propagation time of the first reflected echo pulse t_e to arrive and the speed of sound in air (Fig. 26): $a = 0.5 \cdot t_e \cdot c$

Electromagnetic sensors (radar)

Using a far-ranging radar sensor, ACC systems automatically detect preceding vehicles in the same lane which could eventually necessitate application of the brakes. Here, ACC stands for **A**daptive **C**ruise **C**ontrol. The working frequency is 76 GHz (wavelength approx. 3.8 mm) and permits the relatively low-profile construction as needed for automotive applications. A Gunn-effect oscillator (Gunn diode in a cavity resonator), feeds three Patch antennas arranged adjacent to each other, which also serve to receive the reflected signals again (Fig. 27). Referred to the vehicle axis, a plastic lens (Fresnel lens) concentrates the transmit beam horizontally at an angle of ±5°, and vertically at an angle of ±1.5°. The antenna receive characteristics are aligned in different directions due to the antennas being off-set

25 Antenna radiation diagram of an ultrasonic sensor

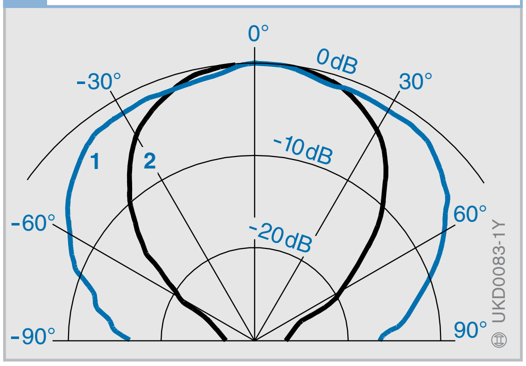

Fig. 25
1 Vertical
2 Horizontal

26 Calculating the distance to a single obstacle using ultrasonics (example)

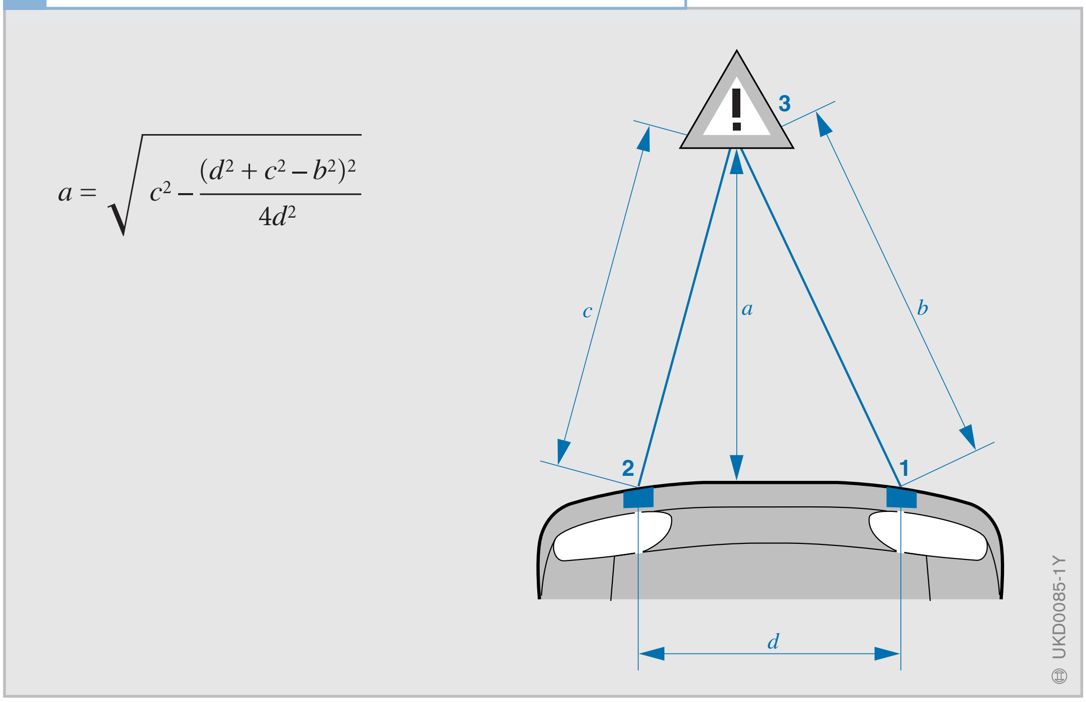

Fig. 26
a Distance between the bumper and the obstacle
b Distance sensor 1 to obstacle
c Distance sensor 2 to obstacle
d Distance sensor 1 to sensor 2
1 Transceiver sensor
2 Receiver sensor
3 Obstacle

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from the center (6 dB width, 4°). This means that in addition to the calculation of the distance to preceding vehicles and their relative speeds, it is also possible to determine the direction in which they are travelling when detected. Directional couplers are used to separate the transmitted and received reflection signals. By mixing the receive frequency and the transmit frequency, three downstream mixers transpose the receive frequency down to practically zero (0...300 kHz). In order to evaluate them, the low-frequency signals are now digitized and put through a high-speed Fourier (harmonic) analysis to determine the frequencies.

The Gunn-effect oscillator frequency is continually compared with that of a stable DRO reference oscillator (**D**ielectric **Reso**nance **O**scillator), and maintained at a stipulated setpoint frequency. To do so, the Gunn-effect oscillator's supply voltage is adjusted until the frequency is correct again. Via a closed control loop, and following a saw-tooth waveform, the Gunn-effect oscillator frequency is briefly raised and lowered by 300 MHz every 100 ms (FMCW **F**requency-**M**odulated **C**ontinuous **W**ave). The signal reflected from a preceding vehicle is delayed in accordance with the propagation time (in other words, in the positive-going edge by the lower frequency, and in the negative-going edge by the higher frequency). Lower and higher frequencies deviate from the basic frequency by the same amount.

The frequency difference Δf is a direct measure of the distance (e.g. 2kHz/m). If, on the other hand, there is also a given relative speed between the two vehicles, the Doppler principle causes the receive frequency f_e to increase in the positive-going and negative-going edges by a certain proportional amount Δf_d (e.g. 512 Hz per m/s). In other words, this results in two different differential frequencies Δf_1 and Δf_2. Adding these two frequencies provides the distance, subtracting them provides the relative speed between the two vehicles (Fig. 27). This method is used to detect and follow a number of vehicles (as many as 32).

28 Distance and speed measurement using FMCW radar

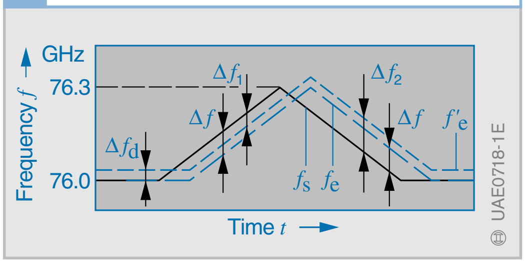
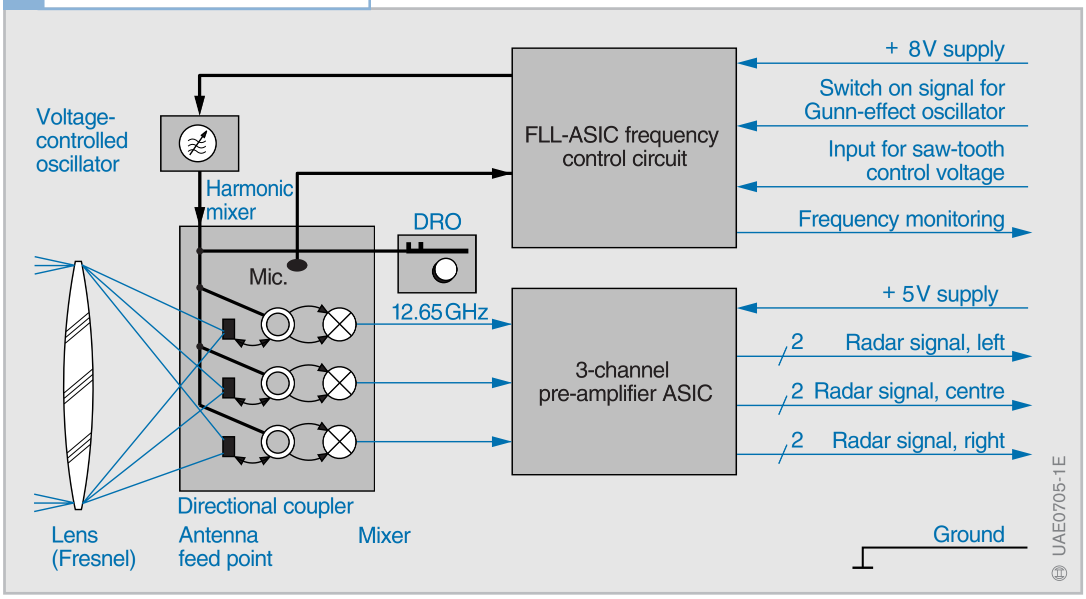


Fig. 28
f_S Transmit frequency
$f_e/f_{e'}$ Receive frequency without/with relative speed
Δf_d Frequency increase due to Doppler effect (relative speed)
$\Delta f_S/$ Frequency difference
$\Delta f_{1,2}$ Without/with relative speed

27 ACC sensor ECU (block diagram)



Sensor-plate potentiometer

Application

The sensor-plate potentiometer is used in the air-flow sensor of the KE-Jetronic fuel-injection system to register the position (angle of rotation) of the sensor flap. The rate at which the driver presses the accelerator pedal is derived from the sensor plate's movement, which is only slightly delayed with respect to the throttle-valve movement. This signal corresponds to the change in intake air quantity as a function of time, in other words approximately engine power. The potentiometer inputs it to the ECU which applies it when triggering the electro-hydraulic pressure actuator (Fig. 2).

1 Sensor-plate potentiometer (highly simplified)

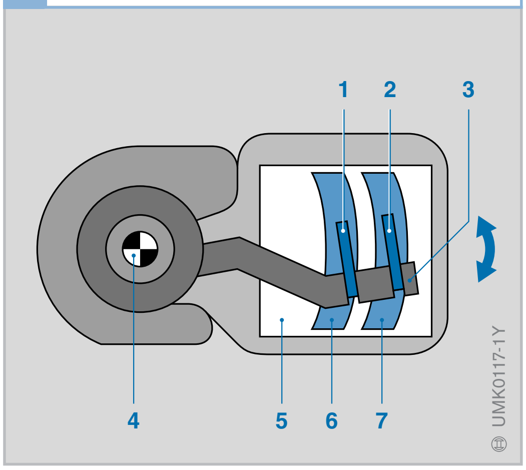


Fig. 1
1 Pick-off wiper brush
2 Main wiper brush
3 Wiper lever
4 Air-flow sensor shaft
5 Potentiometer board
6 Pick-off track
7 Measurement track

2 Sensor-plate potentiometer in the KE-Jetronic air-flow sensor (schematic)

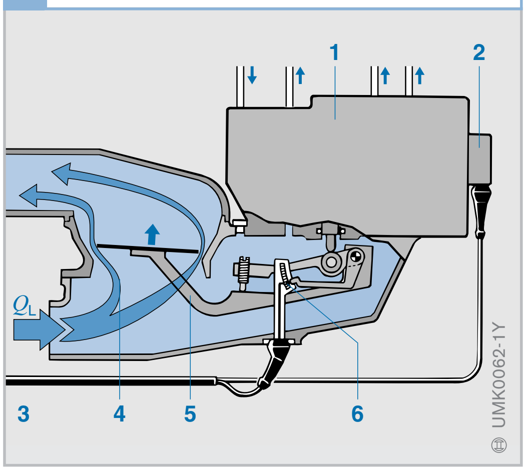


Fig. 2
1 Fuel distributor
2 Electrohydraulic pressure actuator
3 To the ECU
4 Air-flow sensor
5 Sensor plate
6 Potentiometer
Q_L Air quantity

Depending upon the engine's operating state and the corresponding current signal generated by the ECU, the pressure actuator changes the pressure in the vacuum chambers of the differential-pressure valves in the fuel distributor, and with it the amount of fuel metered to the injectors.

Design and operating concept

The potentiometer in the air-flow sensor is produced on a ceramic substrate using film techniques. It is a potentiometer-type angle-of-rotation sensor, which for measurement purposes applies the relationship which exists between the length of a film resistor (printed conductor) and its resistance. The printed-conductor width is varied in order to make the potentiometer characteristic non-linear so that the highest acceleration signal is generated when sensor-plate movement originates from the idle setting. The signal decreases along with increasing engine power output.

The brush wiper slides over the potentiometer tracks (pick-off track and wiper track) and is comprised of a number of very fine wires welded to a lever which is mechanically connected to the sensor-plate shaft (from which it is electrically insulated). The individual wires only apply very light pressure to the potentiometer tracks so that wear remains at a very low level. The large number of wires leads to good electrical contact in case the track surface is very rough and also when the brush is moved very quickly over the track. The wiper voltage is picked-off by a second brush wiper which is connected electrically to the main wiper (Fig. 1).

Damage due to air blowback in the intake manifold is ruled out since the wiper is free to travel far enough beyond the measurement range at both ends of the track. Protection against electrical short circuit is provided by a fixed film resistor connected in series with the wiper.

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Throttle-valve sensor

Application

The throttle-valve sensor registers the angle of rotation of the gasoline-engine throttle valve. On M-Motronic engines, this is used to generate a secondary-load signal which, amongst other things, is used as auxiliary information for dynamic functions, as well as for recognition of operating range (idle, part load, WOL), and as a limp-home or emergency signal in case of failure of the primary-load sensor (air-mass meter). If the throttle-valve sensor is used as the primary-load sensor, the required accuracy is achieved by applying two potentiometers for two angular ranges.

The ME-Motronic adjusts the required engine torque via the throttle valve. In order to check that the throttle valve moves to the required position, the throttle-valve sensor is used to evaluate the valve's position (closed-loop position control). As a safety measure, this sensor is provided with two parallel-operation (redundant) potentiometers with separate reference voltages.

Design and operating concept

The throttle-valve sensor is a potentiometer-type angle-of-rotation sensor with one (or two) linear characteristic curve(s).

The wiper arm is connected mechanically with the throttle-valve shaft, and with its brushes slides across the respective potentiometer tracks. In the process, it converts the rotation of the throttle valve shaft into a voltage ratio U_A/U_V which is proportional to the valve's angle of rotation (Fig. 2). The operating voltage is 5 V. The electrical wiper connection is usually through a second potentiometer track. This has the same surface, but the track itself is formed of a low-resistance printed-conductor material (Figs. 1 and 3).

As a protection against overload, the voltage is applied to the measurement (potentiometer) tracks through small series resistors (also used for zero-point and slope calibration). The shape of the characteristic curve can be adapted by varying the width of the potentiometer track (variation can also apply to sections of the track).

1 Throttle-valve sensor

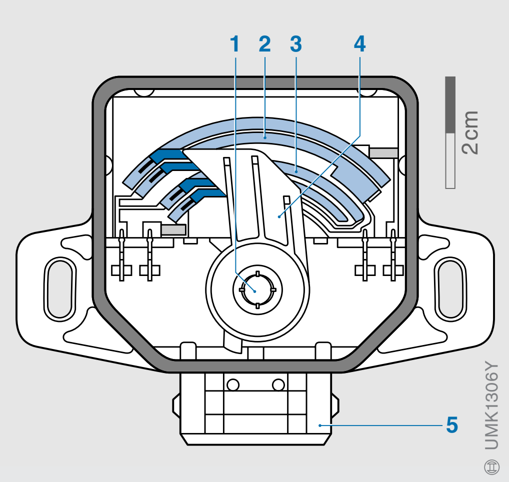

Fig. 1
1 Throttle-valve shaft
2 Resistance track 1
3 Resistance track 2
4 Wiper arm with wipers
5 Electric connection (4-pole)

2 Throttle-valve sensor with two curves

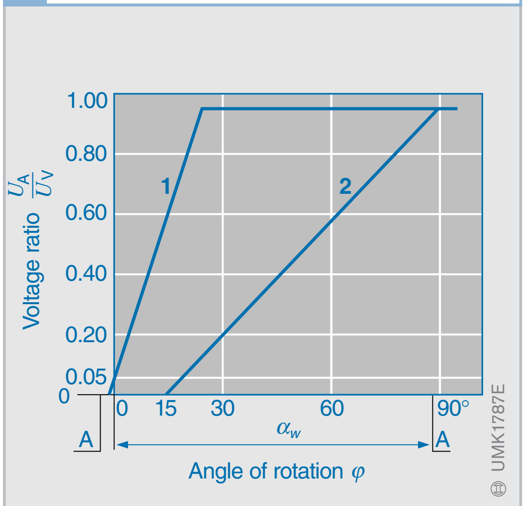

Fig. 2
A Internal stop
1 Curve for high resolution in angular range 0°...23°
2 Curve for angular range 15°...88°
U_0 Supply voltage
U_A Measurement voltage
U_V Operating voltage
α_W Effective measured angle

3 Throttle-valve sensor (circuit)

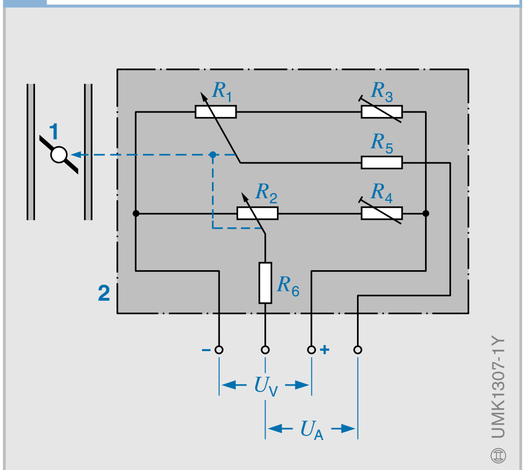

Fig. 3
1 Throttle valve
2 Throttle-valve sensor
U_A Measurement voltage
U_V Operating voltage
R_1, R_2 Resistance tracks 1 and 2
R_3, R_4 Calibration resistors
R_5, R_6 Protective resistors

Half-differential short-circuiting-ring sensors

Application

These sensors are also known as HDK (taken from the German) sensors, and are applied as position sensors for travel or angle, They are wear-free, as well as being very precise, and very robust, and are used as:

- Rack-travel sensors (RWG) for measuring the control-rack setting on in-line diesel injection pumps, and as
- Angle-of-rotation sensors in the injected-fuel-quantity actuators of diesel distributor pumps.

Design and operating concept

These sensors (Figs. 1 and 2) are comprised of a laminated soft-iron core on each limb of which are wound a measuring coil and a reference coil.

Alternating magnetic fields are generated when the alternating current from the ECU flows through these coils. The copper rings surrounding the limbs of the soft-iron cores screen the cores, though, against the effects of the magnetic fields. Whereas the reference short-circuiting rings are fixed in position, the measuring short-circuiting rings are attached to the control rack or control-collar shaft (in-line pumps and distributor pumps respectively), with which they are free to move (control-rack travel *s*, or adjustment angle φ).

When the measuring short-circuiting ring moves along with the control rack or control-collar shaft, the magnetic flux changes and, since the ECU maintains the current constant (load-independent current), the voltage across the coil also changes.

The ratio of the output voltage U_A to the reference voltage U_{Ref} (Fig. 3) is calculated by an evaluation circuit. This ratio is proportional to the deflection of the measuring short-circuiting ring, and is processed by the ECU. Bending the reference short-circuiting ring adjusts the gradient of the characteristic curve, and the basic position of the measuring short-circuiting ring defines the zero position.

1 Design of the half-differential short-circuiting-ring sensor for diesel distributor pumps

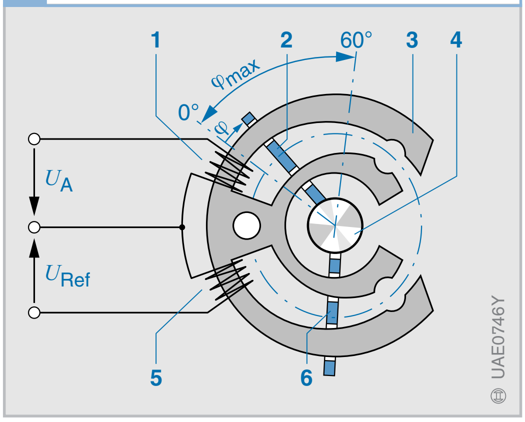

Fig. 1
1 Measuring coil
2 Measuring short-circuiting ring
3 Soft-iron core
4 Control-collar shaft
5 Reference coil
6 Reference short-circuiting ring
φ_{max} Adjustment-angle range for the control-collar shaft
φ Measured angle

2 Design of the rack-travel sensor (RWG) for diesel in-line injection pumps

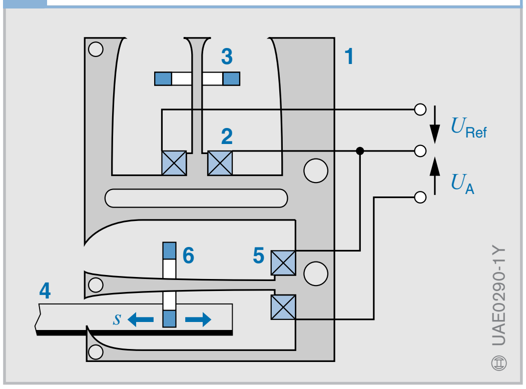

Fig. 2
1 Soft-iron core
2 Reference coil
3 Reference short-circuiting ring
4 Control rack
5 Measuring coil
6 Measuring short-circuiting ring
s Control-rack travel

3 Voltage ratio as a function of control-rack travel

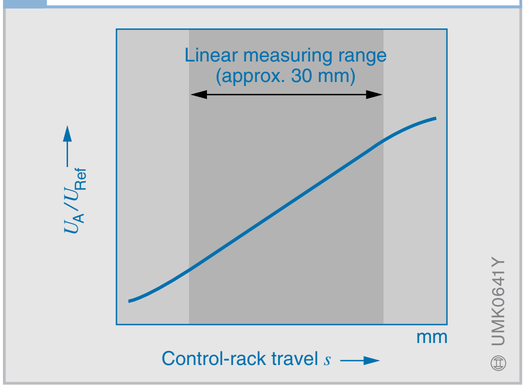

Fig. 3
U_A Output voltage
U_{Ref} Reference voltage

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Fuel-level sensor

Application

It is the job of the fuel-level sensor to register the level of the fuel in the tank and send the appropriate signal to the ECU or to the display device in the vehicle's instrument panel. Together with the electric fuel pump and the fuel filter, it is part of the in-tank unit. These are installed in the fuel tank (gasoline or diesel fuel) and provide for an efficient supply of clean fuel to the engine (Fig. 1).

Design

The fuel-level sensor (Fig. 2) is comprised of a potentiometer with wiper arm (wiper spring), printed conductors (twin-contact), resistor board (pcb), and electrical connections. The complete sensor unit is encapsulated and sealed against fuel. The float (fuel-resistant Nitrophyl) is attached to one end of the wiper lever, the other end of which is fixed to the rotatable potentiometer shaft (and therefore also to the wiper spring). Depending upon the particular version, the float can be either fixed in position on the lever, or it can be free to rotate). The layout of the resistor board (pcb) and the shape of the float lever and float are matched to the particular fuel-tank design.

Operating concept

The potentiometer's wiper spring is fixed to the float lever by a pin. Special wipers (contact rivets) provide the contact between the wiper spring and the potentiometer resistance tracks, and when the fuel level changes the wipers move along these tracks and generate a voltage ratio which is proportional to the float's angle of rotation. End stops limit the rotation range of 100° for maximum and minimum levels as well as preventing noise. Operating voltage is 5...13 V.

1 Fuel-level sensor installed in a fuel tank

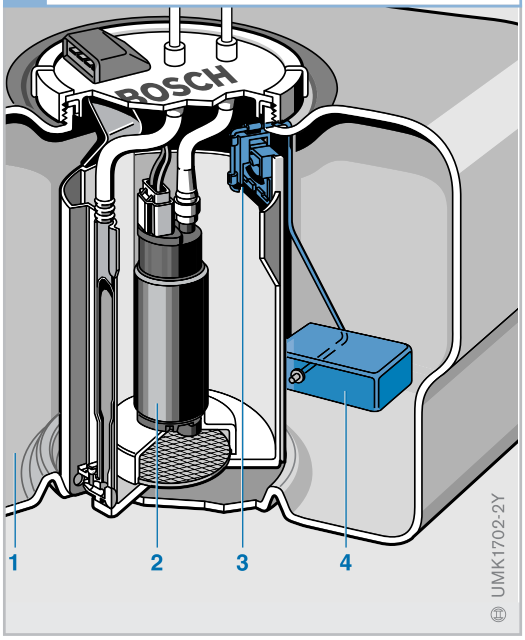

Fig. 1
1 Fuel tank
2 Electric fuel pump
3 Fuel-level sensor
4 Float

2 Fuel-level sensor

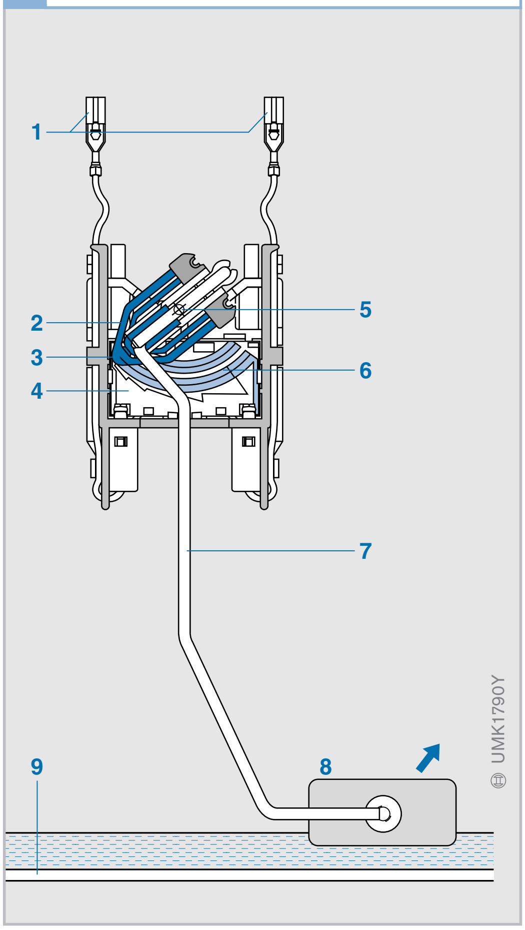

Fig. 2
1 Electrical connections
2 Wiper spring
3 Contact rivet
4 Resistor board
5 Bearing pin
6 Twin contact
7 Float lever
8 Float
9 Fuel-tank floor

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Accelerator-pedal sensors

Application

In conventional engine-management systems, the driver transmits his/her wishes for acceleration, constant speed, or lower speed, to the engine by using the accelerator pedal to intervene mechanically at the throttle plate (gasoline engine) or at the injection pump (diesel engine). Intervention is transmitted from the accelerator pedal to the throttle plate or injection pump by means of a Bowden cable or linkage.

On today's electronic engine-management systems, the Bowden cable and/or linkage have been superseded, and the driver's accelerator-pedal inputs are transmitted to the ECU by an accelerator-pedal sensor which registers the accelerator-pedal travel, or the pedal's angular setting, and sends this to the engine ECU in the form of an electric signal. This system is also known as "drive-by-wire". The accelerator-pedal module (Figs. 2b, 2c) is available as an alternative to the individual accelerator-pedal sensor (Fig. 2a). These modules are ready-to-install units comprising accelerator pedal and sensor, and make adjustments on the vehicle a thing of the past.

Design and operating concept

Potentiometer-type accelerator-pedal sensor

The heart of this sensor is the potentiometer across which a voltage is developed which is a function of the accelerator-pedal setting. In the ECU, a programmed characteristic curve is applied in order to calculate the accelerator-pedal travel, or its angular setting, from this voltage.

A second (redundant) sensor is incorporated for diagnosis purposes and for use in case of malfunctions. It is a component part of the monitoring system. One version of the accelerator-pedal sensor operates with a second potentiometer. The voltage across this potentiometer is always half of that across the first potentiometer. This provides two independent signals which are used for trouble-shooting (Fig. 1). Instead of the second potentiometer, another version uses a low-idle switch which provides a signal for

1 Characteristic curve of an accelerator-pedal sensor with redundant potentiometer

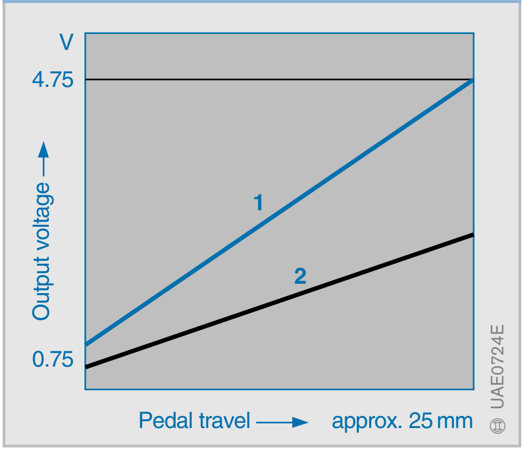

Fig. 1
1 Potentiometer 1 (master potentiometer)
2 Potentiometer 2 (50% of voltage)

2 Accelerator-pedal-sensor versions

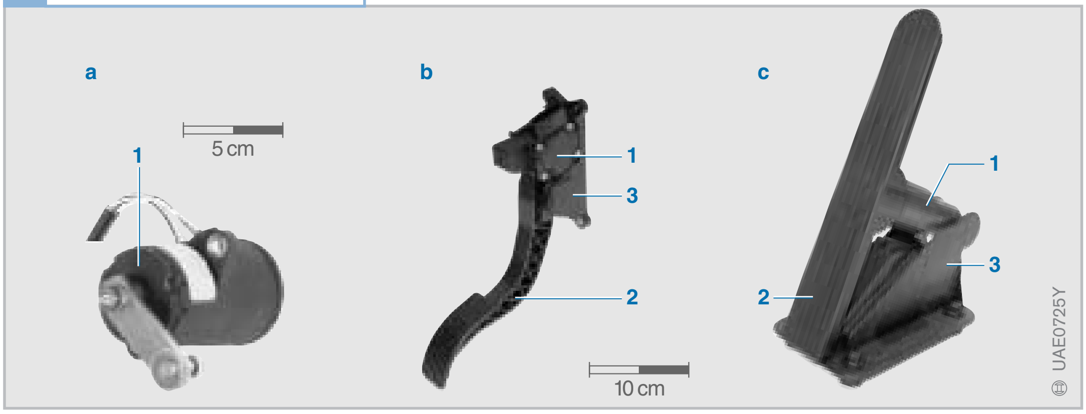

Fig. 2
a Individual accelerator-pedal sensor
b Top-mounted accelerator-pedal module
c Bottom-mounted accelerator-pedal module FMP1
1 Sensor
2 Vehicle-specific pedal
3 Pedal bracket

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the ECU when the accelerator pedal is in the idle position. For automatic transmission vehicles, a further switch can be incorporated for a kick-down signal.

Hall-effect angle-of-rotation sensors

The ARS1 (**A**ngle of **R**otation **S**ensor) is based on the movable-magnet principle. It has a measuring range of approx. 90° (Figs. 3 and 4).

A semicircular permanent-magnet disc rotor (Fig. 4, Pos. 1) generates a magnetic flux which is returned back to the rotor via a pole shoe (2), magnetically soft conductive elements (3) and shaft (6). In the process, the amount of flux which is returned through the conductive elements is a function of the rotor's angle of rotation φ. There is a Hall-effect sensor (5) located in the magnetic path of each conductive element, so that it is possible to generate a practically linear characteristic curve throughout the measuring range.

The ARS2 is a simpler design without magnetically soft conductive elements. Here, a magnet rotates around the Hall-effect sensor. The path it takes describes a circular arc. Since only a small section of the resulting sinusoidal characteristic curve features good linearity, the Hall-effect sensor is located slightly outside the center of the arc. This causes the curve to deviate from its sinusoidal form so that the curve's linear section is increased to more than 180°.

Mechanically, this sensor is highly suitable for installation in an accelerator-pedal module (Fig. 5).

3 Hall-effect angle-of-rotation sensor ARS1

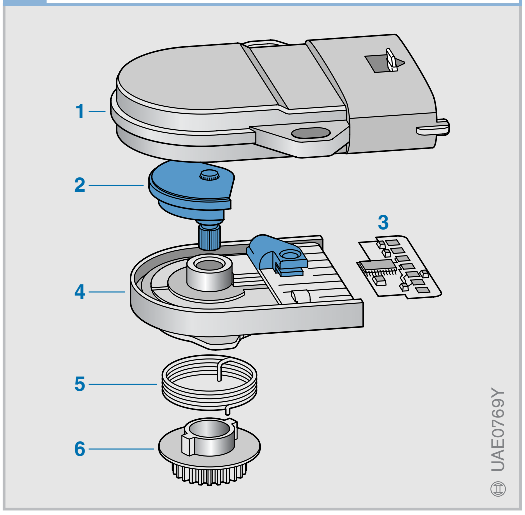

Fig. 3
1 Housing cover
2 Rotor (permanent magnet)
3 Evaluation electronics with Hall-effect sensor
4 Housing base
5 Return spring
6 Coupling element (e.g. gear)

4 Hall-effect angle-of-rotation sensor ARS1 (shown with angular settings a...d)

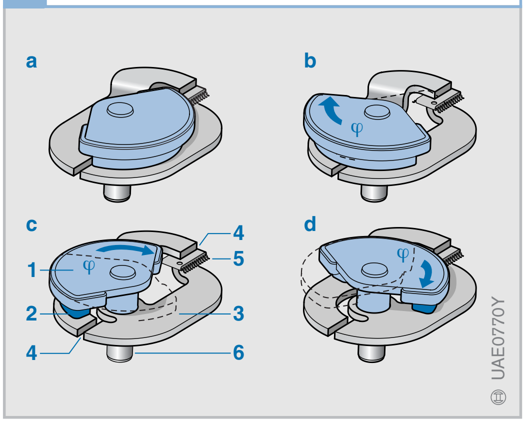

Fig. 4
1 Rotor (permanent magnet)
2 Pole shoe
3 Conductive element
4 Air gap
5 Hall-effect sensor
6 Shaft (magnetically soft)
φ Angle of rotation

5 Hall-effect angle-of-rotation sensor ARS 2

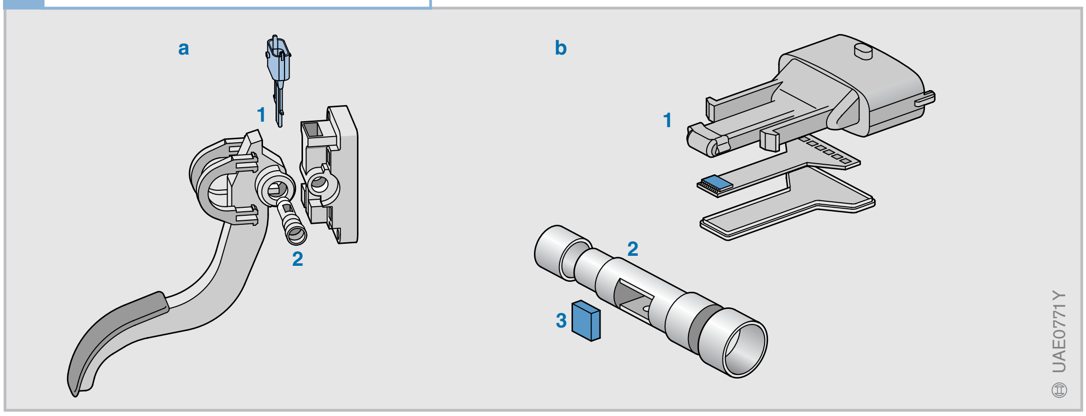

Fig. 5
a Installation in the accelerator-pedal module
b Components
1 Hall-effect sensor
2 Pedal shaft
3 Magnet

Steering-wheel-angle sensors

Application

The Electronic Stability Program (ESP) applies the brakes selectively to the individual wheels in order to keep the vehicle on the desired track selected by the driver. Here, the steering-wheel angle and the applied braking pressure are compared with the vehicle's actual rotary motion (around its vertical axis) and its road speed. If necessary, the brakes are applied at individual wheels. These measures serve to keep the float angle (deviation between the vehicle axis and the actual vehicle movement) down to a minimum and, until the physical limits are reached, prevent the vehicle breaking away.

Basically speaking, practically all types of angle-of-rotation sensors are suitable for registering the steering-wheel angle. Safety considerations, though, dictate that only those types are used which can be easily checked for plausibility, or which in the ideal case automatically check themselves. Potentiometer principles are used, as well as optical code-registration and magnetic principles. Whereas a passenger-car steering wheel turns through ±720° (a total of 4 complete turns), conventional angle-of-rotation sensors can only measure maximum 360°. This means that with the majority of the sensors actually used for this purpose it is necessary to continually register and store the data on the steering wheel's actual setting.

Design and operating concept

There are two absolute-measuring (in contrast to incremental-measuring) magnetic angle-of-rotation sensors available which are matched to the Bosch ECUs. At any instant in time, these sensors can output the steering-wheel angle throughout the complete angular range.

Hall-effect steering-wheel-angle sensor (LWS1)

The LWS1 uses 14 Hall-effect vane switches to register the angle and the rotations of the steering wheel. The Hall-effect vane switch is similar in operation to a light barrier. A Hall-effect element measures the magnetic field of an adjacent magnet. A magnetic code disc rotates with the steering shaft and strongly reduces the magnet's field or screens it off completely. In this manner, with nine Hall ICs it is possible to obtain the steering wheel's angular position in digital form. The remaining five Hall-effect sensors register the particular steering-wheel revolution which is transformed to the final 360° range by 4:1 step-down gearing.

The first item from the top in the exploded view of the LWS 1 steering-wheel-angle sensor (Fig. 1) shows the nine permanent magnets. These are screened individually by the magnetically-soft code disc beneath them when this rotates along with the steering shaft, and depending upon steering-wheel movement. The pcb immediately below the code disc contains Hall-effect switches (IC), and a micro-

1 Exploded view of the digital LWS1 steering-wheel-angle sensor

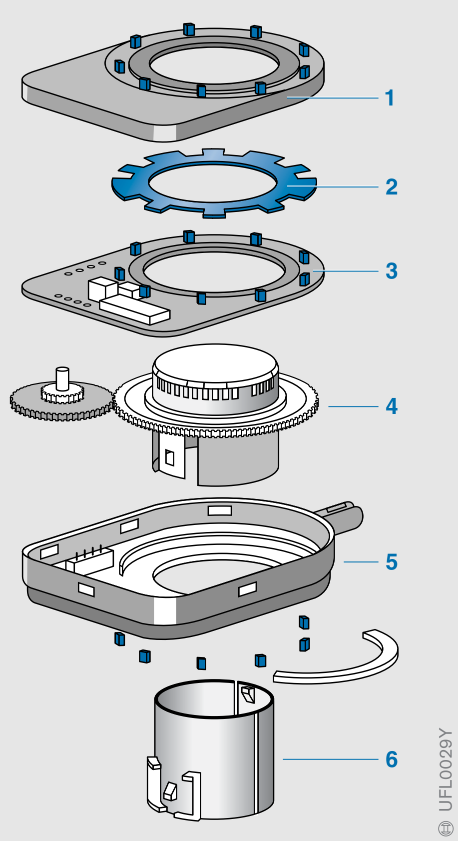

Fig. 1
1 Housing cover with nine equidistantly spaced permanent magnets
2 Code disc (magnetically soft material)
3 pcb with 9 Hall-effect switches and microprocessor
4 Step-down gearing
5 Remaining 5 Hall-effect vane switches
6 Fastening sleeve for steering column

processor in which plausibility tests are performed and information on angular position decoded and conditioned ready for the CAN-Bus. The bottom half of the assembly contains the step-down gearing and the remaining five Hall-effect vane switches.

The LWS1 was superseded by the LWS3 due to the large number of sensor elements required, together with the necessity for the magnets to be aligned with the Hall-IC.

Magnetoresistive steering-wheel-angle sensor LWS3

The LWS 3 also depends upon AMR (anisotropic magnetoresistive sensors) for its operation. The AMR's electrical resistance changes according to the direction of an external magnetic field. In the LWS3, the information on angle across a range of four complete rotations is provided by measuring the angles of two gearwheels which are rotated by a third gearwheel on the steering-column shaft. The first two gearwheels differ by one tooth which means that a definite pair of angular variables is associated with every possible steering-wheel position.

By applying a mathematical algorithm (a computing process which follows a defined step-by-step procedure) referred to here as a modified vernier principle, it is possible to use the above AMR method for calculating the steering-wheel angle in a microcomputer. Here, even the measuring inaccuracy of the two AMR sensors can be compensated for. In addition, a self-check can also be implemented so that a highly plausible measured value can be sent to the ECU.

Fig. 2 shows the schematic representation of the LWS3 steering-wheel-angle sensor. The two gearwheels, with magnets inserted, can be seen. The sensors are located above them togther with the evaluation electronics. With this design too, price pressure forces the development engineers to look for innovative sensing concepts. In this respect, investigation is proceeding on whether, since it only measures up to 360°, a single AMR angle-of-rotation sensor (LWS4) on the end of the steering shaft would be accurate enough for ESP (Fig. 4).

2 AMR steering-wheel-angle sensor LWS3 (principle)

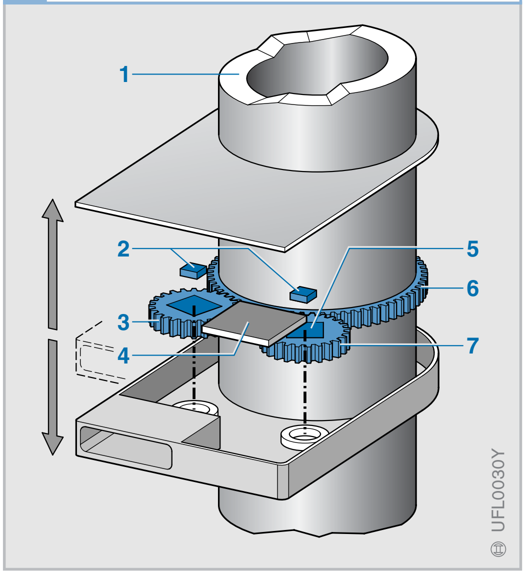

Fig. 2
1 Steering-column shaft
2 AMR sensor elements
3 Gearwheel with m teeth
4 Evaluation electronics
5 Magnets
6 Gearwheel with n > m teeth
7 Gearwheel with m + 1 teeth

3 AMR steering-wheel-angle sensor LWS3

4 AMR steering-wheel-angle sensor LWS4 for attachment to the end of the steering-column shaft

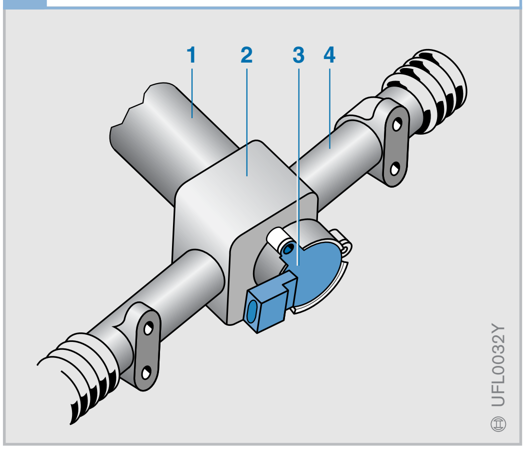

Fig. 4
1 Steering column
2 Steering box
3 Steering-wheel-angle sensor
4 Steering rack

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Axle sensors

Application

The automatic headlight leveling control (ALWR) adjusts the vehicle's headlight range automatically. With the headlamps on low beam, ALWR compensates for the vehicle tilt so that the driver has adequate vision without dazzling oncoming traffic. Whereas, the static ALWR compensates for the vehicle tilt resulting from the vehicle loading, the dynamic version also takes into account the front-end up and down pitching movement caused by braking and acceleration. Here, the axle sensors precisely register the bodywork's angle of inclination.

Design and operating concept

Axle sensors (angle-of-rotation sensors) are used to measure the vehicle tilt. These are attached to the bodywork at the front and rear of the vehicle. Spring deflection is transmitted to the sensors by a pivot lever which is connected through a connecting rod to the particular axle or to the suspension. The vehicle's tilt is then calculated from the difference between the voltages of the front and rear axle sensors.

The axle sensors function according to the Hall effect. A Hall IC is incorporated in the sensor stator (Fig. 1, Pos. 5) and surrounded by a homogeneous magnetic field which generates a Hall voltage in the Hall IC which is proportional to the magnetic-field strength. When the toric magnet (6) is rotated by the shaft (2), the magnetic field through the Hall IC changes accordingly.

When spring deflection takes place due to loading and/or acceleration/braking, the connecting rod (Fig. 2, Pos. 4) transfers the movement to the pivot lever (3) which rotates the shaft (Fig. 2, Pos. 2) so that the spring deflection movement is converted in the sensor to a voltage signal which is proportional to the angle of rotation.

The ECU registers the axle-sensor signals and from them generates the difference between front and rear axle. Using this voltage difference, and taking into account the vehicle's speed, the ECU now calculates the desired value for the positioning-motor settings. With the vehicle driving at constant speed, the dynamic ALWR remains in the status which features a high level of damping whereby the positioning motors are adapted slowly to the vehicle tilt. This prevents bumps, unevenness, or holes in the road causing continuous correction of the headlamp settings. When the vehicle accelerates, or the brakes are applied, the system automatically switches to the dynamic mode, and adjusts the light range within a few milliseconds. The system then switches back to the slower mode.

1 Axle sensor (section)

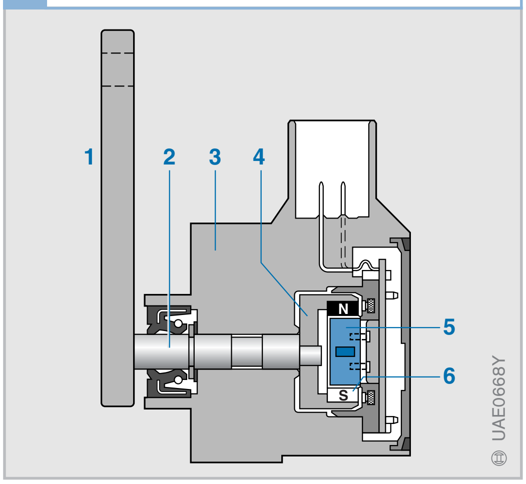

Fig. 1
1 Pivot lever
2 Shaft
3 Sensor case
4 Toric-magnet mount
5 Stator with Hall IC
6 Toric magnet

2 Axle sensor (installed in vehicle)

Fig. 2
1 Attached to the bodywork
2 Axle sensor with plug-in connection
3 Pivot lever
4 Connecting rod
5 Vehicle axle

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Ultrasonic sensors

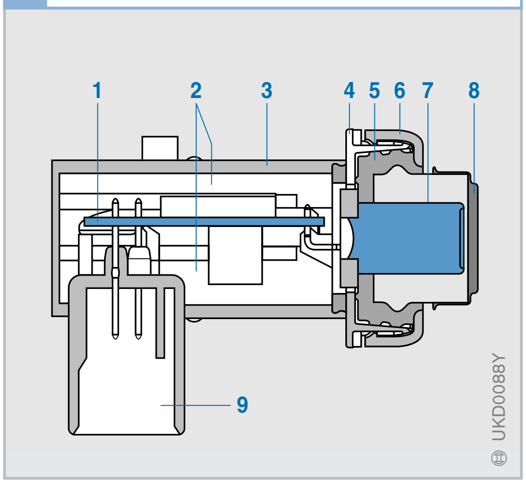
Application
Ultrasonic sensors are integrated in the vehicle's bumpers for determining the distance to obstacles, and for monitoring the area to the front and rear of the vehicle when entering or leaving a parking lot or when manoeuvring. Using "triangulation", the very wide sensing angle which results when a number of sensors are used (4 to the rear, 4...6 to the front), can be applied to calculate the distance and angle to an obstacle. Such a system has a detection range of about 0.25 m...1.5 m.

Design and construction
These sensors are comprised of a plastic case with integrated plug-in connection, an ultrasonic transducer (aluminum diaphragm onto the inside of which has been glued a piezoelectric disc), and a pcb with transmit and evaluation electronics (Fig. 1). Two of the three connecting wires leading to the ECU carry the supply voltage. The third line is bi-directional and is used to trigger the transmit function so that the evaluated receive signal can be reported back to the ECU (open-collector connection with open-circuit potential "high").

Operating concept
These ultrasonic sensors operate according to the pulse/echo principle in combination with triangulation. Upon receiving a digital transmit pulse from the ECU, within typically about 300 μs, the electronic circuitry excites the aluminum diaphragm with square-wave pulses at resonant frequency and causes this to transmit ultrasound. The reflection from the obstacle hits the diaphragm and causes it to go into oscillation again (it had in the meantime stopped oscillating). During the time taken for it to stop oscillating (approx. 900 μs) no reception is possible. These renewed oscillations are outputted by the piezoceramic as analog electrical signals and amplified and converted to a digital signal by the sensor electronics (Fig. 2). The sensor has priority over the ECU, and when it detects an echo signal it switches the signal connection to "low" (<0.5 V). If there is an echo signal on the line, the transmit signal cannot be processed. The ECU excites the sensor to transmit when there is less than 1.5 V on the line.

In order to be able to monitor as extensive a range as possible, a wide sensing angle is used in the horizontal plane. In the vertical plane, on the other hand, only a narrow angle is required in order to avoid disturbance due to road-surface reflections.

1 Ultrasonic sensor (section)



2 Ultrasonic sensor: Block diagram

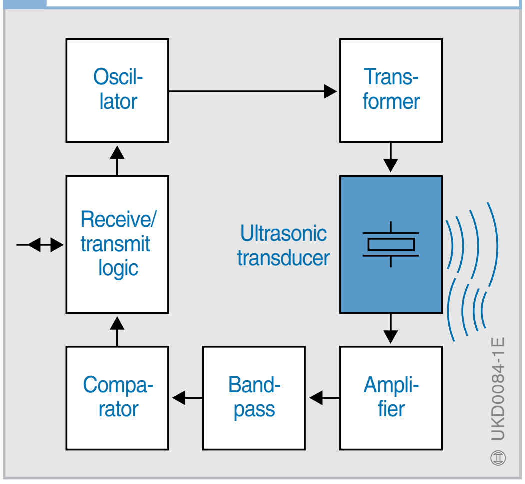


Fig. 1
1 pcb
2 Casting compound
3 Plastic case
4 System mount
5 Decoupling ring (silicon rubber)
6 Sleeve
7 Ultrasonic transducer
8 Cover
9 Electrical connection (plug)

Ranging radar

Yet another sensor?

Of course, since it measures the distance, relative speed, and side offset of the preceding vehicle, the ranging radar (Fig. 1) is a sensor. The radar (standing for **Ra**diation **D**etecting **a**nd **R**anging) installation transmits "packets" of mm-waves in the 76...77 GHz range (wavelength approx. 4 mm). This has been approved for all the world's important automobile markets. After having been transmitted, the wave packets are reflected from metallic surfaces, or from surfaces with a high dielectric constant and picked-up again by the radar's receive stage. The signals received in this manner are "compared" with the transmitted signals with respect to their propagation time and/or frequency. The transmitted wave packet must be modulated in order that this comparison can be used for this application. The most common forms of modulation are pulse modulation in which 10...30 ns pulses are generated, corresponding to a wavelength of 3...10 m, and frequency modulation in which, during transmission, the instantaneous frequency of the waves is varied as a function of time.

The received wave packet must be demodulated in order to extract the required information. In the case of a pulse-modulated signal, the propagation time τ between transmitting and receiving the signal is measured. Using the speed of light c ($\approx$ 300,000 km/s) as a reference, the distance d can be calculated from the delay caused by propagation: $d = \tau \cdot c/2$. Dividing c by 2 takes into account the distance travelled to the reflecting surface and back again (Example: $\tau = 1$ μs corresponds to a distance to the preceding vehicle of $d = 150$ m).

With frequency modulation, the frequency is varied during the transmission process. If the variation is linear, there is a difference in frequency between the transmitted signal and the received (reflected) signal which has been delayed by the propagation time. This frequency difference is proportional to the distance to the preceding vehicle (at 100 MHz/s, for a distance of 150 m this frequency difference would be 100 kHz). Although the relative speed of the other vehicle can be measured using a number of subsequent range measurements, it is calculated more reliably and accurately when the Doppler effect is utilised in the measurement. With the vehicles getting closer (at 76 GHz) the frequency of the received waves increases at a rate of 510 Hz per m/s relative speed.

The third basic quantity which is needed is the side offset (angle) of the preceding vehicle. The only way this can be measured is by radiating the radar beam in a number of different directions. The (reflected) signal strength is then applied to determine from which direction the strongest reflection came. This method needs either high-speed back-and-forth movement of the beam (scanning), or the installation of a multi-beam antenna array.

No longer just a sensor?

Of course the ranging radar is far more than just a sensor. After all, in addition to determining the range to preceding vehicles, and their relative speed and side offset, highly complex processing takes place in the SCU (**S**ensor and **C**ontrol **U**nit) in order to provide the actuator commands for drivetrain and braking-system control (Fig. 2). This device's function has been extended beyond pure ranging control, and can now be termed ACC (**A**daptive **C**ruise **C**ontrol).

1 Ranging radar

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One of the basic functions is the conventional Cruise Control which holds the vehicle speed constant, once it has been set. This function remains permanently in operation as long as a preceding vehicle is not detected which is travelling at a speed below that set by the ACC vehicle's driver. If the system picks up such a vehicle inside the radar's detection zone (approx. 100...150 m) which would prevent the set speed being maintained, the speed of the radar-equipped vehicle is adapted to that of the preceding vehicle. In case of only minor differences in speed it suffices to reduce the accelerator-pedal setting. Considerable differences in speed on the other hand necessitate the brakes being applied.

As soon as the difference in speed has been compensated for, the ACC vehicle follows the preceding vehicle with a relatively constant time gap. That is, as speeds increase so does the gap.

Selection of the "right" target vehicle is the most difficult problem with the signal processing in the SCU of the ACC. Here, first of all, those radar reflections must be identified which belong to the already defined vehicles. Then, it must be ascertained whether these vehicles really are in the same lane. Even though the sensors belonging to the ESP (**E**lectronic **S**tability **P**rogram) provide a whole range of important signals which can be used for comparitive purposes, this is particularly difficult before and in bends.

It's up to the reader to judge for himself whether the ACC SCU is to be regarded as an ECU with integrated sensor, or as a sensor with ECU. One thing is quite certain though: More of these systems which monitor the vehicle's surroundings will definitely appear on the market in the years to come, and, similar to video "sensors", with only one single device will be able to perform a number of functions.

2 ACC Adaptive Cruise Control (block diagram)

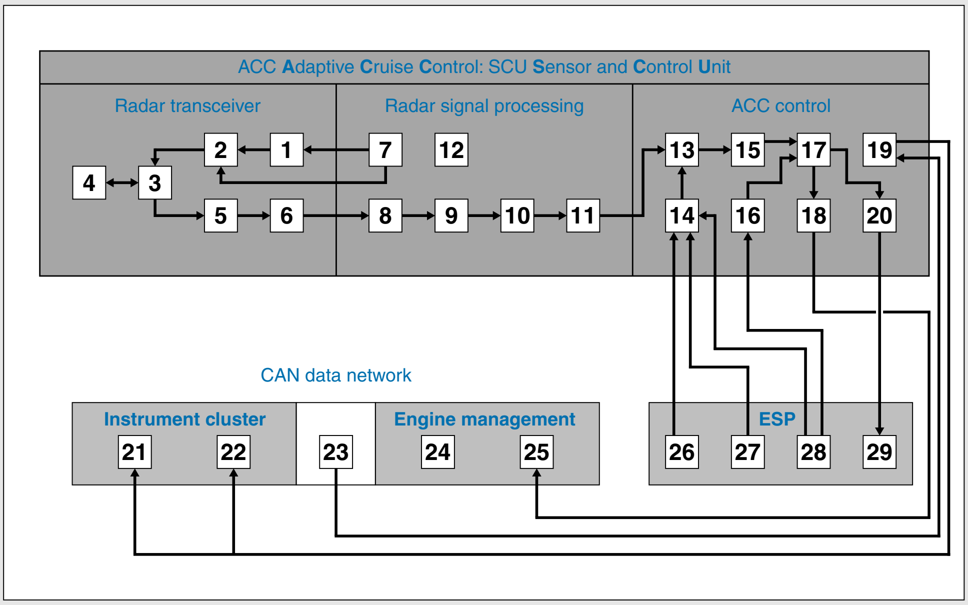

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Fig. 2
1 Oscillator
2 Modulator
3 Transmit/receive switch
4 Antenna
5 Demodulator
6 Amplification
7 Radar control
8 Fourier transformation
9 Detection
10 Matching
11 Tracking
12 Radar monitoring
13 Target selection
14 Curve recognition
15 Ranging control
16 Speed control
17 Prioritization
18 Drivetrain-control commands
19 System monitoring
20 Braking-system control commands
21 ACC status display
22 Display of driver's desired speed, time gap
23 Control switch
24 Monitoring logic
25 Torque control
26 Yaw rate
27 Steering-wheel angle
28 Wheel speeds
29 Electronically controlled brake intervention

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Speed and rpm sensors

Measured variables

Speed and rpm sensors measure the number of revolutions or the distance travelled per unit of time. When automotive applications are concerned, these are in both cases measured variables which occur between two components or with respect to the road surface or another vehicle. In some cases, it is necessary to measure the absolute rotational speed in space or about the vehicle axes. This is often referred to as yaw rate. For instance, for the Electronic Stability Program (ESP), the yaw rate about the vehicle's vertical (or yaw) axis must be picked-off by "sensing".

In the detection of relative yaw rate, depending upon the number and size of the scanned peripheral rotor markings, one differentiates between the following types of sensor (Fig. 1):

- *Increment sensor* with closely spaced peripheral markings. Up to a certain point, this form of sensor permits instantaneous speed to be measured at points on the circumference, or the registration of very fine angular divisions,
- *Segment sensor,* with only a small number of scanned peripheral segments (for instance, equivalent to the number of engine cylinders),
- Simple *rpm sensor,* with only a single scanned marking per revolution, so that only the average rotational speed can be registered.

1 Detection of the relative rotational speed

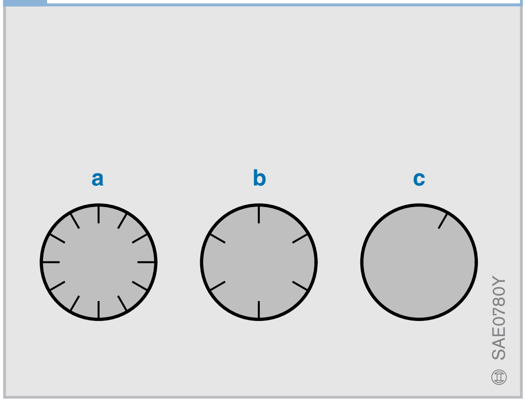

Fig. 1
a Incremental sensor
b Segment sensor
c Rotational-speed sensor

Examples of relative rotational speed are as follows:

- Crankshaft and camshaft speeds,
- Wheel speeds (for ABS/TCS/ESP), and
- Speed of the diesel injection pump.

Here, measurement usually makes use of an incremental pick-up system comprised of a toothed wheel (rotor) and an rpm sensor.

Newer applications include the following:

- Rotational-speed measurement using an rpm sensor incorporated in the bearing (wheel bearing, or the so-called composite seal with sensor (CSWS) on the crankshaft).
- Speed over ground,
- Vehicle yaw rate around the longitudinal (roll) axis and the pitch axis (roll-over protection).

Measuring principles

Conventional sensors used for rotational-speed measurement are based on pronounced measuring effects (e.g. inductive). They are therefore for the most part electrically passive. That is, they are usually not provided with any form of local/on-site electronics. With the newer sensors, however, measurement is based on less-pronounced measuring effects (for instance, the Hall effect), and these sensors thus need local, integrated electronics for signal conditioning. In the broader sense, according to the definition in "Development Trends" at the front of this manual, they belong to the category "intelligent sensors" (which are also often referred to as "active" sensors). In fact, the sensors used for measuring absolute rotating speed (yaw rate) need highly complex electronic circuitry directly at the sensor since the measuring effects used here are not only particularly small, but also require complex signal conditioning.

Incremental rotational-speed measurement takes advantage of a wide variety of different

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physical effects (some of which can be applied in sensors at a very reasonably price). Optical and capacitive sensors, though, are highly unsuitable for the rough operating conditions encountered in the vehicle. Here, magnetic-effect sensors are used almost exclusively.

Presently used sensor shapes

The following shapes of sensor are presently in use (Fig. 2) for speed and rpm sensors:

- Rod sensor,
- Fork-shape sensor,
- Internal and external toroidal sensor

Due to its ease of mounting and simplicity, the rod sensor is the most widespread sensor version. The rod sensor is located near the rotor (Fig. 2 b), the teeth of which approach it and pass by in close proximity. The fork-shaped sensor (Fig. 2a) is permissible in some cases, and is also in service in the field. This sensor must be roughly aligned to the rotor when installed. The sensor type in which the sensor surrounds the rotor shaft in the form of a ring is practically no longer used. From time to time, an inner-ring sensor is used which is introduced into the end of a hollow shaft featuring an incremental internal structure.

Unfortunately, although it is the most widely used sensor type, the rod-shaped sensor features the lowest measuring sensitivity and is problemetical when air gaps become excessive. The fork-shaped sensor on the other hand is practically impervious to axial and radial play. Regarding toroidal sensors, the most widely used form combines a large measurement-signal output with pronounced insensitivity to geometric tolerances.

2 Sensor shapes

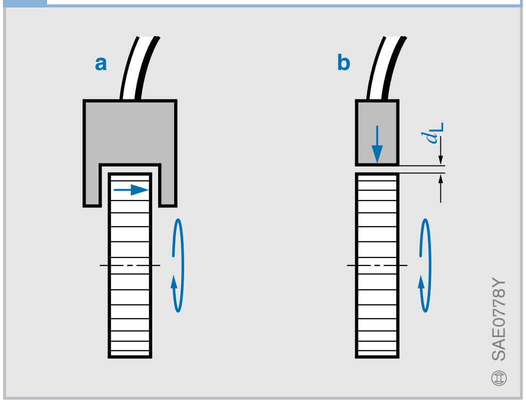

Fig. 2
a Fork shape (vane principle)
b Rod shape (proximity principle)
d_L Air gap

New sensor shapes

In many respects, the traditional inductive-type sensors are highly unsatisfactory. Their output signal features an rpm-dependent amplitude, and for this reason they are unsuitable for measuring low rotational speeds. In addition, they only permit comparitively low-level air-gap tolerances and are usually unable to differentiate between air-gap fluctuations and genuine rotational-speed pulses. And at least the sensor tip must be proof against high temperatures (for instance when installed near the brakes). These disadvantages are behind the additional features aimed at with new, innovative sensors:

- Static detection (that is, at zero speed, or at extremely low cranking or wheel speeds),
- Efficient measurement in large air gaps (non-aligned mounting with air gaps >0),
- Small size,
- Efficient operation independent of air-gap fluctuations,
- Temperature stability (≤ 200 °C),
- Identification of the sense of direction (optional for navigation), and
- Reference-mark identification (ignition).

Magnetostatic sensors (Hall, magnetoresistors, AMR) are highly suitable for complying with the first two demands. And, as a rule, they also permit compliance with the second and third stipulations.

Fig. 3 (next page) shows three basically suitable sensor shapes, which generally are insensitive to air-gap fluctuations. Here, one must differentiate between sensors which sense radially and those which sense tangentially. This means that independent of the air gap, magnetostatic sensors are always able to differenti-

3 Sensors insensitive to air-gap fluctuations

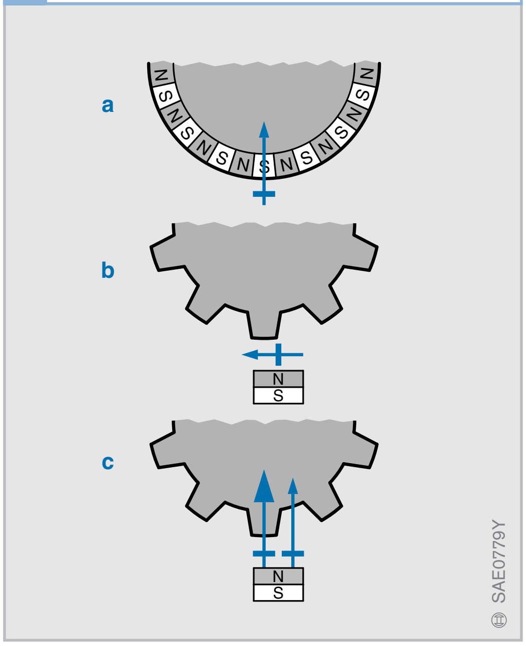

Fig. 3
- a Radial-field sensor with pole wheel
- b Tangential sensor
- c Differential sensor with toothed rotor

ate between the north and south poles of a magnetically active pole wheel or rotor ring.

In the case of magnetically passive rotors, the sign of the output signal is then no longer independent of the air gap when they register the tangential-field strength (here though, the fact that the air gap is often enlarged due to the rotor is a disadvantage).

Radially measuring differential-field or gradient sensors are often used. These always register only the gradients of the radial-field components, the signs of which do not change with the air gap but only with the angle of rotation (Fig. 3).

Rotors

The rotor is of decisive importance when measuring rotational speed. It is usually provided by the vehicle manufacturer, while the sensor itself comes from a component supplier. Up to now, *magnetically passive rotors* have been used almost exclusively. These are made from magnetically passive materials (usually iron), and are less expensive than magnetically hard rotors (also known as pole wheels). Apart from that, since they are not magnetized they are easier to handle, and there is no danger of mutual demagnetisation (for instance during storage). Unfortunately, this form of rotor is the most difficult to scan, particularly in combination with rod sensors.

As a rule, presuming the same increment width and output signal, the pole wheel's intrinsic magnetism *(a pole wheel is defined as a magnetically active rotor)* permits a considerably larger air gap.

Normally, *passive rotors* are in the form of gearwheels. In many cases, these are already present on the engine (for instance the flywheel ring gear). Otherwise they must be installed in a specific position in order to generate the required signal (as needed for instance for ABS). In the latter case, both planar-toothed and axial-scan versions are in use.

An easily identifiable reference mark is required for each revolution when picking-off the crankshaft speed or position (for instance, at the starter ring gear). This reference mark must ensure interference-free, optimal timing of ignition and fuel injection. This applies in particular when there is no camshaft pick-off available. The reference mark can be in the form of a completely (or partially) removed tooth. Due to the fact that a tooth gap "takes more time", the reference mark is immediately identifiable, particularly since the engine speed can only vary gradually and never abruptly.

In addition to toothed gears, stamped perforated discs or wave-shaped metal rings have been introduced in the meantime as low-priced rotors (ABS).

It was the integration of ABS sensors in the vehicle's wheel bearing which led to the introduction of *pole wheels* some of which also assume the role of a shaft seal (plastic-bound magnetic powder). Small, for the most part encapsulated, tachometer sensors connected through a short flexible shaft with one of the vehicle's wheels, also use pole wheels (with only very few poles) for generating a speed signal. These are usually picked-off by means of integrated Hall-effect sensors.

Relative rpm and speed measurement

Inductive-type sensors

Basics

Inductive-type sensors were available on the market as coil versions long before the first suitable microstructure sensor versions (e.g. using the Hall principle) became available. Such inductive-type sensors use Faraday's law when measuring rotational speed. In other words, they generate a voltage U_A at their two-pole output which is proportional to the change (referred to time) of a magnetixc flux Φ (w = number of turns).

$$U_A = U_{ind} = w \cdot d\Phi/dt$$

The magnetic flux Φ is also a function of the rotational position x and the air gap d_L:

With $\Phi = \Phi(x, d_L)$ and d_L = constant, the following applies:
$U_A = U_{ind} = w \cdot \partial\Phi/\partial x \cdot dx/dt$

Whereby, dx/dt represents the (rotating) speed being measured.

The inductive-type sensors' weak point is underlined though by the equation: If it is impossible to keep the air gap d_L constant (due to flutter or other forms of mechanical play), the air-gap fluctuations induce the same change of flux as does a fluctuation of speed. This effect can cause the generation of voltage pulses which are either impossible, or at least difficult to separate from the genuine rpm signals. Since the flux varies exponentially along with the change in air gap, and the air-gap fluctuations are often of the high-frequency type (e.g. brake flutter), these unwanted pulses can easily feature a high voltage amplitude.

Inductive-type sensors are therefore always of the dynamic type, and being as their output signal tends to fall to zero in such cases, they are in principle also unsuitable for the registration of extremely low speeds (quasi-static or static). The only exception here are the coil sensors which are powered by a carrier frequency and which are based on the eddy-current or damping principle. These though are hardly ever used in automotive applications.

Basically, inductive-type sensors are comprised of three important magnetic components (Fig. 1):
- fixed coil,
- soft-iron component, and
- the permanent-magnet component.

The change in flux needed for the generation of the output voltage results from the motion or rotation of the hard or soft-iron magnetic component. Sensors which use a DC applied to the induction coil instead of permanent-magnetic flux were formerly referred to as TDC sensors, and were commonly used for the manual adjustment of the ignition.

The inductive-type sensors in use today are preferably composed of a bar magnet (Fig. 1, Pos. 1) with a soft-magnetic pole pin (2) carrying the 2-connection induction coil (3). When a ferromagnetic gear wheel (5), or some form of similar rotor, rotates in front of this sensor (pick-up) the changing magnetic flux (which varies as a function of time) induces a practically sinusoidal voltage.

1 Inductive-typ rpm sensor

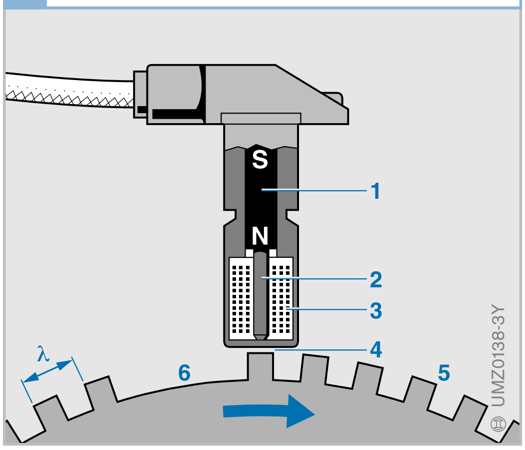

Fig. 1
1 Rod magnet
2 Soft-magnetic pole pin
3 Induction coil
4 Air gap d_L
5 Ferromagnetic gear-wheel (or rotor or trigger wheel)
6 Rotational or reference mark
λ Tooth interval

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For scanning very fine tooth structures, the end of the pole pin is sometimes pointed and acts as a flux-concentrating element. In other words it is shaped like a pole "blade" which usually projects through the metal or plastic housing and is adapted to the increment structure regarding shape and direction.

The rotor can be provided with one or more peripheral markings (6). Fig. 2 shows the flux curve and the voltage induced by a single peripheral or reference mark (slot, cam, or pole pin).

Normally, the steep passage through zero which takes place at the mid-point of maximum flux is utilised for the electronic registration of such a peripheral or reference mark. According to Faraday's Law, in all phases the signal's amplitude is proportional to rotational speed.

In order to ensure adequate, interference-free evaluation in the ECU, the spacing between the peaks of a double pulse (or of a periodic voltage pulse) U_{SS} should be at least 30 mV. The major disadvantage of the inductive-type sensors is the fact that at high rotational speeds their output voltages can reach levels far in excess of 100 V which are difficult to process electronically.

If Zener diodes are used to clip the high voltage peaks, the resulting changes in the sensor's load impedance rapidly lead to considerable phase-angle errors. With camshaft and crankshaft sensors this can have highly undesirable results with regard to the ignition where the correctness of phase relationship must be better than approx. 0.2°.

Normally, the prepulse generated by the magnetic return field can be ignored at low speeds. With some *magnetically passive or active peripheral markings* though, at high speeds the prepulse voltage can increase to such an extent that it exceeds the threshold value of the downstream threshold discriminator and can cause an even greater error (Fig. 2a). For this reason, the threshold values of the ECU input circuit are adapted dynamically to the speed in question.

Provided that the tooth gap is not too narrow, a uniform tooth structure results in the practically sinusoidal voltage curve shown in Fig. 2b. The rotational speed can be taken from the spacing between the passages through zero of this generated voltage. Its amplitude is proportional to the rotational speed.

The signal amplitude is highly dependent (exponentially) upon air gap and tooth size. As is the case with all magnetic increment processes, up to air gaps of d_L, teeth can be efficiently detected as from half or 1/3 of a tooth interval λ.

$$d_L \leq \lambda/(2 \dots 3)$$

The conventional toothed rotors for ABS and crankshaft applications cover air gaps of up to 1.5 and 0.8 mm respectively. The reference mark needed for the ignition results from leaving out a tooth or by closing a tooth gap. The reference point is detected when the distance between the passages through zero changes abruptly and causes a far higher signal voltage (corresponding to an apparently larger tooth) which has a negative effect upon the previous and upon the subsequent incremental voltage – this can under certain circumstances be undesirable.

Assessment

Advantages

- Low manufacturing costs,
- High-level EMC: Low static internal resistance (dynamic resistance is higher), no local electronic circuitry (electrically passive) which needs protection,
- No problems with DC voltage drift (dynamic measuring concept),
- Broad temperature range (limited primarily by the casting-compound characteristics).

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Disadvantages

- Conventional coil technology imposes limits on size reduction,
- The output signal is rpm-dependent, unsuitable for quasi-static movements,
- Sensitive to air-gap fluctuations.

Examples of application

- Inductive engine-speed sensor (crankshaft-rpm sensor),
- Inductive-type wheel-speed sensor,
- Inductive-type camshaft sensor (transistorized ignition with induction-type pulse generator TC-I,
- Needle-motion sensor (diesel fuel injection).

2 Flux path and voltage curve for an inductive-type sensor with a single magnetic marking per revolution, a periodic increment structure (e.g. a toothed rotor or a pole wheel), or an evaluation circuit

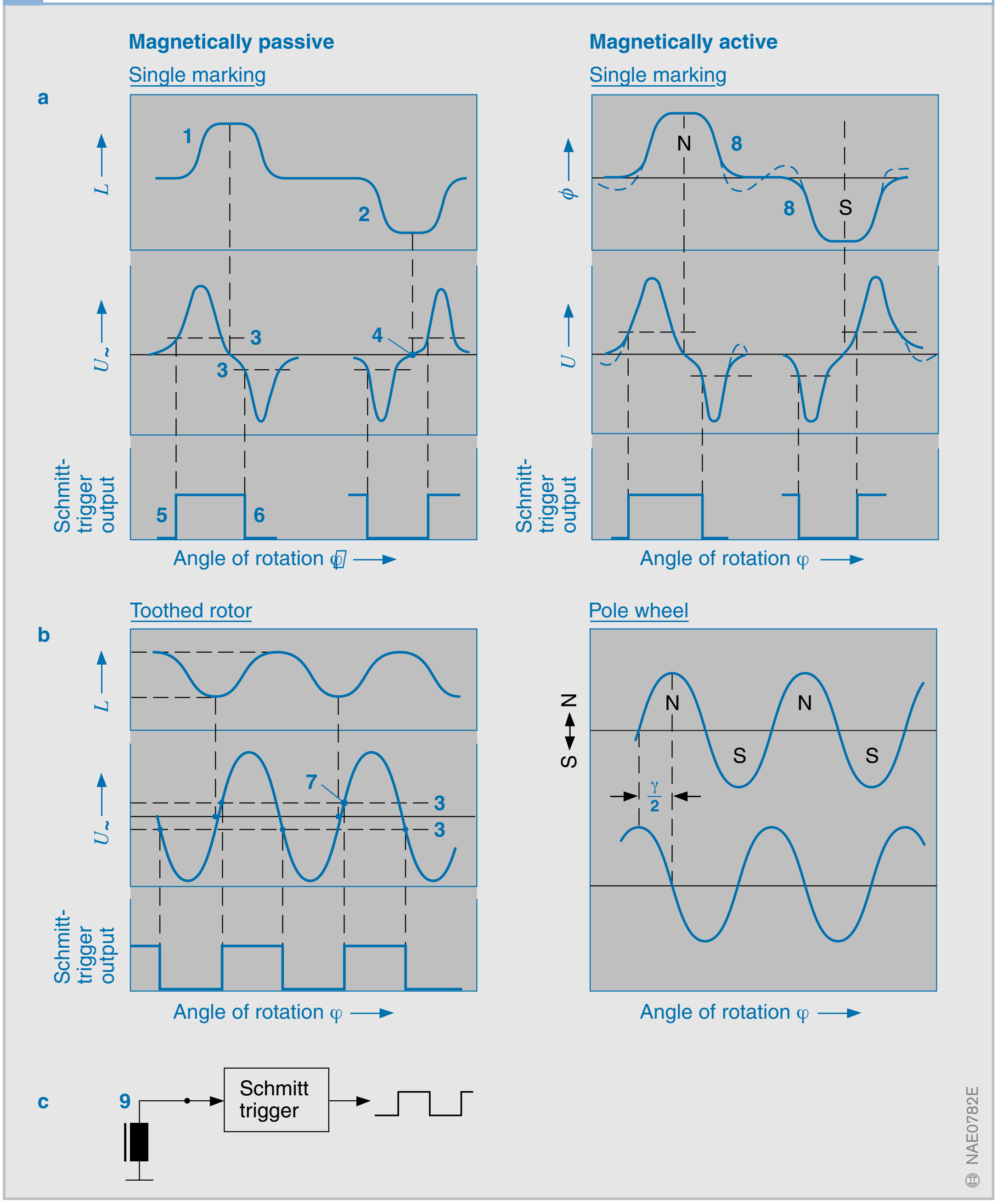

Fig. 2
a Single magnetic marking per revolution
b Periodic increment structure (e.g. toothed rotor, pole wheel)
c Evaluation circuit
1 Cam
2 Slot
3 Switching point
4 Steep passage through zero evaluated
5 Priming edge
6 Switching flank
7 Switching point
8 Pole pin
9 Sensor
$\gamma/2$ Phase shift

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Magnetostatic sensors

Overview

Quasi-static speed measurement is best performed using magnetostatic sensors. Their output signal is independent of rotational speed and depends solely on field strength, so that at high rotational speeds their low signal voltages are easier to handle electronically. Furthermore, they not only have the advantage of imposing practically no limits with regard to *size reduction*, but also *signal amplification and/or signal processing* can be integrated locally. The fact that they are very small means that multiple systems such as differential configurations, or arrangements with integrated recognition of direction, present no difficulties.

On the other hand, such active sensors have a serious disadvantage, and that is the fact that their *operating-temperature* range is for the most part defined by the relevant Si (silicon) evaluation electronics which as a rule cannot withstand such high temperatures as the sensor element itself. For some time now, active sensors have been available with the option of a two-pole current output, so that the two-core connection can no longer be regarded as a specific advantage of the inductive-type coil sensor.

3 Hall-effect vane switch

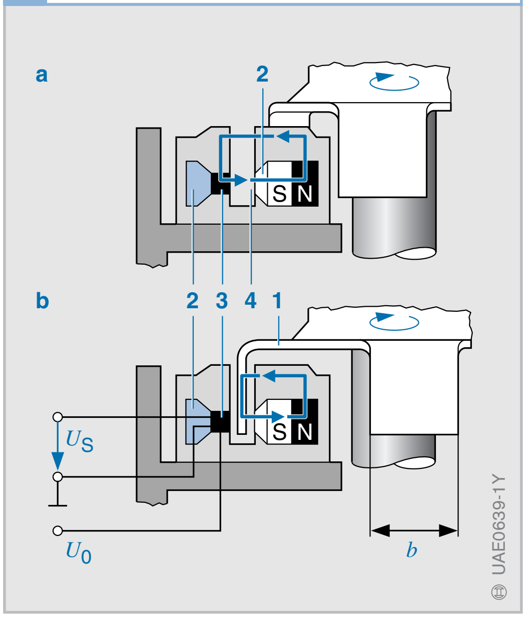


Fig. 3
a Magnetic flux: Unhindered
b Magnetic flux: Short-circuited
1 Vane width b
2 Soft-magnetic conductive element
3 Hall IC
4 Air gap
U_0 Supply voltage
U_S Sensor voltage

Hall-effect vane switches

If Hall-effect Si sensors are to be used for incremental rpm measurement, pronounced manufacturing scatter together with the effects of temperature mean that they must be provided with an adequate induction jump of typically 40...50 mT in order to ensure reliable high-speed switching. With conventional Hall-effect sensors and acceptable air gaps, this was only possible with the sensor in the form of a "Hall-effect vane switch" (for instance when used as ignition-triggering sensors in the ignition distributor). The sensor and its electronic circuitry for supply and signal evaluation are integrated directly on the sensor chip.

This "Hall-IC" (using bipolar techniques, for sustained temperatures up to 150 °C, and for direct connection into the vehicle's on-board electrical supply), is located in a practically closed magnetic circuit comprising permanent magnet and pole pieces (Fig. 3). A soft-magnetic trigger wheel (driven, for instance, by the camshaft) rotates through the air gap. With a trigger-wheel vane in the air gap, the magnetic flux is short-circuited past the sensor element. On the other hand though, when a trigger-wheel opening passes through the air gap the flux is unhindered on its way to the sensor. This principle ensures that the sensor also performs perfectly when the trigger-wheel varies in how far it penetrates into the air gap, or in case the air-gap shifts radially, that is vertically to the direction of rotation.

Since Hall-effect vane switches of this type feature limited peripheral resolution they are mainly used as segment sensors. If the vane slot is too narrow, it is practically impossible for the magnetic flux to pass through, with the result that the required induction jump is not generated.

Simple Hall-effect rod sensors

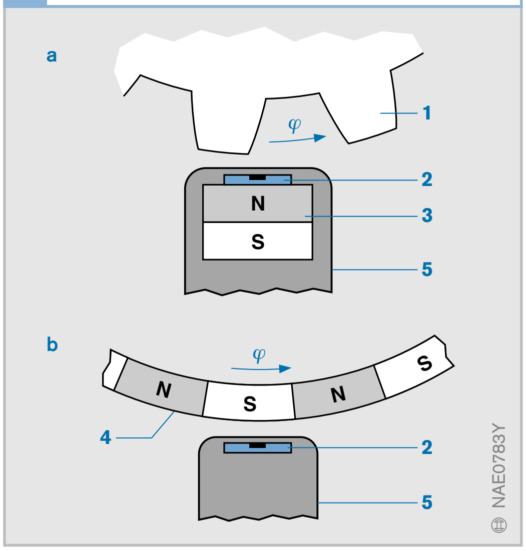
In contrast to the Hall-effect vane switch, the working-point magnetization depends too much upon the width of the air gap, and the induction excursion is too small for reliable switching with this configuration. Simple rod-shaped Hall-effect sensors provided with a working-point magnet are therefore unsuitable for static or quasi-static scanning of a *magnetically passive rotor* (Fig. 4a, toothed rotor). The switching point of a downstream threshold comparator (Schmitt trigger) would have to be continually adapted to the varying working point. Such applications are only feasible when DC coupling is dispensed with and therefore also static signal evaluation. The coupling capacitors required for such configurations (also known as $\Delta\Phi$ sensors) involve high costs though and lead to reduced operational reliability.

On the other hand, simple Hall-effect sensors are highly suitable for scanning a *magnetically active rotor* (Fig. 4b, pole wheel). In this case, a working-point magnet is unnecessary. The sensor is triggered by the pole wheel with varying polarity only in the vicinity of the magnetic zero point. Although the magnetic control excursion reduces along with increasing air gap, the position of the working point ($B = 0$) remains unchanged. Being as the working point on new types of Hall-effect sensors is to a great extent thermally stable, the switching points of the downstream threshold comparator can be set relatively close together. This means that relatively wide air gaps become possible. Air-gap fluctuations in this configuration cannot cause missing pulses as they do not lead to polarity change which is the only thing that characterises the continuing measurement motion (rotation).

Gradient sensors

When it comes to scanning passive rotors, gradient sensors (Fig. 5) designed on the basis of differential Hall sensors or differential magnetoresistive sensors, are far better than simple Hall-effect sensors. They are provided with a permanent magnet. This pole face of this magnet facing the rotor is homogenised by a thin ferromagnetic wafer (Pos. 2). There are two galvanometric elements (generic term for Hall-effect sensors and magnetoresistors) located on each wafer about half a tooth gap apart. This means that one of the elements directly faces a tooth gap while the other faces a tooth. The sensor measures the difference in field strength between two neighboring points on

4 Hall rod-type sensors for scanning magnetically passive and active rotors



5 Gradient sensor for toothed-rotor scanning

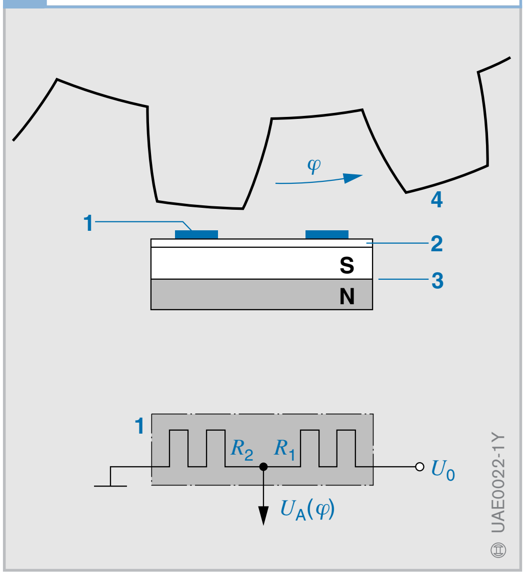


Fig. 4
- a Passive rotor
- b Active rotor
- 1 Incremental rotor
- 2 Simple Hall-effect sensor
- 3 Permanent magnet
- 4 Pole wheel
- 5 Case
- φ Angle of rotation

Fig. 5
- 1 Magnetoresistors R_1, R_2 or Hall-effect elements H_1, H_2
- 2 Soft-magnetic substrate
- 3 Permanent magnet
- 4 Toothed rotor
- U_0 Supply voltage
- $U_A(\varphi)$ Measurement voltage for a rotational angle of φ

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the circumference of the rotor. The output signal corresponds roughly to the field strength derived as a function of the angle at the circumference, and its sign is therefore independent of the air gap. Being as they do not alter the gradient signal's sign, air-gap fluctuations does not cause missing pulses.

For *signal evaluation*, it is a simple matter to connect the two *magnetoresistors* as a voltage divider which is supplied by a constant voltage and whose (usually unloaded) output signal is registered by the ECU. At room temperatures and with the customary air gap, this signal is in the volts range, and even at high temperatures it is suitable for transmission to the ECU without any form of preamplification.

Provided appropriate circuitry is used, measuring the loaded output current of the magnetoresister divider instead of its open-circuit voltage, permits the sensor's pronounced temperature sensitivity to be compensated for to a great extent.

In the case of a gradient sensor based on the Hall effect, the current paths of both Hall-effect elements can be connected in parallel, and their opposite-polarity output voltages in series, so that their differential voltage can be picked off directly and inputted to the downstream amplification and evaluation stages.

6 AMR rotational-speed sensor in the form of a tangential-field sensor for toothed-rotor scanning

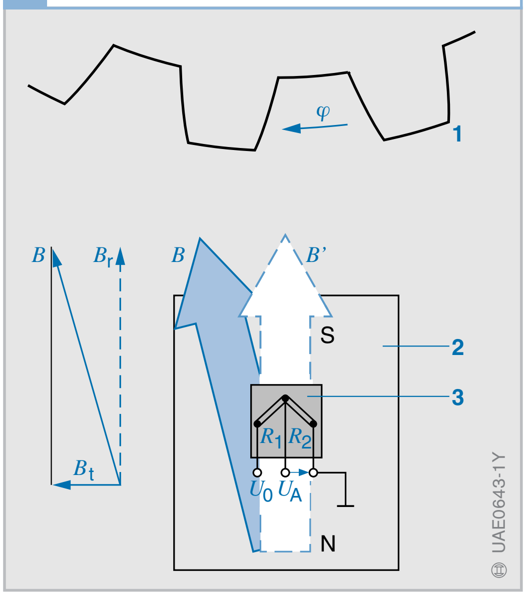

Fig. 6
1 Toothed rotor (Fe)
2 Permanent magnet
3 Sensor
B Control-field strength with tangential components B_t, and radial components B_r (B' off position, $B_t = 0$). R_1, R_2 permalloy thin-film resistors (AMR)
φ Angle of rotation
U_0 Supply voltage
U_A Measurement voltage

Tangential sensors

In contrast to gradient sensors, tangential sensors react to the sign and the intensity of the magnetic-field components which are tangential to the rotor's circumference. Using AMR thin-film techniques, tangential sensors are available as barber-pole or permalloy resistor types in full-bridge or half-bridge circuits (Fig. 6). In contrast to gradient sensors, they need not be matched to the particular tooth pitch of the rotor and can in fact be designed to sense practically at a given point. Local amplification is necessary, even though their measuring effect is 1...2 orders of magnitude larger than that of the silicon-Hall sensors.

In the case of the crankshaft-speed sensor integrated in the bearing (composite seal with sensor), the AMR thin-film sensor is mounted together with an evaluation IC on a common leadframe.

In order to save space and protect against high temperatures, the evaluation IC is turned through 90° and located further away from the sensor tip.

Giant magnetoresistive (GMR) elements

In 1988, Baibich discovered that in multilayer (CuCo) elements of only a few nanometers (nm) thickness, the resistance changes by 50% when an external magnetic field is applied at low temperatures. This resistance change, which became known as the **G**iant **M**agneto **R**esistance effect (GMR), is considerably more pronounced than on AMR sensors.

The resistance changes because the magnetisation which was originally inverse-parallel aligned, re-orientates itself in parallel when an external magnetic field is applied.

The effect reaches saturation at a defined magnetic-field strength.

GMR sensors are already in use as the reading head in high-capacity data disc drives. In the automotive sector, rotational-speed measurement is the priority applica-

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tion aimed at at present – it is even more important than the sensor's use for travel/angle measurement.

Application examples:
- Hall-effect sensor (transistorized ignition TI-H),
- Hall phase sensor (camshaft),
- Gearbox Hall-effect sensor (RS50, RS51),
- Active Hall rotational-speed sensor,
- Active AMR rotational-speed sensor,
- Magnetoresistive sensor (for diesel radial-piston distributor pumps).

Absolute rotating-speed measurement

Oscillation gyroscope

Basics

Mechanical gyroscopes (gyros for short) utilise inertial forces in precisely measuring angular movements in space independent of the reference system. Notwithstanding their pronounced measuring effect, rotating gyroscopes as well as optical sensors based on the interferometric *Sagnac effect* (laser and fiber gyroscopes), are out of the question for automotive applications due to the high costs involved.

On the other hand, with the new automotive systems, the slightly less-severe requirements regarding precision can be complied with by *gyroscopes* manufactured using fine-mechanical and micromechanical processes. Instead of a rotational movement, these units use an equivalent, elastic, oscillatory movement to generate the measuring effect. These sensors are known as tuning-fork sensors and up to now have been used primarily for stabilisation controls. They also comply adequately with other automotive stipulations such as freedom from maintenance, long service life, switch-on time constant etc., not to forget the question of costs.

Oscillation gyroscopes measure the absolute yaw rate Ω_z at the vehicle's vertical axis (yaw axis). This applies for instance in vehicle-dynamics systems (ESP or Electronic Stability Program for the prevention of skidding), and for short-term navigation (for instance at a road junction). Highly advanced systems for triggering roll-over protection systems need data on the yaw rates Ω_x and Ω_y around the vehicle's pitch and roll axes. In principle, these sensors are similar to mechanical gyroscopes. They utilise the so-called *Coriolis accelerations* which are generated when rotation Ω is coupled with an oscillatory component (velocity v). In line with the familiar vector law, these accelerations are vertical with respect to the x and y axes (Fig. 1).

1 Interrelationship between yaw rate, oscillation, and Coriolis acceleration at a lumped mass m.

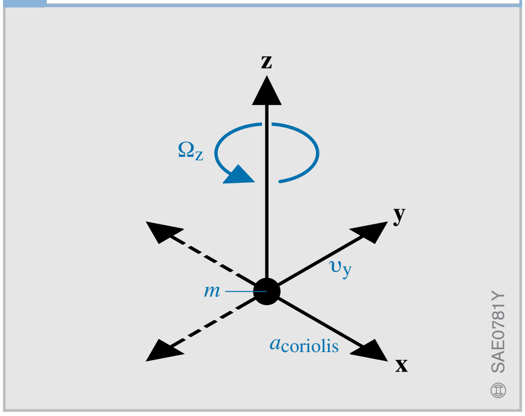

Fig. 1
Ω_z Yaw rate
v_y Velocity of the oscillatory motion
$a_{Coriolis}$ Coriolis acceleration
m Lumped mass

$$\vec{a}_{\text{Coriolis}} = a_x = 2 \cdot \vec{v}_y \cdot x \cdot \vec{\Omega}_z \quad (1)$$

Whereby, the velocity v_y changes sinusoidally in accordance with the oscillatory movement:

$$v_y = \hat{v}_y \cdot \sin \omega \cdot t \quad (2)$$

Assuming a constant yaw rate Ω_z, therefore, this means that a sinuosoidal Coriolis acceleration a_{Coriolis} of the same freuqncy and phase is also measured. The amplitude is then:

$$\vec{a}_{\text{Coriolis}} = 2 \cdot \hat{v}_y \cdot \Omega_z \quad (3)$$

Hypothetically, this acceleration could be felt and measured by anyone located on the lumped mass m.

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To register the yaw rate, the amplitude of velocity of the oscillatory motion is maintained at a constant level by means of appropriate control circuitry. The Coriolis acceleration measured at the oscillating mass m is then subjected to frequency and phase-selective rectification. Here, for instance, a lock-in amplifier can be used. In the process, unwanted acceleration from the outside (e.g. bodywork acceleration) is removed.

An output voltage is generated which is proportional to the yaw rate:

$$U_A = const \cdot \hat{a}_{Coriolis} = const' \cdot \Omega \quad (4)$$

The acceleration a_y which is also applied to the mass m in the oscillatory direction is usually several orders of magnitude higher than the useful Coriolis acceleration.

$$a_y = \frac{\mathrm{d}\upsilon_y}{\mathrm{d}t} = \omega \cdot \hat{\upsilon}_y \cdot \cos \omega \cdot t \quad (5)$$

The falsifying effect of the acceleration a_y caused by over-response is counteracted by both the directional selectivity of the Coriolis acceleration sensor and its correct mounting position (factor $10^2 \dots 10^4$), as well as by the correct-phase rectification of the Coriolis signal. Compared to the useful signal, namely, the interfering oscillatory acceleration is off-phase by 90°. With increasing frequency though, the signal-to-disturbance ratio increases proportionally.

Examples of application

- Piezoelectric yaw-rate sensors,
- Micromechanical yaw-rate sensors MM1 and MM2.

Radar sensors

On special-purpose vehicles with high levels of drive slip (e.g. agricultural tractors), simple low-cost close-range Doppler-effect radar systems (24...35 GHz) are used to measure the quantity "vehicle speed over ground υ_F" (Figs. 1 and 2).

Each side of the vehicle is equipped with a transceiver probe which directs its radar beam onto the ground at an oblique angle of α, and with a frequency f_0. If a receiver were situated at this point on the ground, due to the Doppler effect it would receive this permanent signal at a higher frequency f_1 since the transmitter is moving towards it. This is similar to the acoustic effect experienced when overtaken by an emergency vehicle with its warning siren in operation:

$$f_1 = f_0 \frac{c}{c - \upsilon_F \cdot \cos \alpha} \quad (6)$$

The ground underneath the tractor, though, reflects the signal back to the transceiver probes, and again a higher frequency f_2 is measured at the receiver, since in this case the receiver is moving towards the source.

$$f_2 = f_1 \frac{c + \upsilon_F \cdot \cos \alpha}{c} = f_0 \frac{c + \upsilon_F \cdot \cos \alpha}{c - \upsilon_F \cdot \cos \alpha} \quad (7)$$

All in all, this results in a frequency shift Δf of:

$$\Delta f_2 = f_2 - f_1 = f_0 \frac{2 \cdot \upsilon_F \cdot \cos \alpha}{c - \upsilon_F \cdot \cos \alpha} \quad (8)$$

or, conversely, the speed υ_F:

$$\upsilon_F = \frac{c}{\cos \alpha} \cdot \frac{f_2 - f_0}{f_2 + f_0} \approx \frac{1}{2} \cdot \frac{c}{\cos \alpha} \cdot \frac{\Delta f_F}{f_0} \quad (9)$$

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This speed v_F is directly proportional to the frequency shift Δf.

The vehicle's rocking or tilting movements slightly change the angle α at which the signal is transmitted to ground. The probe which is rigidly attached to the bodywork utilises a radar system which "looks to the rear". This is known as the *Janus principle* (Fig. 2).

With the tractor horizontal, both systems measure the same value. If the vehicle tilts to the front or rear, since the beam angle increases on the one system by the same amount as it decreases on the other, the systems indicate opposite deviations from this (horizontal) value.

Averaging the two values eliminates the error resulting from tilt. The low measuring effect necessitates a relatively long-term averaging of the signals (approx. 1 s), so that rapid measurements of speed are impossible with this system.

The difference in the signals from the systems on each side of the vehicle provide a good indication of the angle-of-travel actually taken by the vehicle.

1 Doppler effect

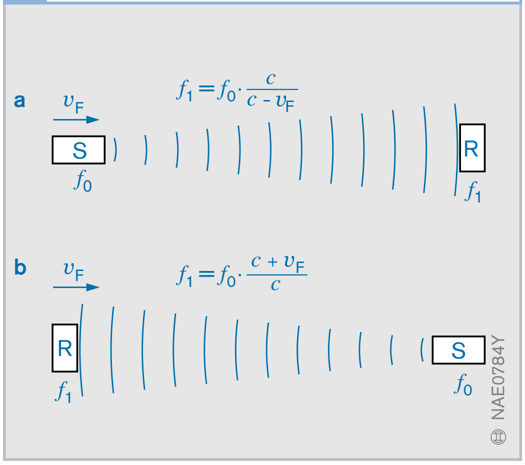

Fig. 1
a Transmitter S moves towards the stationary receiver R
b Receiver R moves towards stationary transmitter S
f_0 Transmit-signal frequency
f_1 Frequency of signal arriving at the receiver
v_F Vehicle speed

2 Janus principle

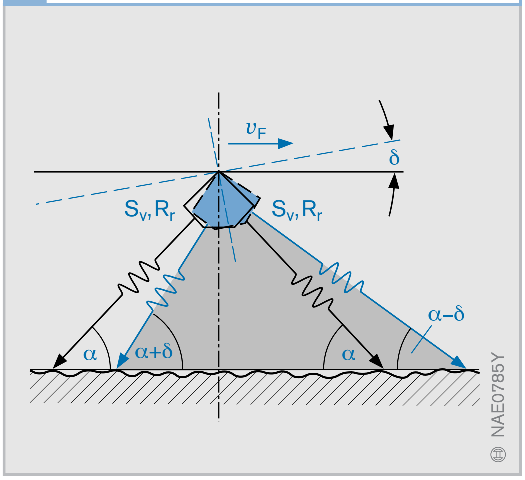

Fig. 2
S/R Transmitter/receiver
S_r, R_r Rearward-measuring system
S_v, R_v Forward-measuring system
v_F Vehicle speed
α Alignment angle of the measuring system
φ Vehicle's angle of tilt referred to the ground

3 Measurement of the the tractor's speed over ground v_F using Doppler-effect radar

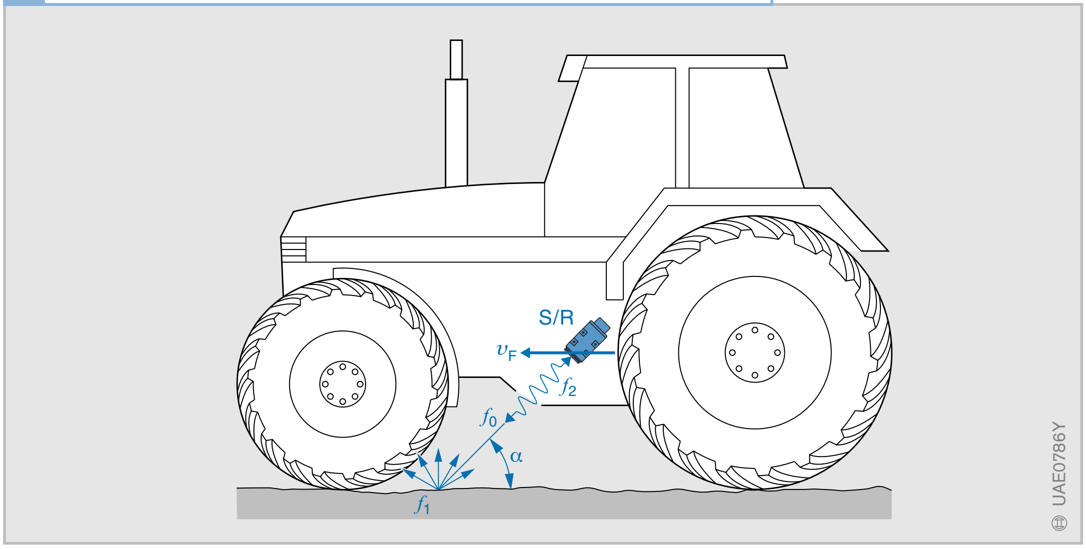

Fig. 3
S/R Transmitter/receiver
v_F Vehicle speed
f_0 Transmit-signal frequency
f_1 Frequency of signal arriving at the ground
f_2 Frequency of signal arriving at the receiver
α Alignment angle of the measuring system

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Inductive engine-speed sensors

Applications

Such engine-speed sensors are used for measuring:

- Engine rpm,
- Crankshaft position (for information on the position of the engine pistons).

The rotational speed is calculated from the sensor's signal frequency. The output signal from the rotational-speed sensor is one of the most important quantities in electronic engine management.

Design and operating concept

The sensor is mounted directly opposite a ferromagnetic trigger wheel (Fig. 1, Pos, 7) from which it is separated by a narrow air gap. It has a soft-iron core (pole pin) (4), which is enclosed by the solenoid winding (5). The pole pin is also connected to a permanent magnet (1), and a magnetic field extends through the pole pin and into the trigger wheel. The level of the magnetic flux through the winding depends upon whether the sensor is opposite a trigger-wheel tooth or gap. Whereas the magnet's stray flux is concentrated by a tooth and leads to an increase in the working flux through the winding, it is weakened by a gap. When the trigger wheel rotates therefore, this causes a fluctuation of the flux which in turn generates a sinusoidal voltage in the solenoid winding which is proportional to the rate of change of the flux (Fig. 2). The amplitude of the AC voltage increases strongly along with increasing trigger-wheel speed (several mV...>100 V). At least about 30 rpm are needed to generate an adequate signal level.

The number of teeth on the trigger wheel depends upon the particular application. On solenoid-valve-controlled engine-management systems for instance, a 60-pitch trigger wheel is normally used, although 2 teeth are omitted (7) so that the trigger wheel has 60 – 2 = 58 teeth. The very large tooth gap is allocated to a defined crankshaft position and serves as a reference mark for synchronizing the ECU.

There is another version of the trigger wheel which has one tooth per engine cylinder. In the case of a 4-cylinder engine, therefore, the trigger wheel has 4 teeth, and 4 pulses are generated per revolution.

The geometries of the trigger-wheel teeth and the pole pin must be matched to each other. The evaluation-electronics circuitry in the ECU converts the sinusoidal voltage, which is characterized by strongly varying amplitudes, into a constant-amplitude square-wave voltage for evaluation in the ECU microcontroller.

1 Inductive rpm sensor

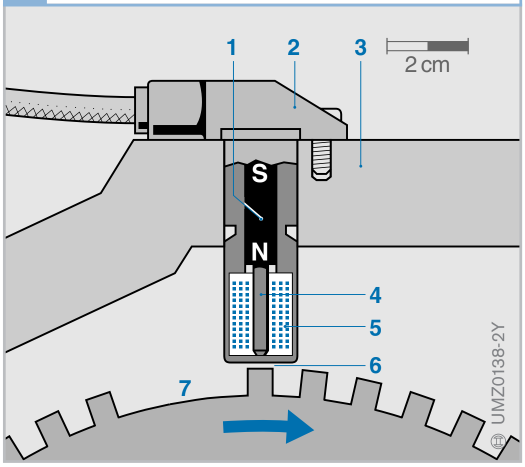

Fig. 1
1 Permanent magnet
2 Sensor housing
3 Engine block
4 Pole pin
5 Solenoid winding
6 Air gap
7 Trigger wheel with reference-mark gap

2 Signal from an inductive rpm sensor

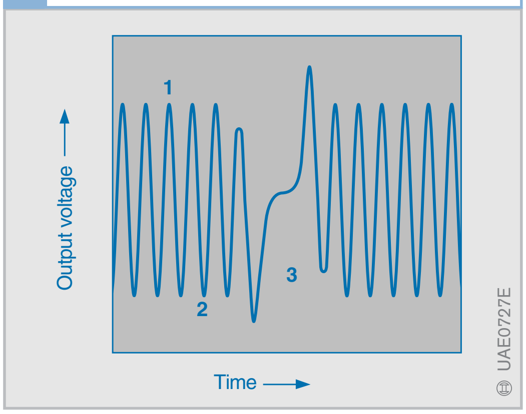

Fig. 2
1 Tooth
2 Tooth gap
3 Reference mark

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Rotational-speed (rpm) sensors and incremental angle-of-rotation sensors

Application

The above sensors are installed in distributor-type diesel injection pumps with solenoid-valve control. Their signals are used for:

- The measurement of the injection pump's speed,
- Determining the instantaneous angular position of pump and camshaft,
- Measurement of the instantaneous setting of the timing device.

The pump speed at a given instant is one of the input variables to the distributor pump's ECU which uses it to calculate the triggering time for the high-pressure solenoid valve, and, if necessary, for the timing-device solenoid valve.

The triggering time for the high-pressure solenoid valve must be calculated in order to inject the appropriate fuel quantity for the particular operating conditions. The cam plate's instantaneous angular setting defines the triggering point for the high-pressure solenoid valve. Only when triggering takes place at exactly the right cam-plate angle, can it be guaranteed that the opening and closing points for the high-pressure solenoid valve are correct for the particular cam lift. Precise triggering defines the correct start-of-injection point and the correct injected fuel quantity.

The correct timing-device setting as needed for timing-device control is ascertained by comparing the signals from the camshaft rpm sensor with those of the angle-of-rotation sensor.

Design and operating concept

The rpm sensor, or the angle-of-rotation sensor, scans a toothed pulse disc with 120 teeth which is attached to the distributor pump's driveshaft. There are tooth gaps, the number of which correspond to the number of engine cylinders, evenly spaced around the disc's circumference. A double differential magnetoresistive sensor is used.

Magnetoresistors are magnetically controllable semiconductor resistors, and similar in design to Hall-effect sensors. The double differential sensor has four resistors connected to form a full bridge circuit.

The sensor has a permanent magnet, and the magnet's pole face opposite the toothed pulse disc is homegenized by a thin ferromagnetic wafer on which are mounted the four magnetoresistors, separated from each other by half a tooth gap. This means that alternately there are two magnetoresistors opposite tooth gaps and two opposite teeth (Fig. 1). The magnetoresistors for automotive applications are designed for operation in temperatures of ≤ 170 °C (≤ 200 °C briefly).

1 Rotation-speed/angle-of-rotation sensor (principle)

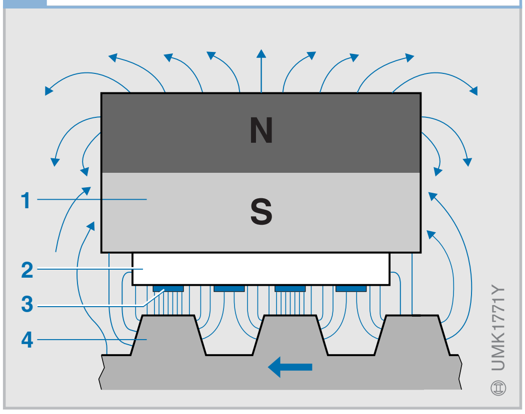

Fig. 1
1 Magnet
2 Homogenization wafer (Fe)
3 Magnetoresistor
4 Toothed pulse disc

2 Rotation-speed/angle-of-rotation sensor (as installed)

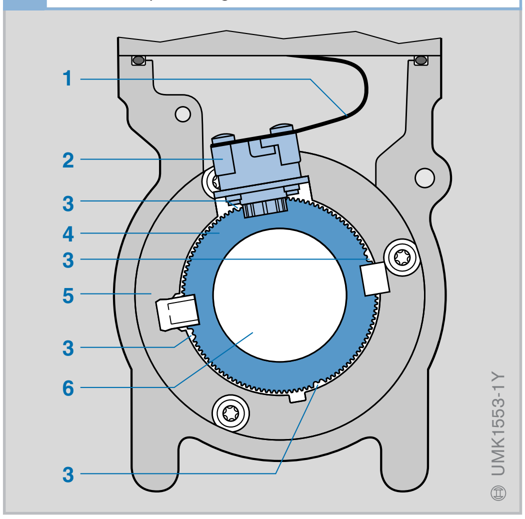

Fig. 2
1 Flexible conductive foil
2 Rotation-speed (rpm)/angle-of-rotation sensor
3 Tooth gap
4 Toothed pulse wheel (trigger wheel),
5 Rotatable mounting
6 Driveshaft

Hall-effect phase sensors

Application

The engine's camshaft rotates at half the crankshaft speed. Taking a given piston on its way to TDC, the camshaft's rotational position is an indication as to whether the piston is in the compression or exhaust stroke. The phase sensor on the camshaft provides the ECU with this information.

Design and operating concept

Hall-effect rod sensors

As the name implies, such sensors (Fig. 2a) make use of the Hall effect. A ferromagnetic trigger wheel (with teeth, segments, or perforated rotor, Pos. 7) rotates with the camshaft. The Hall-effect IC is located between the trigger wheel and a permanent magnet (Pos. 5) which generates a magnetic field strength perpendicular to the Hall element.

If one of the trigger-wheel teeth (Z) now passes the current-carrying rod-sensor element (semiconductor wafer), it changes the magnetic field strength perpendicular to the Hall element. This causes the electrons, which are driven by a longitudinal voltage across the element to be deflected perpendicularly to the direction of current (Fig. 1, angle α).

This results in a voltage signal (Hall voltage) which is in the millivolt range, and which is independent of the relative speed between sensor and trigger wheel. The evaluation electronics integrated in the sensor's Hall IC conditions the signal and outputs it in the form of a rectangular-pulse signal (Fig. 2b "High"/"Low").

Differential Hall-effect rod sensors

Rod sensors operating as per the differential principle are provided with two Hall elements. These elements are offset from each other either radially or axially (Fig. 3, S1 and S2), and generate an output signal which is proportional to the difference in magnetic flux at the element measuring points. A two-track perforated plate (Fig. 3a) or a two-track trigger wheel (Fig. 3b) are needed in order to generate the opposing signals in the Hall elements (Fig. 4) as needed for this measurement.

Such sensors are used when particularly severe demands are made on accuracy. Further advantages are their relatively wide air-gap range and good temperature-compensation characteristics.

1 Hall element (Hall-effect vane switch)

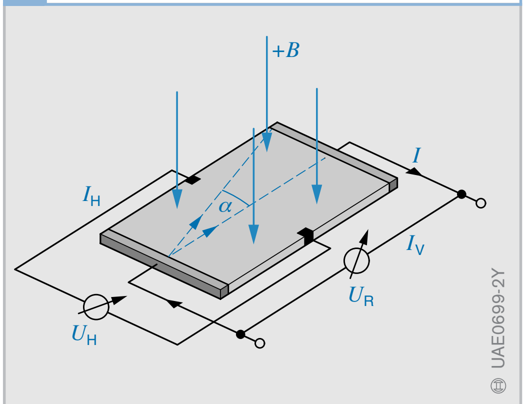

Fig. 1
- I Wafer current
- I_H Hall current
- I_V Supply current
- U_H Hall voltage
- U_R Longitudinal voltage
- B Magnetic induction
- α Deflection of the electrons by the magnetic field

2 Hall-effect rod sensor

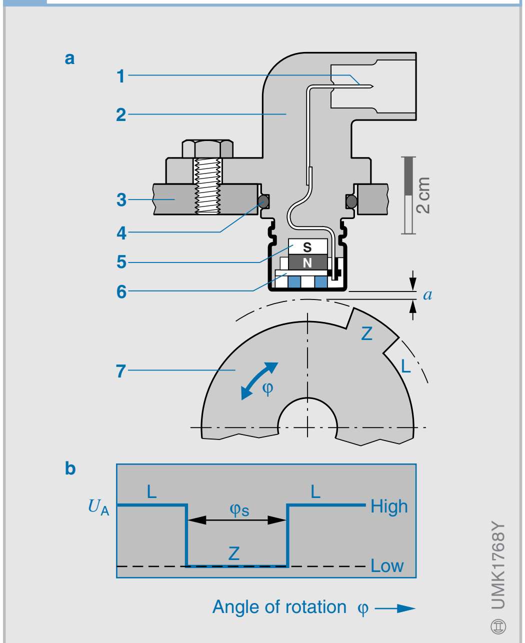

Fig. 2
- a Positioning of sensor and single-track trigger wheel
- b Output signal characteristic U_A

1. Electrical connection (plug)
2. Sensor housing
3. Engine block
4. Seal ring
5. Permanent magnet
6. Hall-IC
7. Trigger wheel with tooth/segment (Z) and gap (L)

- a Air gap
- φ Angle of rotation

3 Differential Hall-effect rod sensors

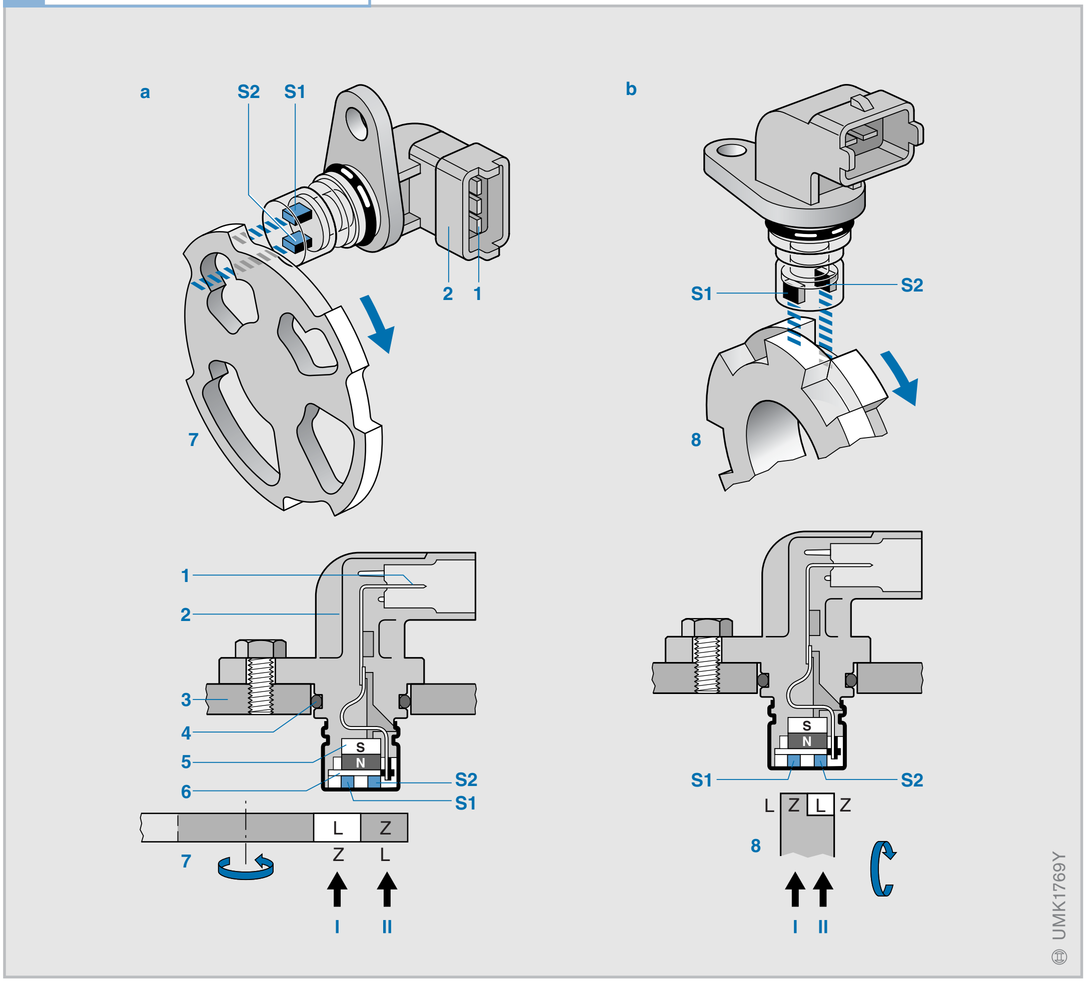

Fig. 3
- a Axial tap-off (perforated plate)
- b Radial tap-off (two-track trigger wheel)

1. Electrical connection (plug)
2. Sensor housing
3. Engine block
4. Seal ring
5. Permanent magnet
6. Differential Hall-IC with Hall elements S1 and S2
7. Perforated plate
8. Two-track trigger wheel

- I Track 1
- II Track 2

4 Characteristic curve of the output signal U_A from a differential Hall-effect rod sensor

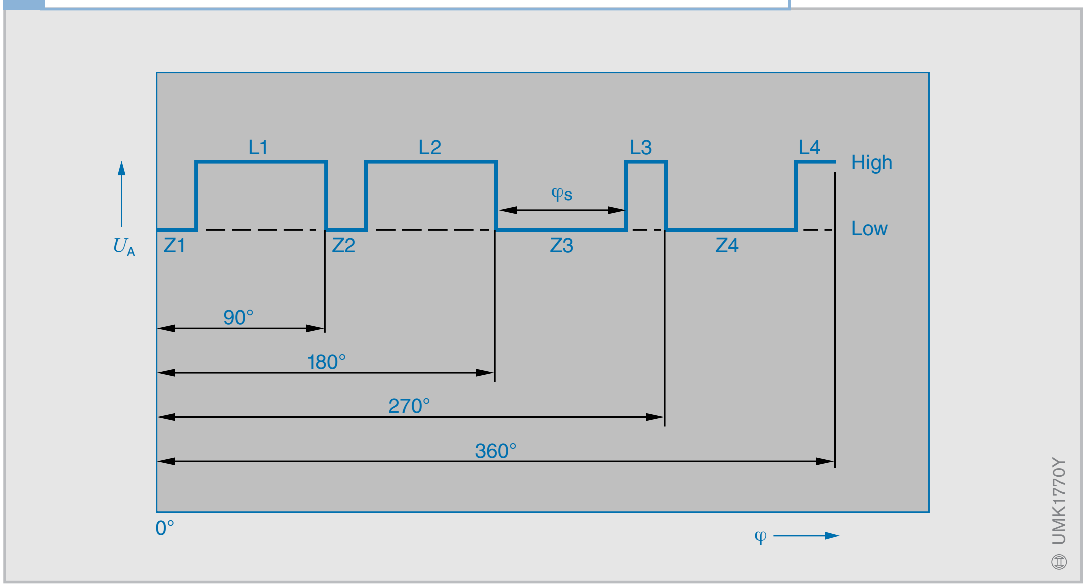

Fig. 4

Output signal "Low": Material (Z) in front of S1, gap (L) in front of S2

Output signal "High": Gap (L) in front of S1, material (Z) in front of S2

φ_S signal width

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Wheel-speed sensors

Application

It is from the wheel-speed sensor signals that the ABS, TCS, and ESP control units (ECUs) derive the wheel-rotation rates. These wheel speeds are applied in preventing the wheels blocking or spinning so that the vehicle's stability and steerability are maintained. In verhicle navigation systems, the signals are used for calculating the distance travelled.

Design and operating concept

Passive (inductive) wheel-speed sensors

The inductive wheel-speed sensor's pole pin, surrounded by its coil winding, is installed directly above a trigger wheel (rotor) attached to the wheel hub. This soft-magnetic pole pin is connected to a permanent magnet which projects a magnetic field toward and into the trigger wheel. The continuously alternating sequence of teeth and gaps that accompanies the wheel's rotation induces corresponding fluctuations in the magnetic field through the pole pin and its coil winding. These fluctuations induce an alternating current in the coil suitable for monitoring at the ends of its winding.

The frequency and amplitude of this alternating current are proportional to wheel speed, and with the wheel not rotating, the induced voltage is zero. Tooth shape, air gap, rate of voltage rise, and the ECU input sensitivity define the smallest still measurable rotation rate and thus, for ABS applications, the minimum switching speed.

To ensure interference-free signal detection, the gap separating the wheel-speed sensor and the trigger wheel is only approx. 1 mm, and installation tolerances are narrow. The wheel-speed sensor is also installed on a stable mounting to prevent oscillation patterns in the vicinity of the brakes from distorting the sensor's signals. Various pole-pin configurations and installation options are available to adapt the system to the different installation conditions encountered with various wheels. The most common variant is the *chisel-type pole pin* (also called a flat pole pin Fig. 1a) for radial installation at right angles to the pulse rotor. The *rhombus-type (lozenge-shaped) pole pin* (Figure 1b) designed for axial installation is located radially with respect to the trigger wheel. Both pole-pin designs necessitate precise alignment to the trigger wheel. Although precise alignment is not so important with the *round pole pin* (Figure 1c), the trigger wheel must have a large enough diameter, or less teeth.

1 Wheel-speed sensors: Pole-pin shapes and types of installation (DF6 as example)

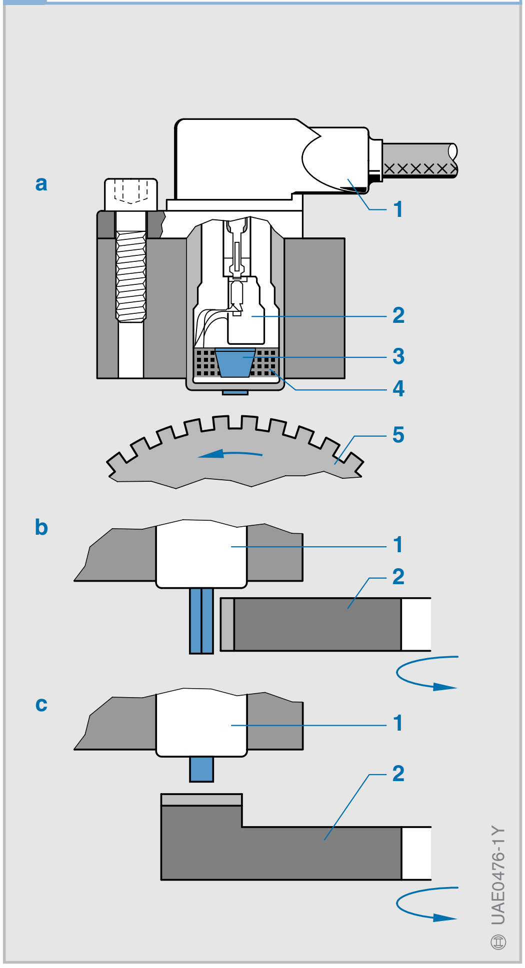

Fig. 1

a Chisel pole pin: Radial installation, radial scan
b Rhombus pole pin: Axial installation, radial scan
c Round pole pin: Radial installation, axial scan
1 Sensor case with electrical connections
2 Permanent magnet
3 Soft-iron core (pole pin)
4 Winding
5 Trigger wheel

Active wheel-speed sensors

The conventional inductive units are increasingly being replaced by active wheel-speed sensor types in which the function formerly performed by the trigger ring's teeth is taken over by peripheral magnets incorporated around the periphery of a multipole ring so that their polarities alternate (Fig. 2).

The sensor element of such an active wheel-speed sensor is located in the continuously changing fields generated by these magnets. Rotation of the multipole ring is thus accompanied by a continuous alternation in the magnetic flux through the sensor element.

Compact dimensions combine with low weight to make the active wheel-speed sensor suitable for installation on and even within the vehicle's wheel-bearing assemblies (Fig. 3). In the latter case, the bearing seal contains magnetic powder instead of fixed magnets. This means that a second function has been added and the bearing seal now becomes a multipole device.

The most important sensor components are either Hall or magnetoresistive elements, both of which generate a voltage that varies according to the magnetic flux through the measuring element. This voltage is then conditioned by the active wheel-speed sensor. One of the active sensor's advantages is the fact that in contrast to the inductive sensors, its output voltage is independent of the wheel speed. This fact permits monitoring to continue until the wheel is practically stationary.

A typical feature of the active wheel-speed sensor is the local amplifier circuit. Both components - measuring element and amplifier - are integrated in a single sensor casing. The active sensor requires a power supply of between 4.5 and 20 volts, and it is connected to the ECU by a two-conductor wire. The wheel-speed data is impressed on one of the two conductors (supply lines) as load-independent current. As with the inductive wheel-speed sensor, the current's frequency is proportional to wheel speed. This single-wire data-transmission strategy uses pre-conditioned digital signals. These are less sensitive to interference than the signals from the inductive sensor. The concept also features the following options:

- Data transmission identifying the wheel's direction of travel. This option is especially significant for the "hill-holding" feature, which relies on selective braking to prevent the vehicle from rolling backwards when starting off on a hill. Also used in vehicle navigation systems.
- Relay of information on sensor-signal quality, including a display indicating that the driver should have the vehicle serviced in order to check correct sensor functioning.

2 Active wheel-speed sensor showing a section of the multipole ring

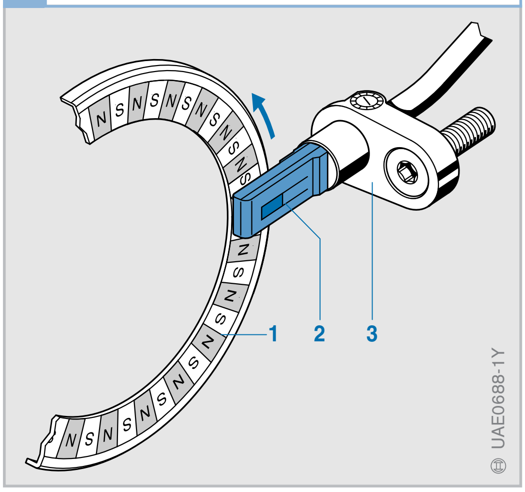

Fig. 2
1 Multipole ring
2 Sensor element
3 Sensor case

3 Example of sensor installation in the wheel bearing

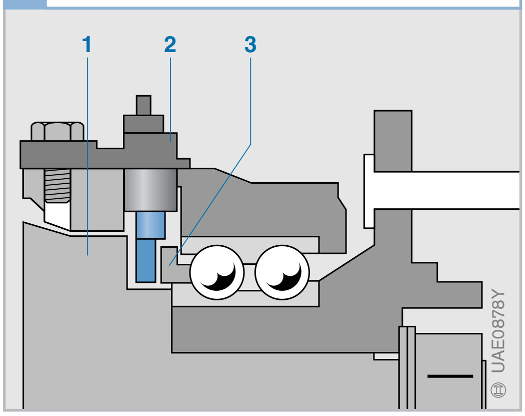

Fig. 3
1 Wheel bearing
2 Sensor
3 Multipole ring/ Bearing seal

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Gearbox-rpm sensors

Application

Such gearbox-rpm sensors scan the speeds in automatic-transmissions, continuously-variable transmissions, and automatic shift transmissions (AT, AST, and CVT respectively). For such applications, the sensors are designed to be insensitive to ATF gearbox oils. The "packaging concept" provides for sensor integration in the transmission-shift control module or for a "stand-alone" version. The sensor needs a power supply of 4.5...16.5 V and operates in the termperature range –40...+150 °C.

Design and operating concept

The active rpm sensor is provided with a differential Hall-effect IC with 2-wire current interface. For operation, the sensor must be connected to a voltage source (supply voltage U_V). It applies the Hall effect when scanning ferromagnetic toothed rotors, punched-sheet rotors, or multipole rings (air-gap range: 0.1...2.5 mm), and generates a constant-amplitude signal which is independent of rotational speed. This means that it is possible to register rotational speeds down to practically $n = 0$. For signal output, the supply current is modulated by the incremental signal. Using a measuring resistor R_M, the current modulation (Low: 7 mA; High: 14 mA) can then be converted in the ECU into a signal voltage U_{RM} (Fig. 1).

There are two different types of gearbox-rpm sensors (Fig. 2):

RS50

Data protocol: rpm information in the form of a rectangular-pulse signal.
Functional scope: A frequency signal triggered by the rotor passing the sensor surface. It is proportional to the rotor speed.

RS51

Data protocol: rpm information in the form of a rectangular-pulse signal with supplementary information which are transmitted using the pulse-width-modulation (pwm) principle.
Functional scope: rpm signal, detection of standstill, direction of rotation, air-gap reserve, and installation position.

1 Example of a Hall-effect sensor with 2-wire current interface

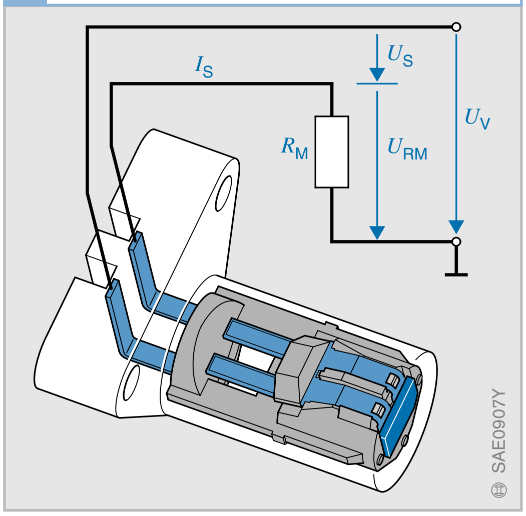
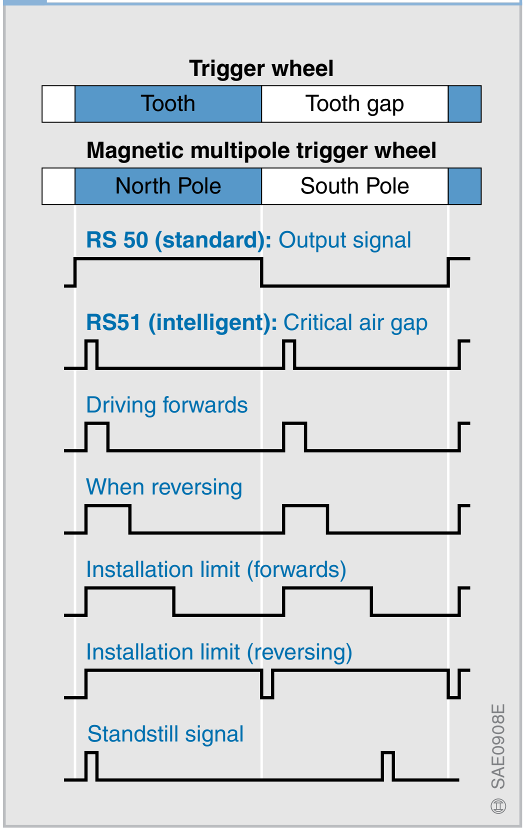


Fig. 1
- I_S Sensor current (supply and signal)
- R_M Measuring resistor (in ECU)
- R_{RM} Signal voltage
- U_V Supply voltage
- U_S Sensor voltage

2 Shape and information content of the output signals from various sensor versions



Nozzle holder with needle-motion sensor

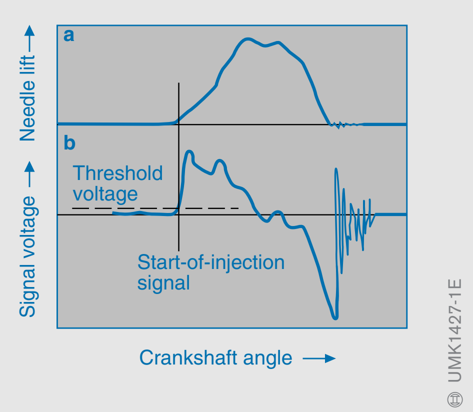
Application

The start-of-injection point is an important parameter for optimum diesel-engine operation. For intance, its measurement permits load and speed-dependent injection timing, and/or control of the EGR rate within a closed control loop. On the inline and distributor injection pumps, a nozzle-holder with needle-motion sensor is used for this purpose (Fig. 2) which outputs a signal as soon as the deedle moves.

Design and operating concept

A current of approx. 30 mA flows through the pick-up coil (Fig. 2, Pos. 11) and generates a magnetic field. The long pressure pin (12) extends into guide pin (9). The so-called immersion dimension "X", defines the magnetic flux in the pick-up coil. Nozzle-needle motion causes a change of flux. This, in turn, generates a velocity-dependent signal voltage which is directly processed in an ECU evaluation circuit. When a given threshold voltage is exceeded, this serves as the signal for the start of injection (Fig. 1).

1 Needle-motion sensor signal



2 Two-spring nozzle holder with needle-motion sensor for DI engines

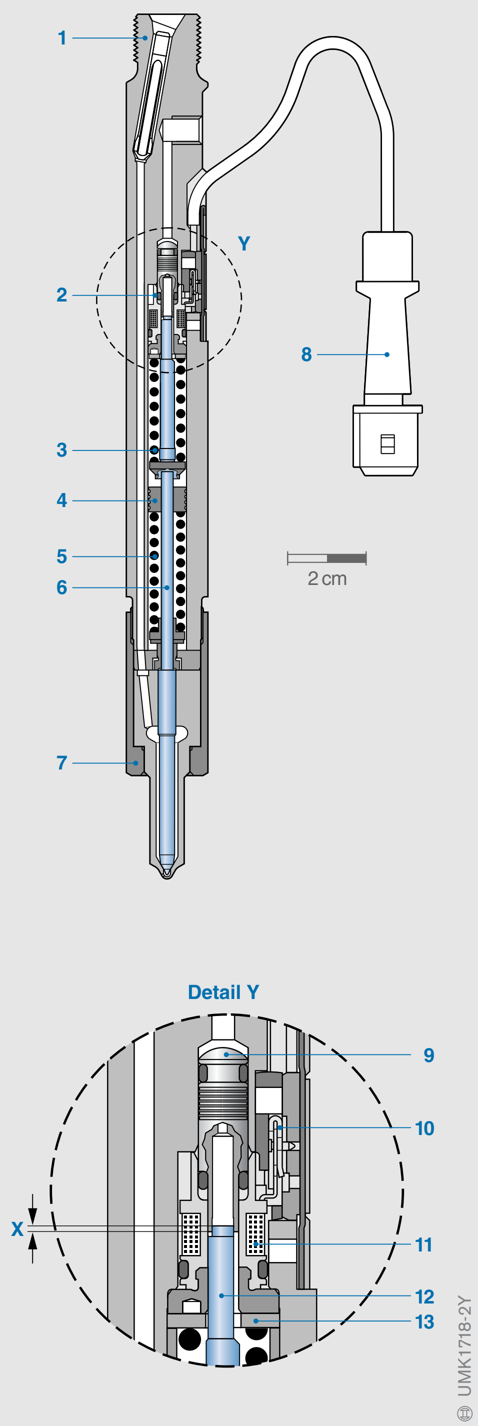


Fig. 1
a Needle-lift curve
b Signal-voltage curve

Fig. 2
1 Mount
2 Needle-motion sensor
3 Spring
4 Guide element
5 Spring
6 Pressure pin
7 Nozzle retaining nut
8 Connection for evaluation circuit
9 Guide pin
10 Contact lug
11 Pick-up coil
12 Pressure pin
13 Spring seat
x Immersion dimension

Induction-type sensors for transistorized ignition

Applications

For ignition-triggering purposes, the TC-I transistorized ignition uses an induction-type sensor which serves as an AC generator. The switch-on point for the dwell angle is defined by comparing its AC signal with that of a voltage signal which corresponds to the current-control time.

Design and construction

The induction-type sensor is incorporated in the ignition-distributor housing in place of the former contact-breaker points (Fig. 1).

The soft-magnetic core of the induction winding is disc-shaped, and together with the permanent magnet and the induction winding, forms a fixed, enclosed subassembly, the stator.

The rotor (trigger wheel) on the distributor shaft rotates past the ends of the stators. Similar to the distributor cam for the former contact breaker assembly, it is firmly attached to the hollow shaft surrounding the distributor shaft.

Core and rotor are produced from soft-magnetic material and have toothed extensions (stator teeth and rotor teeth). The stator teeth are at the ends of the stator "limbs" and bent upwards at right angles. The rotor has similar teeth, but these are bent downwards at right angles.

As a rule, the number of teeth on rotor and stator correspond to the number of cylinders in the engine. The fixed and rotating teeth are separated by a mere 0.5 mm when directly opposite to each other.

Operating concept

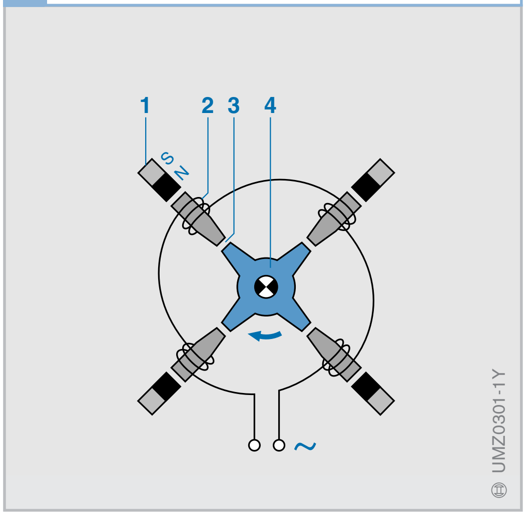
The principle of functioning depends upon the air gap between the rotor teeth and the stator teeth, and thus the magnetic flux, changing periodically along with rotation of the rotor. This change in magnetic flux induces an AC voltage in the induction winding whose peak voltage $\pm \hat{U}_S$ is proportional to the rotor's speed of rotation. At low speeds it is approx. 0.5 V and at high speeds approx. 100 V. The frequency f of this AC voltage (Fig. 2) corresponds to the number of ignition sparks per minute (sparking rate). The following applies

$$f = z \cdot n/2$$

where

f Frequency or sparking rate (min⁻¹),
z Number of engine cylinders,
n Engine speed (min⁻¹).

1 Induction-type sensor in the ignition distributor (principle)



2 Induction-type sensor in the ignition distributor (characteristic)

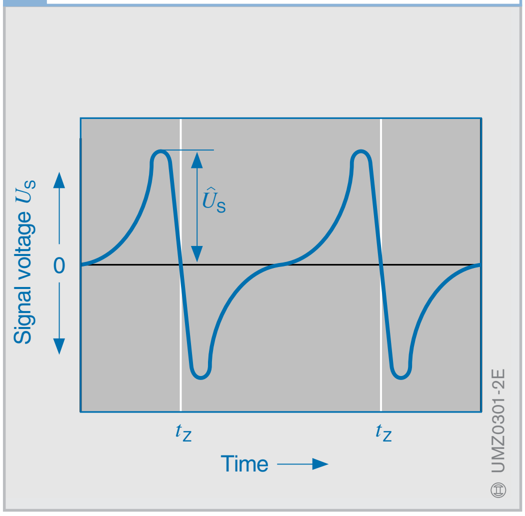


Fig. 1
1 Permanent magnet
2 Induction winding with core
3 Variable air gap
4 Rotor

Fig. 2
U_S Signal voltage
$\hat{U}_S$ Peak voltage
t_Z Ignition point

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Hall-effect sensors for transistorized ignition

Application

The Hall-effect sensor is also used as the ignition-triggering sensor for the TI-H transistorized ignition system. The information contained in the signal from the Hall generator located in the ignition distributor corresponds to that in the signal generated by the breaker points in a conventional breaker-triggered coil-ignition system. Whereas with the conventional ignition system the distributor cam defines the dwell angle via the contact-breaker points, on the transistorized system the Hall-effect sensor in the ignition distributor defines the on/off ratio by means of the rotor (trigger-wheel) vane.

Design and construction

The Hall-effect sensor (Fig. 1) is installed in the ignition distributor, and its vane switch is attached to the movable mounting plate. The Hall IC is mounted on a ceramic substrate and in order to protect it against moisture, dirt, and mechanical damage is encapsulated in plastic at one of the conductive elements. The conductive elements and the rotor are made of a soft-magnetic material. The number of vanes on the rotor corresponds to the number of cylinders in the engine. Depending on the type of ignition trigger box, the width b of the rotor's individual conductive elements can define the ignition system's maximum dwell angle. The dwell angle therefore remains practically constant throughout the Hall sensor's service life and dwell-angle adjustment is unnecessary.

Operating concept

When the ignition-distributor shaft rotates, the rotor vane's pass through the Hall IC air gap without making contact. If the air gap is not occupied by a vane, the magnetic field is free to permeate the Hall IC and the Hall-effect sensor element (Fig. 1). The magnetic flux density is high, the Hall voltage is at its maximum, and the Hall-IC is switched on. As soon as a rotor vane enters the air gap, the majority of the magnetic flux is diverted through the vane and is isolated from the Hall-IC. The magnetic flux density at the Hall sensor element reduces to a negligible level which results from the leakage field, and the Hall voltage drops to a minimum. The dwell angle is defined by the rotor vane's shape as follows: A ramp voltage is generated from the signal voltage U_S (converted Hall voltage, Fig. 2). The switch-on point for the dwell angle is shifted as required along this ramp. The Hall-effect sensor's priniple of operation and its construction permit the ignition to be adjusted with the engine at standstill provided no provision is made for peak-coil-current cut-off.

1 Hall-effect sensor in the ignition distributor (principle of operation)

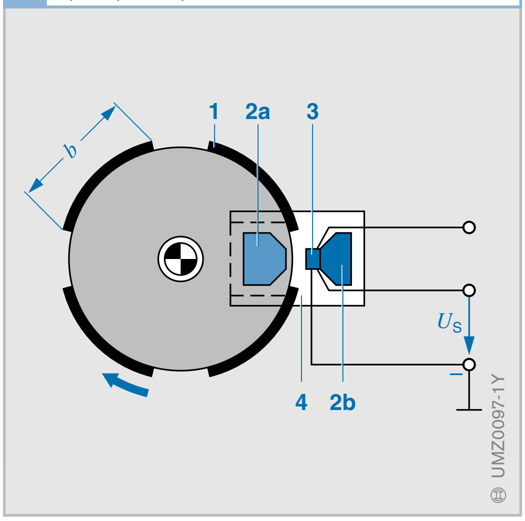


Fig. 1
1 Vane with width b
2a Permanent magnet
2b Soft-magnetic conductive element
3 Hall-IC
4 Air gap
U_S Signal voltage (converted Hall voltage)

2 Hall-effect sensor in the ignition distributor (characteristic curve)

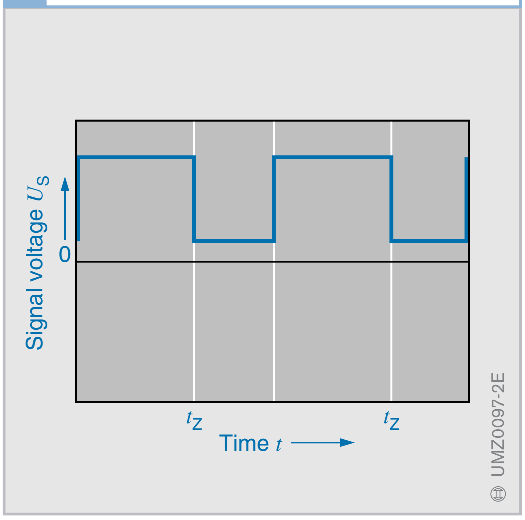


Fig. 2
U_S Signal voltage (converted Hall voltage)
t_z Ignition point

Piezoelectric "tuning-fork" yaw-rate sensor

Application

In order that it can use the digital road map stored on the CD-ROM to calculate the distance driven, the computer in the vehicle's navigation system needs information on the vehicle's movements (composite navigation).

When cornering (for instance at road junctions), the navigation system's yaw-rate sensor registers the vehicles rotation about its vertical axis. With the voltage signal it generates in the process, and taking into account the signals from the tachometer or the radar sensor, the navigation computer calculates the curve radius and from this derives the change in vehicle direction.

Design and construction

The angle-of-rotation sensor is comprised of a steel element shaped like a tuning fork. This incorporates four piezo elements (two above, two below) and the sensor electronics.

This sensor measures very accurately and is insensitive to magnetic interference.

Operating concept

When voltage is applied, the bottom piezo elements start to oscillate and excite the upper section of the "tuning fork", together with its upper piezo elements, which then starts counter-phase oscillation.

Straight-ahead driving

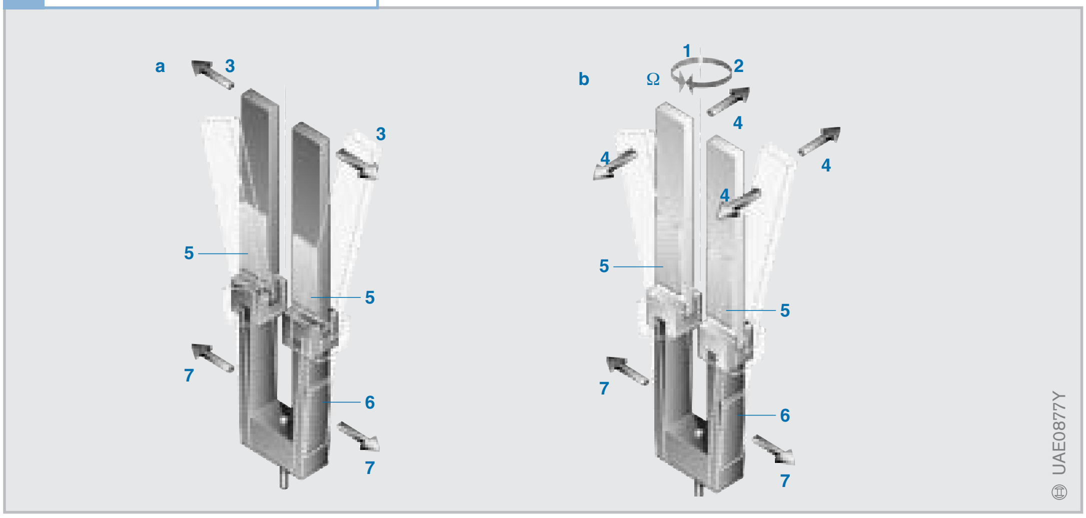
With the vehicle being driven in a straight line there are no Coriolis forces applied at the tuning fork, and since the upper piezo elements always oscillate in counter-phase and are only sensitive vertical to the direction of oscillation (Fig. 1a) they do not generate a voltage.

Cornering

When cornering on the other hand, the Coriolis acceleration which occurs in connection with the oscillation (but vertical to it) is applied for measurement purposes. The rotational movement now causes the upper portion of the tuning fork to leave the oscillatory plane (Fig. 1b) so that an AC voltage is generated in the upper piezo elements which is transferred to the navigation computer by an electronic circuit in the sensor housing. The voltage-signal amplitude is a function of both the yaw rate and the oscillatory speed. Its sign depends on the direction (left or right) taken by the curve.

Fig. 1
- a Excursion during straight-ahead driving
- b Excursion when cornering
- 1 Tuning-fork direction of oscillation resulting from cornering
- 2 Direction of rotation of the vehicle
- 3 Directiion of oscillation resulting from straight-ahead driving
- 4 Coriolis force
- 5 Upper piezo elements (sensing)
- 6 Bottom piezo elements (drive)
- 7 Excitation oscillation direction
- Ω Yaw

1 "Tuning-fork" piezo yaw-rate sensor



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Piezoelectric "oscillating drum" yaw-rate sensors

Applications

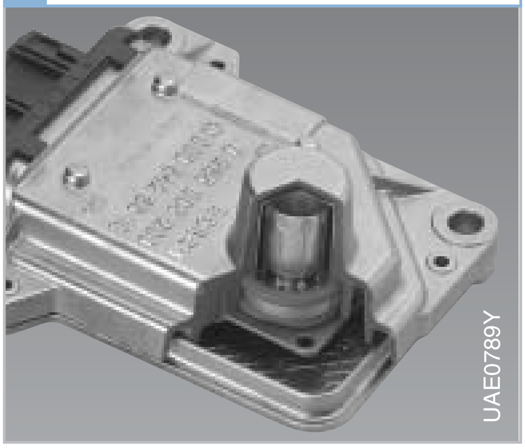
In vehicle's with vehicle-dynamics control (ESP), the piezoelectric yaw-rate sensors (otherwise known as gyrometers) register the vehicle's rotation about its vertical axis, for instance when cornering, but also when the vehicle swerves or goes into a skid.

Design and construction

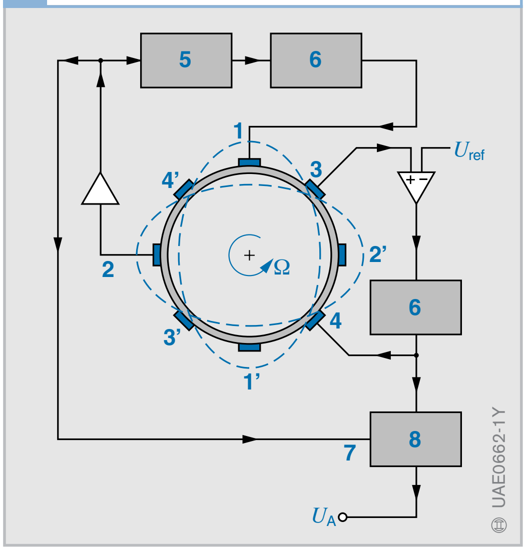
The piezoelectric yaw-rate sensors are high-precision mechanical sensors. Two diametrically opposed piezoceramic elements (Fig. 1, 1 + 1′) are used to cause sympathetic oscillations in a hollow metal cylinder. Another pair of piezoceramic elements (2 + 2′) are used to control and maintain this oscillation at a constant amplitude which has four axially aligned oscillation nodes (offset by 45° to the direction of excitation). Refer to Figs. 1...3.

When rotation takes place at a yaw rate Ω about the cylinder's axis, the nodes are shifted slightly at the circumference due to the effects of Coriolis acceleration. The result is that in the nodes, which otherwise feature zero force, forces are now generated which are proportional to rotational speed and which are detected by a third pair of piezo elements (3 + 3′). Using a fourth pair of piezo excitation elements (4 + 4′) in a closed control loop, these forces are then controlled back to a reference value $U_{ref} = 0$. The manipulated variable needed here is then carefully filtered and subjected to phase-synchronous rectification before being used as a highly accurate output signal. The selective, temporary change of the desired value to $U_{ref} = 0$ permits an easy check of the overall sensor system ("built-in test"). This sensor's temperature sensitivity necessitates a complex compensation circuit, and the material-based aging of the piezoceramic elements necessitates painstaking preliminary aging.

2 Piezoelectric yaw-rate sensor



1 Piezoelectric yaw-rate sensor (measuring principle)



3 Piezoelectric yaw-rate sensor (design principle)

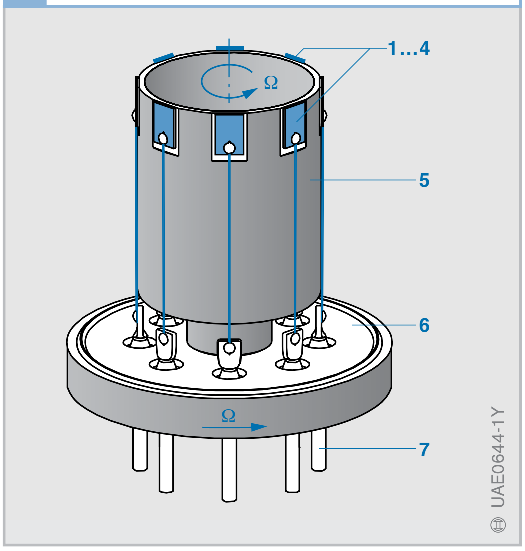


Fig. 1
1....4 Piezo elements
5 Circuit
6 Bandpass filter (phase-locked)
7 Phase reference
8 Rectifier (phase-selective)
U_A Output voltage
Ω Yaw rate
$U_{ref} = 0$ (normal operation)
$U_{ref} \neq 0$ ("built-in" test)

Fig. 3
1....4 Piezo element pairs
5 Oscillatory cylinder
6 Baseplate
7 Connection pins
Ω Yaw rate

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Micromechanical yaw-rate sensors

Applications

In vehicles with Electronic Stability Program (ESP), the rotation of the vehicle about its vertical axis is registered by micromechanical yaw-rate (or yaw-speed) sensors (also known as gyrometers) and applied for vehicle-dynamics control. This takes place during normal cornering, but also when the vehicle breaks away or goes into a skid.

These sensors are reasonably priced as well as being very compact. They are in the process of forcing out the conventional high-precision mechanical sensors.

1 Structure of the MM1 yaw-rate sensor

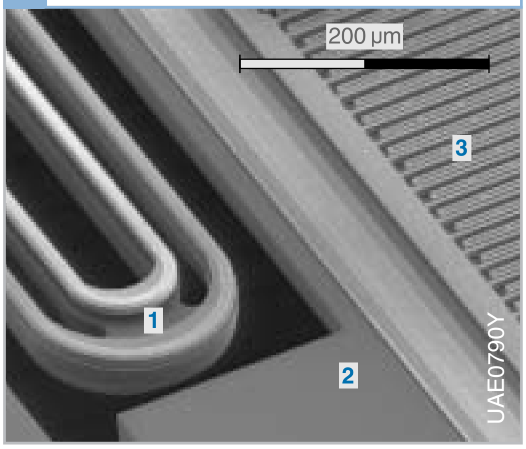

Fig. 1
1 Retaining/guide spring
2 Part of the oscillating element
3 Coriolis acceleration sensor

Design and construction

MM1 micromechanical yaw-rate sensor

A mixed form of technology is applied in order to achieve the high accuracies needed for vehicle-dynamics systems. That is, two somewhat thicker oscillating elements (mass plates) which have been machined from a wafer using bulk micromechanics oscillate in counter-phase to their resonant frequency which is defined by their mass and their coupling springs (>2 kHz). On each of these oscillating elements, there is a miniature, surface-type micromechanical capacitive acceleration sensor. When the sensor chip rotates about its vertical axis at yaw rate Ω, these register the Coriolis acceleration in the wafer plane vertical to the direction of oscillation (Figs. 1 and 2). These accelerations are proportional to the product of yaw rate and and the oscillatory velocity which is maintained electronically at a constant value.

To drive the sensor, all that is required is a simple, current-carrying printed conductor on each oscillating element. In the permanent-magnet field B vertical to the chip surface, this oscillating element is subjected to an electrodynamic (Lorentz) force. Using a further, simple printed conductor (which saves on chip surface), the same magnetic field is used to directly measure the oscillation velocity by inductive means. The different physical construction of drive system

2 MM1 micromechanical yaw-rate sensor

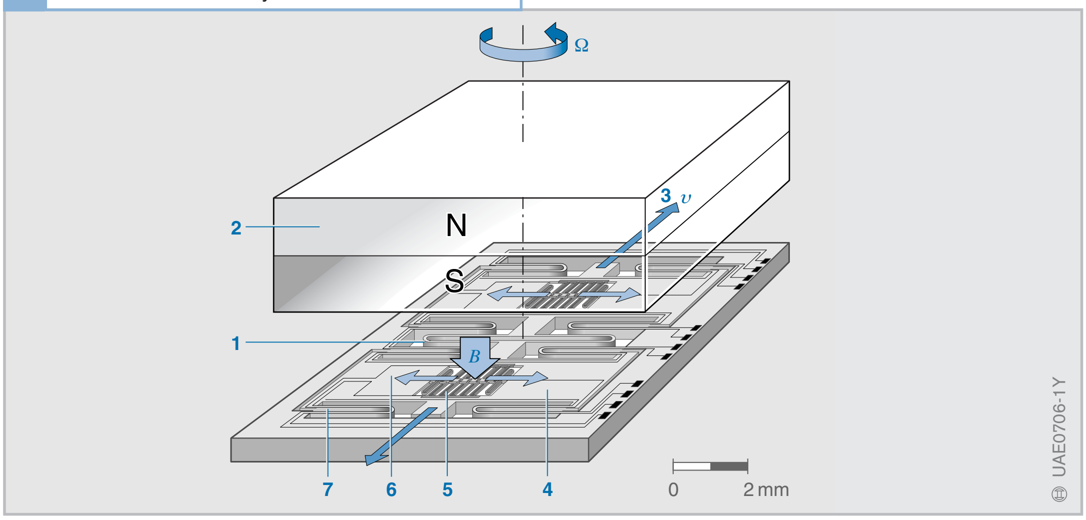

Fig. 2
1 Frequency-determining coupling spring
2 Permanent magnet
3 Direction of oscillation
4 Oscillating element
5 Coriolis acceleration sensor
6 Direction of Coriolis acceleration
7 Retaining/guide spring
Ω Yaw rate
υ Oscillating velocity
B Permanent-magnet field

and sensor system serves to avoid undesirable coupling between the two sections. In order to suppress unwanted external acceleration effects, the opposing sensor signals are subtracted from each other. The external acceleration effects can be measured by applying summation. The high-precision micromechanical construction helps to suppress the effects of high oscillatory acceleration which is several factors of 10 higher than the low-level Coriolis acceleration (cross sensitivity far below 40 dB). Here, the drive and measurement systems are rigorously decoupled from each other.

MM2 micromechanical yaw-rate sensor

Whereas this silicon yaw-rate sensor is produced completely using surface-micromechanic techniques, and the magnetic drive and control system have been superseded by an electrostatic system, absolute decoupling of the power/drive system and measuring system is impossible. Comb-like structures (Figs. 3 and 4) electrostatically force a centrally mounted rotary oscillator to oscillate. The amplitude of these oscillations is held constant by means of a similar capacitive pick-off. Coriolis forces result at the same time in an out-of-plane tilting movement, the amplitude of which is proportional to the yaw rate Ω, and which is detected capacitively by the electrodes underneath the oscillator. To avoid excessive damping of this movement, the sensor must be operated in a vacuum. Although the chip's small size and the somewhat simpler production process result in considerable cost reductions, this miniaturisation is at the expense of reductions in the measuring effect, which in any case is not very pronounced, and therefore of the achievable precision. It also places more severe demands on the electronics. The system's high flexural stability, and mounting in the axis of gravity, serve to mechanically suppress the effects of unwanted acceleration from the side.

4 MM2 yaw-rate sensor: Structure

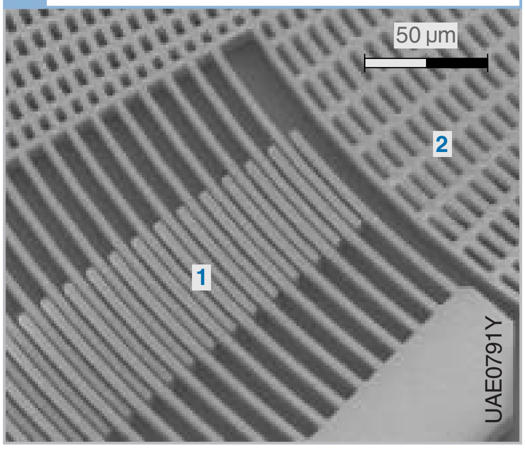

Fig. 4
1 Comb-like structure
2 Rotary oscillator

3 MM2 surface-micromechanical yaw-rate sensor

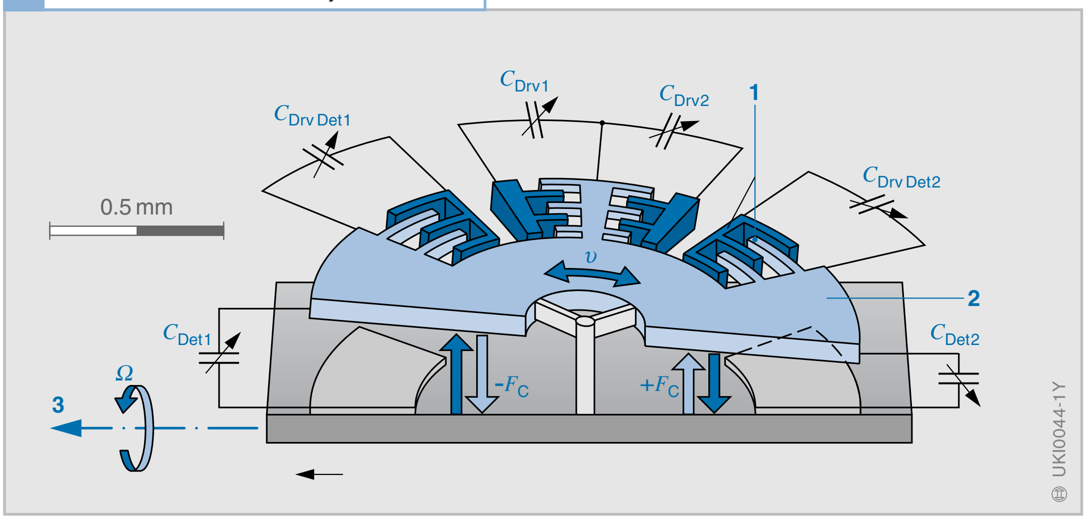

Fig. 3
1 Comb-like structure
2 Rotary oscillator
3 Measuring axis
C_{Drv} Drive electrodes
C_{Det} Capactive pick-off
F_C Coriolis force
υ Oscillatory velocity
$\Omega = \Delta C_{Det}$, measured yaw rate

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Acceleration sensors and vibration sensors

Measured variables

Acceleration and vibration sensors are suitable for IC-engine knock control, as well as for triggering passenger-protection and restraint systems (airbag, seat-belt tightener, roll-over bar), and for the registration of the acceleration in a bend and road-speed changes on 4-wheel-drive vehicles equipped with ABS or ESP or chassis control.

Acceleration a is the measured quantity, and is often given as a multiple of the acceleration of free fall g ($1g = 9.81\ \text{m/s}^2$). Typical values encountered in automotive engineering are given in Table 1.

Table 1

1 Acceleration and vibration sensors	
Application	**Measuring range**
Knock control	1 ... 10 g
Passenger-restraint and protection:	
– Airbag, seat-belt tightener	50 g
– Roll-over bar	4 g
– Seat-belt locking	0.4 g
ABS, ESP	0.8...1.2 g
Chassis control:	
– Body/superstructure	1 g
– Axle	10 g

Measuring principles

In principle, all acceleration sensors measure according to the basic law of mechanics: The force F applied to an inert mass m due to the acceleration a, irrespective of whether it is dynamic (vibration sensors) or static:

$$F = m \cdot a \qquad (1)$$

Here, similar to force measurement, systems are available which measure displacement or travel, as well as mechanical strain-measurement systems.

Displacement or travel-measuring systems

Such systems (Fig. 1), are used in particular in applications concerning very low levels of acceleration. They also permit the use of the *compensation method* in which the system excursion caused by acceleration is compensated for by an equivalent restoring force so that ideally the system practically always operates very close to the restoring-force zero point (high linearity, minimum cross sensitivity, high temperature stability).

Due to their closed-loop control, these closed-loop position-controlled systems (Fig. 1b) feature higher stability and have a higher limit frequency than their "excursion"-measuring counterparts (Fig. 1a).

1 Displacement or travel-measuring acceleration sensors

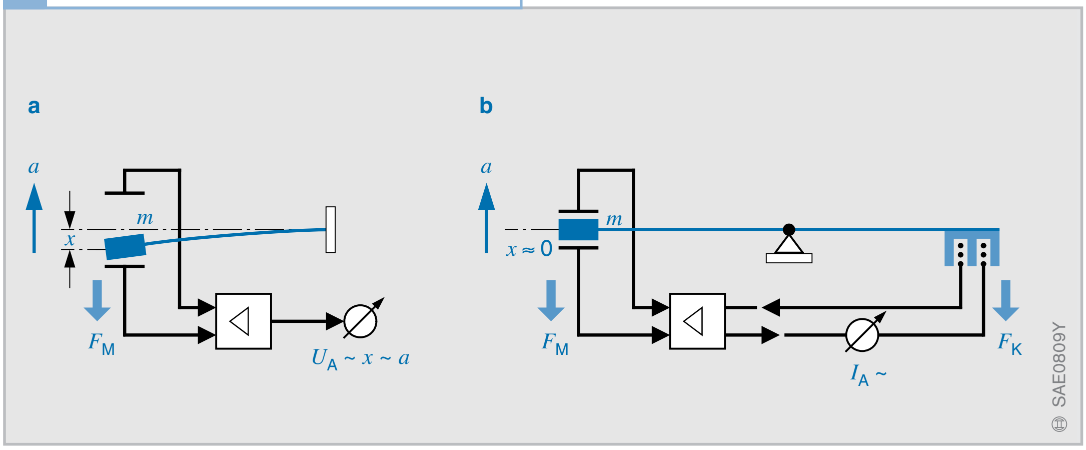

Fig. 1
Schematic:
a Excursion-measuring
b Closed-loop position controlled

a Measured acceleration
x System excursion
F_M Measuring force (inertial force on the mass m)
F_K Compensating force
I_A Output current
U_A Output voltage

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On all acceleration sensors, with the exception of the gravity pendelum, the inert mass is attached flexibly to the body whose acceleration is to be measured. This means that in the static case, the acceleration force is in equilibrium with the restoring force applied to the spring which has been deflected by x:

$$F = m \cdot a = c \cdot x \qquad (2)$$

where
c is the spring constant.

The system's measurement sensitivity S is therefore:

$$S = x/a = m/c \qquad (3)$$

This indicates that a large mass together with low spring stiffness (or constant) result in high measurement sensitivity. If however, Equation 2 is written in full for the static and for the dynamic case, then it becomes apparent that not only the spring's elasticity must be taken into account but also a friction force and an inertial force. These are proportional to the derivations with respect to time of the excursion x (p friction coefficient).

The resulting equation (4) defines a (resonant) system capable of oscillation:

$$F = m \cdot a = c \cdot x + p \cdot \dot{x} + m\ddot{x} \qquad (4)$$

Presuming negligible friction ($p \approx 0$), this system has a resonant frequency of:

$$\omega_0 = \sqrt{\frac{c}{m}} \qquad (5)$$

This means that in accordance with Equation 3, the measuring sensitivity S is directly linked to the resonant frequency ω_0 in the following manner:

$$S \cdot {\omega_0}^2 = 1 \qquad (6)$$

In other words, it can be expected that sensitivity drops by factor 4 when the resonant frequency is increased by a factor of 2. Of course, it is only below their resonant frequency that such spring-mass systems display adequate proportionality between measured quantity and excursion.

In addition to closed-loop position control, there is another method which can be applied in overcoming the invariable interdependence between measuring sensitivity and bandwidth as defined in Equation 6. This is taken from Equation 4 and can be successfully applied up to at least the system's first harmonic ($2\omega_0$):

Friction and inertia terms can be derived from the excursion term $(c \cdot x)$. If, mathematically, these are added to the excursion term, the resulting sum is a precise measure for the acceleration being measured a – independent of the effects of resonance and damping.

In order to achieve a frequency response which is as constant as possible, and to avoid a disturbing increase of resonant frequency (which can easily lead to system destruction), *damping* is needed which is to be defined as precisely as possible and independent of temperature. If the friction coefficient p is normalized to the other parameters in Equation 4, this results in a standard damping factor D:

$$D = \frac{p}{2 \cdot c} \cdot \omega_0 = \frac{p}{2 \cdot \sqrt{c \cdot m}} \qquad (7)$$

2 Resonance curves for the transfer function G

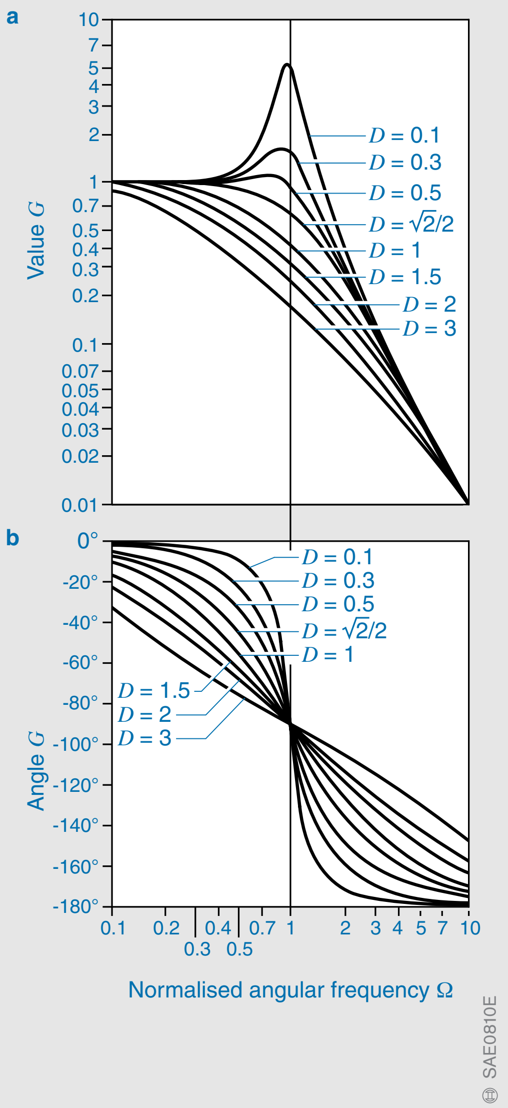

Fig. 2
a Amplitude resonance curve
b Phase resonance curve of the complex transfer function $\underline{G}(i \cdot \Omega) = [\underline{x}(i \cdot \Omega)]/[\underline{a}(i \cdot \Omega)]$
$\underline{x}(i \cdot \Omega)$ Deflection amplitude
$\underline{a}(i \cdot \Omega)$ Acceleration excitement amplitude
$\Omega = \omega/\omega_0$ Normalised angular frequency
D Damping

To a great extent, transient response and resonant response are defined by this damping factor. Whereas with periodic excitation, for damping $D > 1/\sqrt{2} = 0.707$, no resonance sharpness results, for values $D > 1$ all oscillating transient response has already disappeared in case of jump excitation. In order to achieve a bandwidth which is as broad as possible, a compromise is usually applied in practice with values of $D = 0.5...0.7$ (Fig. 2).

Compared to the extremely temperature-dependent damping as exhibited by silicone/oil mixtures, air damping using an air gap has proved itself in practice since it has only a very low level of temperature sensitivity. Electrodynamic damping (permanent magnet and conductor plate) has proved to be equally good, but is considerably more expensive and voluminous.

In the case of position-controlled systems, damping can be implemented and adjusted in the electronic (closed-loop) control circuit. Since in operation their deflection is in any case practically zero, in the switched-off, non-damped state, these systems are usually protected with "tight" overload stops to protect them against damage.

Packaging

Similar to the majority of sensors on the market, the so-called "packaging" which is tailor made to suit each individual application, also plays a decisive role for acceleration sensors. Since inertia-type sensors register the measured quantity without any form of movable connection to the outside

Table 2

2 Acceleration sensors (listed according to electrical pick-off and spring-mass system)

Electrical pick-off	**Spring-mass system**					
	Ceramic		Metal		Silicon	
	Piezoelectric	Insulating	Steel	CuBe	Bulk	OMM [1]
Voltage measurement						
Piezoresistive (DMS)						
Piezoelectric	X					
Travel measurement						
Hall			X			
Capacitive						X

(X) Actually in production. [1]) OMM = Surface micromechanics. Under consideration.

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world, it is no problem to encapsulate them hermetically. They need a suitable rigid mechanical coupling to attach them to the structure at which measurement takes place, otherwise flexible or loose elements could lead to falsification of the measurement. On the other hand, this rigid, fixed coupling must not lead to thermal expansion which may occur at the structure being transferred to the sensor so that measurements are falsified.

Table 2 is arranged according to different spring-mass systems and electrical pick-offs. It presents a systematic overview of the possibility of implementing various sensors. The combinations have been marked to indicate either those which are already actually in production and which will be dealt with in more detail in the following (X), or those which are already being closely considered for production (marked in blue):

Often, the spring's own mass is adequate as the seismic mass for achieving adequate measurement sensitivity. If this is not the case, mass must be added (usually of the same material, or in metallic form).

The present-day trend is definitely towards minimum-dimension sensors using *Si-OMM technologies and capacitive signal take-off*. Not least thanks to hermetic encapsulation, this form of pick-off is practically only influenced by the sensor's geometrical parameters and is therefore unaffected by such other material constants and influencing variables as temperature etc. The local electronic circuitry, without which operation is impossible, also provides effective protection against electromagnetic interference (EMC). The threat of damage due to electromagnetic interference, which is common to this type of pick-off, is effectively counteracted by the local electronic circuitry.

Although the measurement capacities which can be generated here are extremely small, the variations that can be achieved due to the effects of acceleration are typically as much as about ±25 %. Further advantages of this technology are its comparatively low current consumption, and the possibility of designing the system as a closed-loop position-controlled system by feeding in electrostatic forces (at the measuring electrodes or at an additional electrode pair).

Systems for measuring mechanical strain and stress

Whereas all other forms of pick-off listed in Table 2, have already been dealt with, *piezoelectric pick-ups* in the vehicle (apart from the piezoelectric yaw-rate sensors) are only used in acceleration sensors. This measuring principle will therefore be discussed here in more detail.

When subjected to mechanical strain/stress which has been caused by outside forces F (Fig. 3), charges Q are generated on the surface of piezoelectric materials provided with electrodes. Crystalline material samples (e.g. quartz crystal) display this feature naturally. Artificially produced materials, on the other hand, such as piezoceramic must first of all be polarized with a strong electric field.

Similar to the magnetic materials, this piezoelectric effect is also subjected to a "Curie temperature" above which the phenomenon disappears completely. For crystals this is reversible, but not for piezoceramic materials. With piezoceramics this so-called "depolarisation" can be caused by intense mechanical

3 Piezoelectric effect

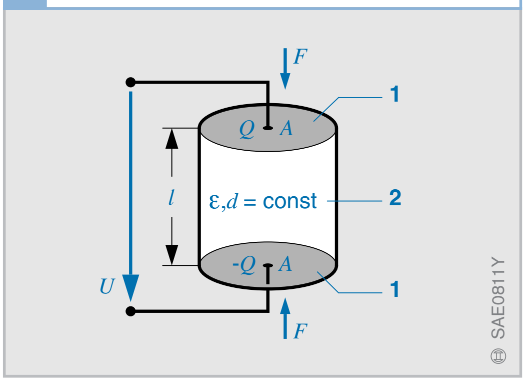

Fig. 3
1 Electrodes
2 Piezoelectric material sample
l Length
A Cross-setional area of the sample
F Force
Q Charge
U Voltage
ε Dielectric coefficient
d Piezoelectric charge coefficient

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shock which casues the crystallites in the material to return to their original random positioning.

Whereas the Curie temperature for conventional ceramics is approx. 340 °C, on special quartz sections it can extend to as high as 440 °C. With ceramics, in order to avoid depolaristion during operation the operating temperature must remain a considerable distance from the Curie temperature. On conventional ceramics, this temperature limit is approx. 160 °C.

Not only cemamics, but also special very thin plastic foils also demonstrate piezoelectric characteristics. In contrast to crystalline materials, the man-made piezo materials, which are only used in automotive applications, can be produced very cheaply. On the other hand though, their measurement characteristics (temperature sensitivity, hysteresis, resistance to aging, sensitivity scatter, internal resistance, etc.) are considerably inferior to those of the crystalline materials. Practically all man-made materials demonstrate a very marked, and usually undesirable, pyroelectric effect. Due to this effect, temperature changes generate charges on these materials which are superimposed on the charges generated due to mechanical force.

The generated charges though do not remain the whole time force is applied, but are discharged through the external resistance of the measuring circuit or through the piezo sensor’s internal resistance. The time constant of this discharge is the product of the sensor capacity and the effective total resistance. Such sensors cannot measure statically, and are only used where *dynamic* measurement is needed. Whereas high-performance pick-ups can achieve quasi-static measuring times of approx. 15...60 min, maximum measuring times for ceramics are often in the range of only about 1 s ... 1 ms.

The "piezoelectric charge coefficient d" (sometimes referred to as "piezomodule K"), is mainly responsible for the electrical behaviour of these sensors. In the simplest case, taking σ to be the mechanical tension applied during the test, and D to be the dielectric displacement density, the following relationship applies:

$$\sigma = F/A \quad (1) \qquad \text{und} \qquad D = d \cdot \sigma \quad (2)$$

Using the dielectric coefficients
$\varepsilon = \varepsilon_r \cdot \varepsilon_0$
the charge Q and the voltage U at the sensor electrodes can be calculated as follows:

$$Q = A \cdot D = A \cdot d \cdot \sigma = d \cdot F \qquad (3)$$

$$U = \frac{Q}{c} = \frac{d \cdot F}{\varepsilon \cdot A} \cdot L = \frac{d}{\varepsilon} \cdot \frac{L}{A} \cdot F \qquad (4)$$

$$= g \cdot \frac{L}{A} \cdot F = g \cdot L \cdot \sigma$$

with the piezoelectric voltage coefficient
$g = d/\varepsilon$ (5)
and an electric field strength in the test sample
$E = U/L = g \cdot \sigma$ (6)

4 Types of piezoelectric effects

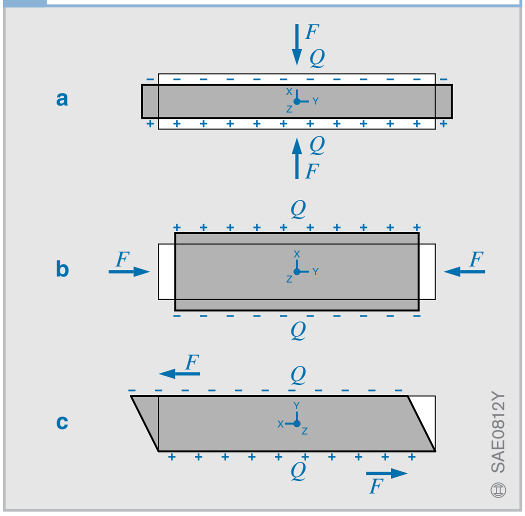

Fig. 4
- a Longitudinal effect
- b Transverse effect
- c Tangential force
- F Force
- Q Charge

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In addition to the often-used *longitudinal* piezoelectric effect, *transverse and tangential* effects must also be considered (Fig. 4).

Depending upon the material used, these effects can occur singly or, as is often the case in practice all together. If Equation 2 is formulated as a tensor equation this fully defines all the above-named piezoelectric effects.

The *transverse effect* is used for example in "bimorphous plates". These are composed of two oppositely polarised piezoceramic plates joined together and used for the measurement of bending stresses. When the two-layer ceramic composite bends, one half is stretched ($\varepsilon > 0$) and the other compressed ($\varepsilon < 0$). The opposed-polarity of the ceramic plates means that the resulting part voltages U_1 and U_2 now add to form a total voltage U which can be picked-off across the two outside metal layers (Fig. 5). In principle, metallisation is not needed between the two ceramic plates. Bimorphous strips measure their own bending movement, but if they are glued or soldered to a metal diaphragm they also register the diaphragm's deformation (for instance the microphone).

Electrical signal evaluation

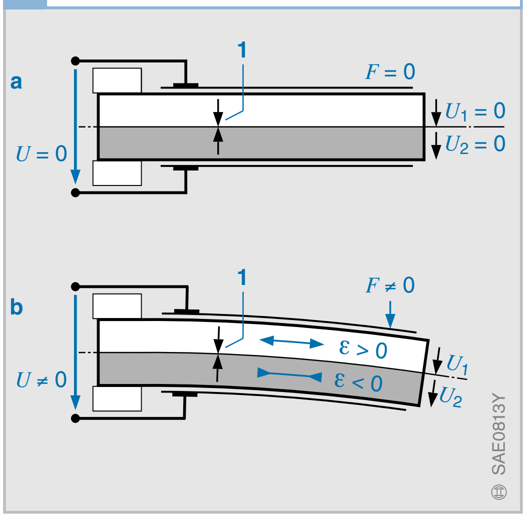
Voltage pick-off: Since piezoelectric sensors feature a high internal resistance, when registering their output voltage U it is recommended that a decoupling amplifier is installed as near as possible to the sensor (if practical, inside a hermetically sealed housing together with the sensor). With long feed lines, the parasitic capacity (voltage divider) and the parastic equivalent resistance falsify the signal (Fig. 6a).

Charge pick-off: With piezoelectric sensors, it is advisable to use a charge amplifier which stores the charge generated by the sensor in a high-precision measuring capacitor C_M and in doing so keeps the sensor itself free of charge and voltage. With this type of signal evaluation, the harmful parasitic influences of a feed line are for the most part suppressed, so that it is not absolutely necessary to integrate the sensor and the amplifier (Fig. 6b).

Examples of application

- Hall-effect acceleration sensors,
- Piezoelectric acceleration sensors (bimorphous bending elements, longitudinal elements such as knock sensors),
- Micromechanical acceleration sensors.

5 Piezoelectric bimorphous plates



6 Pick-off on piezoelectric sensors

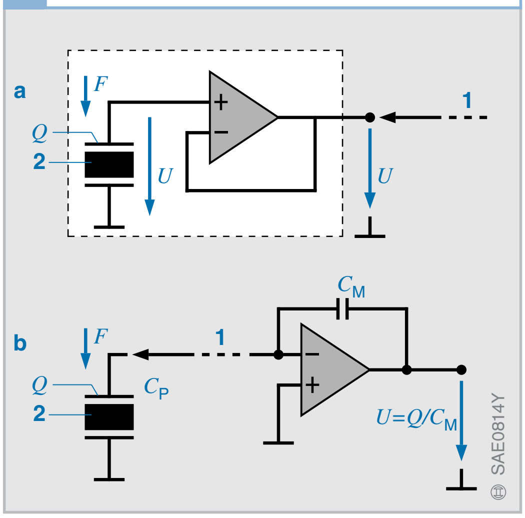


Fig. 5

- a Non-active state
- b Bent state, upper plate expanded ($\varepsilon > 0$), lower plate compressed ($\varepsilon < 0$)
- 1 Direction of polarisation
- F Measuring force
- U Total voltage
- U_1, U_2 Part voltages

Fig. 6

- a Voltage pick-off
- b Charge pick-off
- 1 Feed line
- 2 Piezoelectric sample with capacity C_P
- C_M Measuring capacity
- F Measuring force
- Q Charge
- U Voltage

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Hall-effect acceleration sensors

Applications

Vehicles equipped with the Antilock Braking System ABS, the Traction Control System TCS, all-wheel drive, and/or Electronic Stability Program ESP, also have a Hall-effect acceleration sensor in addition to the wheel-speed sensors. This measures the vehicle's longitudinal and transverse accelerations (depending upon installation position referred to the direction of travel).

Design and construction

A resiliently mounted spring-mass system is used in the Hall-effect acceleration sensors (Figs. 1 and 2).

It comprises an edgewise-mounted strip spring (3) tightly clamped at one end. Attached to its other end is a permanent magnet (2) which acts as the seismic mass. The actual Hall-effect sensor (1) is located above the permanent magnet together with the evaluation electronics. There is a small copper damping plate (4) underneath the magnet.

Operating concept

When the sensor is subjected to acceleration which is lateral to the spring, the spring-mass system changes its neutral position accordingly. Its deflection is a measure for the acceleration. The magnetic flux F from the moving magnet generates a Hall voltage U_H in the Hall-effect sensor. The output voltage U_A from the evaluation circuit is derived from this Hall voltage and climbs linearly along with acceleration (Fig. 3, measuring range approx. 1 g).

This sensor is designed for a narrow bandwidth of several Hz and is electrodynamically damped.

1 Hall-effect acceleration sensor (opened)

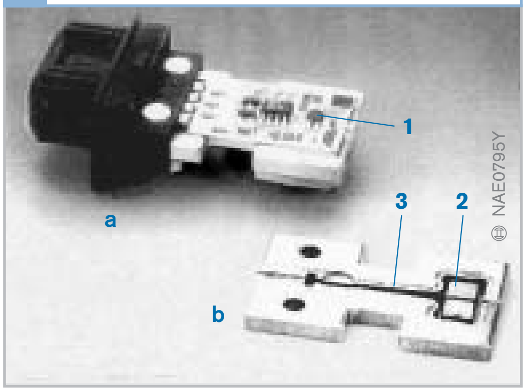


Fig. 1
a Electronic circuitry
b Spring-mass system
1 Hall-effect sensor
2 Permanent magnet
3 Spring

2 Hall-effect acceleration sensor

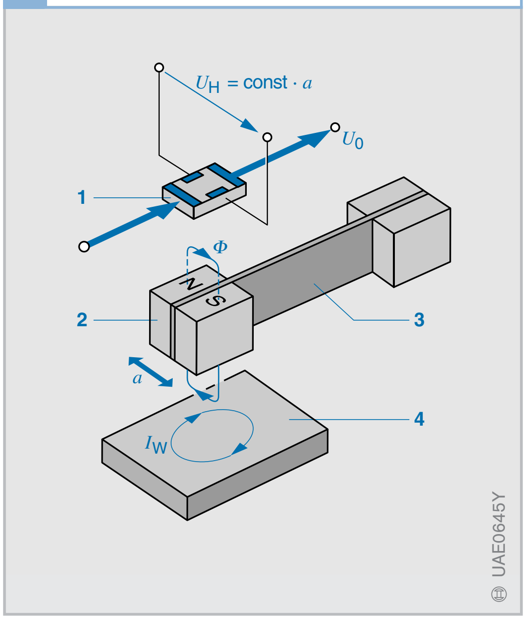
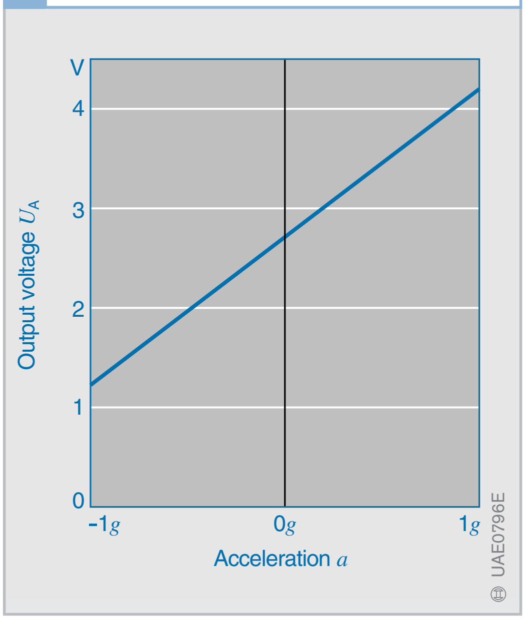


Fig. 2
1 Hall-effect sensor
2 Permanent magnet
3 Spring
4 Damping plate
I_W Eddy currents (damping)
U_H Hall voltage
U_0 Supply voltage
Φ Magnetic flux
a Applied (transverse) acceleration

3 Hall-effect acceleration sensor (example of curve)



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Micromechanical bulk silicon acceleration sensors

Application

Micromechanical bulk silicon acceleration sensors are used in passsenger-restraint systems to register the acceleration values of a frontal or side collision. They serve to trigger the seatbelt tightener, the airbag, and the roll-over bar.

Design and operating concept

Anisotropic and selective etching techniques are used to form the required spring-mass system from the solid wafer (bulk silicon micromechanics), and to shape the spring shoulders. Capacitive pick-offs have proved themselves for the correct measurement of the mass deflection. They require a wafer-thick silicon or glass plate with counterelectrodes (1, 4), on each side of the spring-held mass (Fig. 1, pos. 2), thus forming a triplex construction. Here, the plates with the counter-electrodes also act as an overload protection.

This plate configuration corresponds to a series circuit with two differential capacitors $C_{1\text{–}2}$ and $C_{2\text{–}4}$ (structure capacities 10... 20 pF). Opposed-phase AC voltages are applied across their terminals, and their superimpositions picked-off between the capacitors at C_M (measurement capacity), in other words at the Si center plate (seismic mass).

1 Bulk silicon acceleration sensor with capacitive pick-off

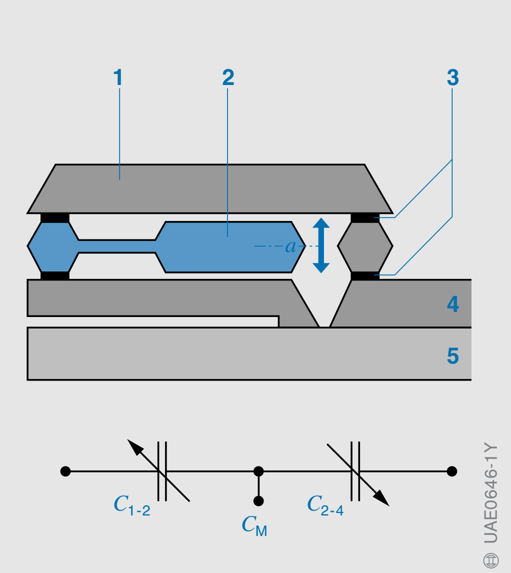

Fig. 1
1 Upper Si plate
2 Center Si plate (seismic mass)
3 Si-oxide
4 Bottom Si plate
5 Glass substrate
a Accelartion in the sensing direction
C_M Measurement capacity

When acceleration a is applied in the sensing direction, the Si center plate (the seismic mass) is caused to deflect. This causes a change in the spacing to the upper and/or lower plate, and with it a capacitance change in the capacitors $C_{1\text{–}2}$ and $C_{2\text{–}4}$ which leads to a change in the electrical signal. In the evaluation electronics circuit (CMOS), this change is amplified, and then filtered and digitalised ready for further signal processing in the airbag ECU.

Filling the sensor's hermetically sealed oscillatory system with a precisely metered charge of air leads to a very space-saving, inexpensive form of damping which also exhibits low temperature sensitivity. Today, almost without exception, the three silicon plates are connected together using the "fusion-bonding process". Due to the differences in the expansion due to temperature, the oscillatory system's attachment to the housing base also has a decisive effect on measuring accuracy. Connection to the housing base is therefore practically in a straight-line, and the oscillatory system is unsupported in the sensitive areas.

This type of sensor is above all used in the low acceleration ranges (< 2 g) and necessitates a 2-chip concept:
Sensor chip + CMOS evaluation chip with integral protective function.

The change-over to expanded signal evaluation leads to the seismic mass automatically returning to the zero position, whereby the actuating signal appears as an output quantity.

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Surface micromechanical acceleration sensors

Application

Surface micromechanical acceleration sensors are used in passenger-restraint systems to register the acceleration values of a frontal or side collision. They serve to trigger the seatbelt tightener, the airbag, and the rollover bar.

Design and operating concept

Although these sensors were initially intended for use with higher accelerations (50...100 g), they also operate with lower acceleration figures when used in passenger-restraint systems. They are much smaller than the bulk silicon sensors (typical edge length: approx. 100...500 µm), and are mounted together with their evaluation electronics (ASIC) in a waterproof casing (Fig. 1). An additive process is used to build up their spring-mass system on the surface of the silicon wafer.

The seismic mass with its comb-like electrodes (Figs. 2 and 3, pos. 1) is spring-mounted in the measuring cell. There are fixed comb-like electrodes (3, 6) on the chip on each side of these movable electrodes. This configuration comprising fixed amd movable electrodes corresponds to a series circuit comprising two differential capacitors (capacity of the comb-like structure: approx. 1 pF). Opposed-phase AC voltages are applied across the terminals C_1 and C_2, and their superimpositions picked-off between the capacitors at C_M (measurement capacity), in other words at the seismic mass.

Since the seismic mass is spring-mounted (2), linear acceleration in the sensing direction results in a change of the spacing between the fixed and movable electrodes, and therefore also to a change in the capacity of C_1 and C_2 which in turn causes the electrical signal to change. In the evaluation electronics circuit, this change is amplified, and then filtered and digitalised ready for further signal processing in the airbag ECU. Due to the low capacity of approx. 1 pF, the evaluation electronics is situated at the sensor and is

1 Surface micromechanical acceleration sensors for airbag triggering (Example)

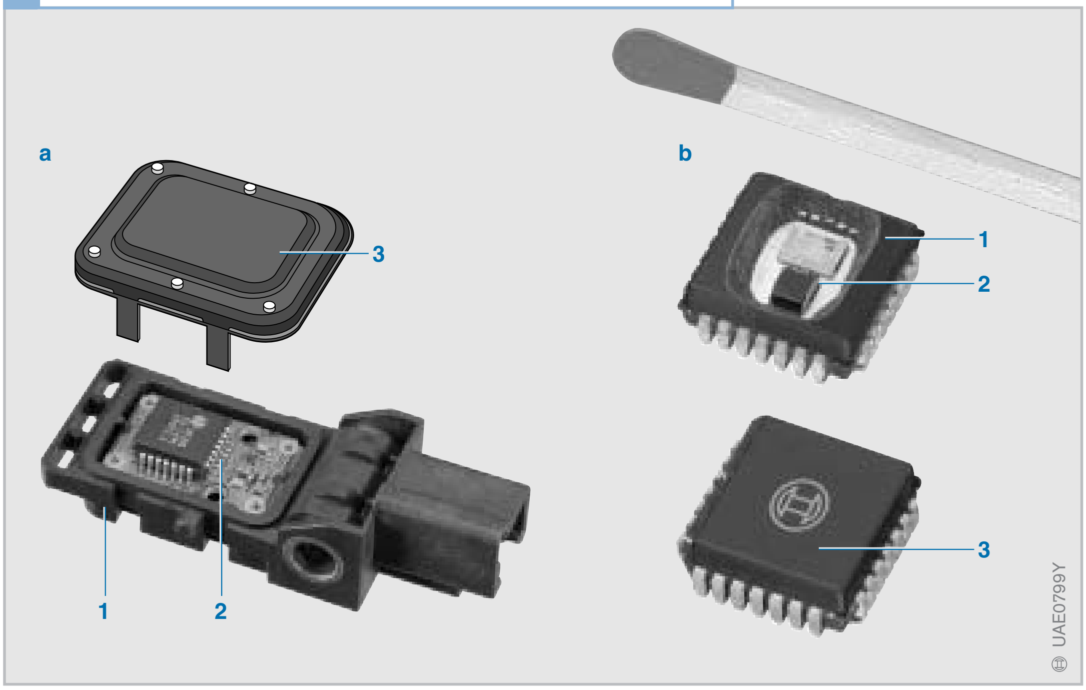

Fig. 1
a Side-airbag sensor
b Front-airbag sensor
1 Casing
2 Sensor and evaluation chip
3 Cover

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either integrated with the sensor on the same chip, or is located very close to it. Closed-loop position controls with electrostatic return are also available.

The evaluation circuit incorporates functions for sensor-deviation compensation and for self-diagnosis during the sensor start-up phase. During self-diagnosis, electrostatic forces are applied to deflect the comb-like structure and simulate the processes which take place during acceleration in the vehicle.

Dual micromechanical sensors (4) are used for instance in the ESP Electronic Stability Program for vehicle dynamics control: Basically, these consist of two individual sensors, whereby a micromechanical yaw-rate sensor and a micromechanical acceleration sensor are combined to form a single unit. This reduces the number of individual components and signal lines, as well as requiring less room and less attachment hardware in the vehicle.

2 Comb-like structure of the sensor measuring element

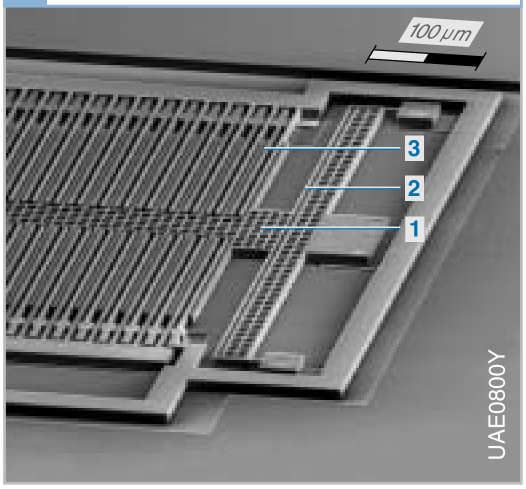

Fig. 2
1 Spring-mounted seismic mass with electrode
2 Spring
3 Fixed electrodes

4 Lateral-acceleration sensor combined with yaw-rate sensor (dual sensor)

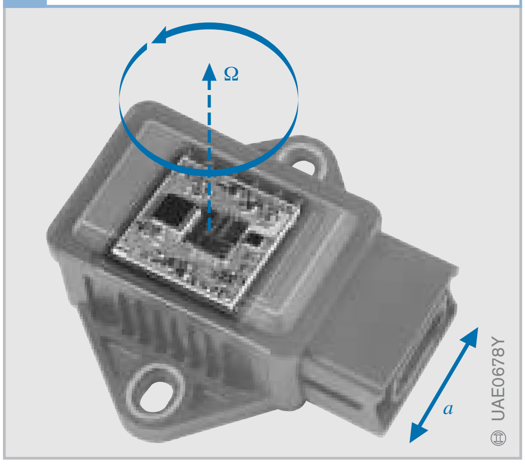

Fig. 4
a Acceleration in sensing direction
Ω Yaw rate

3 Surface micromechanical acceleration sensor with capacitive pick-off

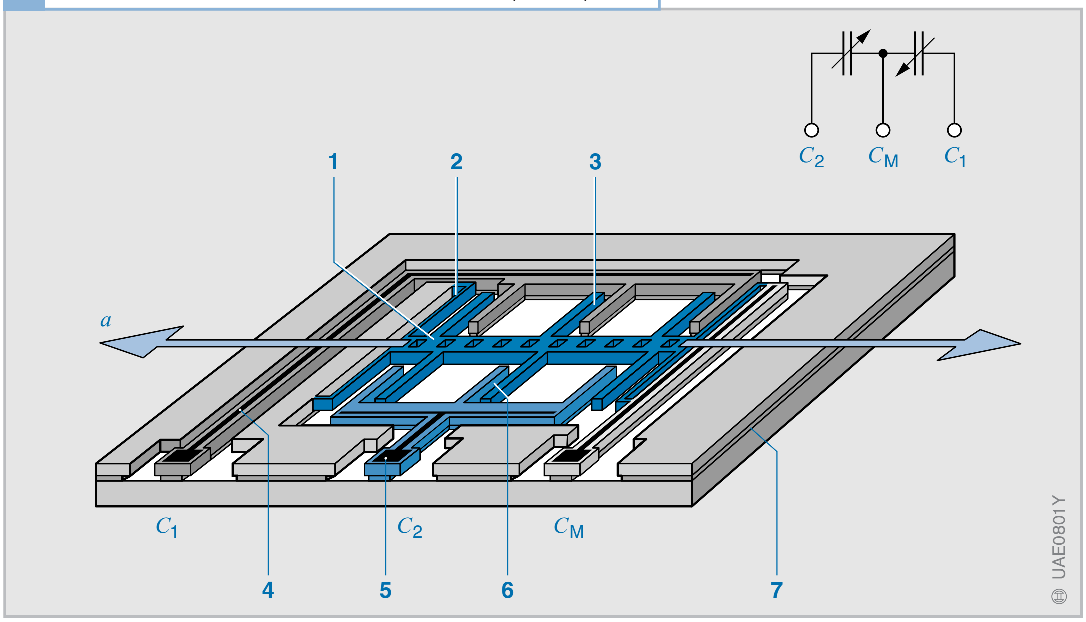

Fig. 3
1 Spring-mounted seismic mass with electrodes
2 Spring
3 Fixed electrodes with capacity C_1
4 Printed Al conductor
5 Bond pad
6 Fixed electrodes with capacity C_2
7 Silicon oxide
a Acceleration in sensing direction
C_M Measuring capacity

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Piezoelectric acceleration sensors

Application

Piezoelectric bimorphous bending elements and two-layer piezoceramic elements are used as acceleration sensors in passenger-restraint systems for triggering the seat-belt tighteners, the airbags, and the roll-over bar.

Design and operating concept

A piezo bending element is at the heart of this acceleration sensor. It is a bonded structure comprising two piezoelectric layers of opposite polarities ("bimorphous bending element"). When subjected to acceleration, one half of this structure bends and the other compresses, so that a mechanical bending stress results (Fig. 1).

The voltage resulting from the element bend is picked off at the electrodes attached to the sensor element's outside metallised surfaces.

The sensor element shares a hermetically-sealed housing with the initial signal-amplification stage, and is sometimes encased in gel for mechanical protection.

1 Bending element from a piezoelectric acceleration sensor

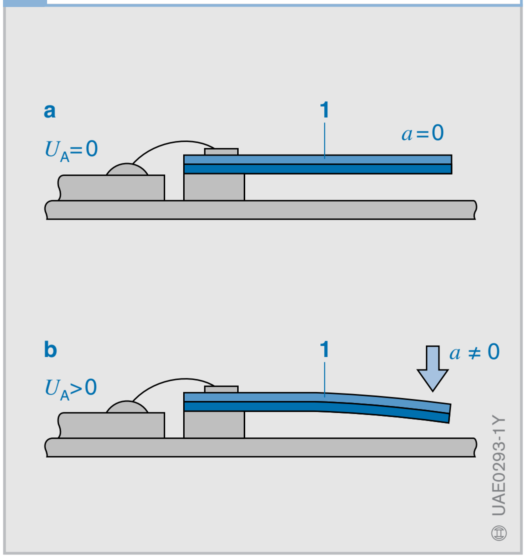

Fig. 1
a Not subject to acceleration
b Subject to acceleration a
1 Piezoceramic bimorphous bending element
U_A Measurement voltage

2 Piezoelectric acceleration sensor (dual sensor for vertical mounting)

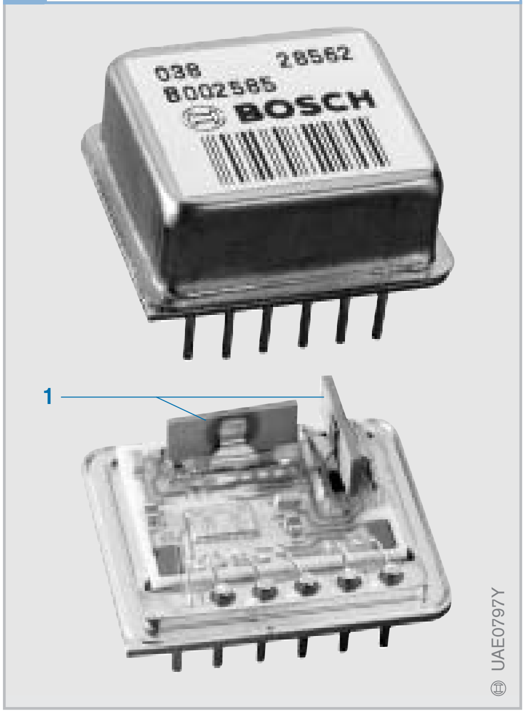

Fig. 2
1 Bending element

For signal conditioning, the acceleration sensor is provided with a hybrid circuit comprised of an impedance converter, a filter, and an amplifier. This serves to define the sensitivity and useful frequency range. The filter suppresses the high-frequency signal components. When subjected to acceleration, the piezo bending elements deflect to such an extent due to their own mass that they generate a dynamic, easy-to-evaluate non-DC signal with a maximum frequency which is typically 10 Hz.

By "reversing" the actuator principle and applying voltage, the sensor's correct operation can be checked within the framework of OBD "on-board diagnosis". All that is required is an additional actuator electrode.

Depending upon installation position and direction of acceleration, there are single or dual sensors available (Fig. 2). Sensors are also on the market which are designed specifically for vertical or horizontal mounting (Fig. 2).

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Piezoelectric knock sensors

Application

Regarding their principle of functioning, knock sensors are basically vibration sensors and are suitable for detecting structure-borne acoustic oscillations. These occur as "knock" for instance in a vehicle engine when uncontrolled ignition takes place, and are converted into electrical signals by the sensor and inputted to the ECU. As a rule, 4-cylinder in-line engines are equipped with *one* knock sensor; 5 and 6-cylinder engines, with *two;* and 8 and 12-cylinder engines have *two or more.* They are switched in accordance with the ignition sequence.

Design and operating concept

Due to its inertia, a mass excited by a given oscillation or vibration exerts a compressive force on a toroidal piezoceramic element at the same frequency as the excitation oscillation. Inside the ceramic element, these compressive forces cause a charge transfer so that a voltage appears across the ceramic element's two outer faces which is picked-off by contact discs and inputted to the ECU for processing. Sensitivity is defined as the output voltage per unit of acceleration [mV/g].

1 Knock-sensor signal

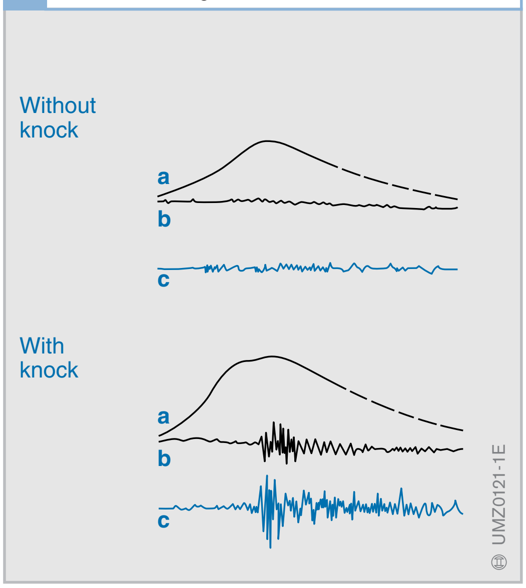

Fig. 1
- a Cylinder-pressure curve
- b Filtered pressure signal
- c Knock-sensor signal

2 Knock sensor (design and mounting)

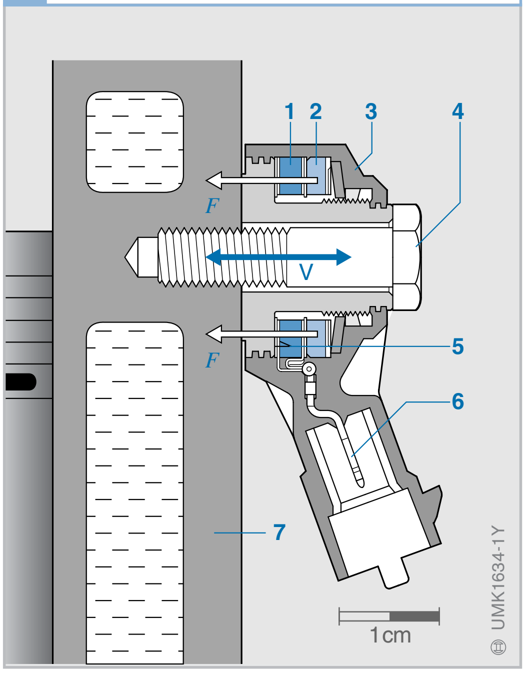

Fig. 2
- 1 Piezoceramic element
- 2 Seismic mass with compressive forces *F*
- 3 Housing
- 4 Fastening screw
- 5 Contact surface
- 6 Electrical connection
- 7 Cylinder block
- V Vibration

The sensor's voltage output is evaluated by a high-resistance AC amplifier in the ECU of the ignition or Motronic engine-management system (Figs. 1 and 2).

Mounting

Depending on the particular engine, the knock-sensor installation point is selected so that knock can be reliably detected from each cylinder. The sensor is usually screwed to the side of the engine-cylinder block. In order that the resulting signals (structure-borne oscillations) can be transferred from the measuring point on the engine block and into the sensor without resonant-frequency effects and in agreement with the stipulated characteristic curve, the following points must be observed:

- The fastening bolt must have been tightened with a defined torque,
- The sensor's contact surface and bore in the engine block must comply with certain quality requirements, and
- No washers of any type may be used.

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Pressure sensors

Measured variables

Pressure measurement takes place either directly, by way of diaphragm deformation, or using a force sensor. Examples of pressure measurement are given below:

- Intake-manifold pressure (1...5 bar) for gasoline injection,
- Braking pressure (10 bar) on electropneumatic brakes,
- Air-spring pressure (16 bar) on pneumatic-suspension vehicles,
- Tire pressure (5 bar absolute) for tire-pressure monitoring and tire-pressure closed-loop control,
- Hydraulic supply pressure (approx. 200 bar) for ABS and power-assisted steering,
- Shock-absorber pressure (+200 bar) for chassis-control systems,
- Coolant pressure (35 bar) for air-conditioning systems,
- Modulation pressure (35 bar) on automatic gearboxes,
- Braking pressure in master cylinder and wheel-brake cylinders (200 bar), and automatic yaw-moment compensation on the electronically-controlled brake,
- Overpressure/low pressure (0.5 bar) and OBD "On-Board Diagnosis",
- Combustion-chamber pressure (100 bar, dynamic) for detection of missfire and combustion knock,
- Element pressure on the diesel fuel-injection pump (1000 bar, dynamic) for EDC (Electronic Diesel Control),
- Fuel pressure on the diesel Common Rail System (1500 or 1800 bar), and
- Fuel pressure on the gasoline Common Rail System (100 bar).

1 Pressure measurement

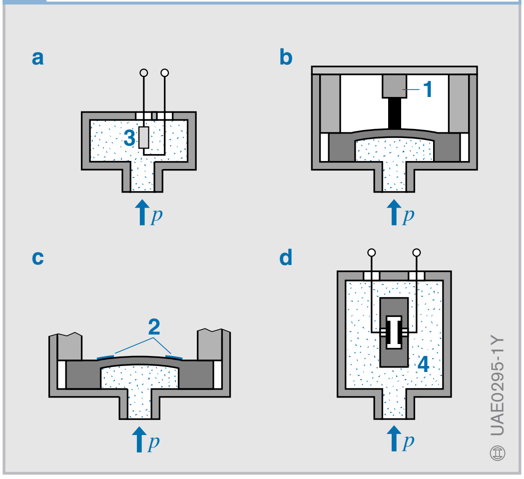

Fig. 1
a Direct measurement, pressure-dependent resistor (3)
b Measurement using a force sensor (1)
c Measuring the diaphragm deformation/ DMS (2)
d Capacitive measurement using the deformation of a diaphragm cell

Measuring principles

The measured variable "pressure" is a dynamic effect which occurs in gases and fluids and which is effective in all directions. It propagates well in fluids, and in gel-like substances and soft casting compounds, a fact which is sometimes taken advantage of for a number of reasons. There are static and dynamic pick-ups or sensors for the measurement of pressure.

The *dynamic* pressure sensors include for instance all microphones which, since they are insensitive to static pressures, are used to measure pressure oscillations in gaseous and/or liquid mediums.

Since up to now, practically only static sensors have been used in automotive engineering, these will be dealt with in more detail here.

Direct pressure measurement

Being as all resistors are more or less pressure-dependent (volumetric effect), when very high pressures (>10^4 bar) are to be measured it would suffice theoretically to simply subject an electrical resistor to the pressure medium. On the other hand, they are at the same time more or less temperature-dependent, a characteristic which it is usually very difficult to suppress. Furthermore, the sealed lead-out of their connections from the pressure medium presents difficulties. Encapsulated capacitive measuring modules have more favorable characteristics and, depending upon the particular application, are easier to manufacture.

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Diaphragm-type sensors

The most common method used for pressure measurement (also in automotive applications) uses a thin diaphragm as the intermediate stage. The pressure to be measured is first of all applied to one side of this diaphragm so that this bends to a greater or lesser degreee as a function of the pressure. Within a very wide range, its diameter and thickness can be adapted to the particular pressure range. Low-pressure measuring ranges lead to large diaphragms which can easily deform by as much as 1...0.1 mm. Higher pressures though demand thicker, low-diameter diaphrams which only deform very slightly by a few µm. In case (capacitive) pick-offs for spacing or distance measurements are also required, voltage-measuring methods dominate in the medium-pressure to high-pressure ranges. Here, practically only DMS techniques are used.

Capacitive pick-off

In contrast to their application in inertia sensors (see acceleration/yaw-rate sensors), capacitive pressure sensors are still only rarely encountered even though they could possibly provide similar advantages (particularly with respect to their accuracy). This is more than likely the result of one important difference compared to the other sensors dealt with above:

Pressure sensors need direct contact with the pressure medium, whose dieelectric characteristics practically always affect the calibration of such capacitive pressure sensors. This means that the calibration would then not only be dependent upon the medium in question, but would also be impossible without it (that is, in the "dry" state). Clear separation of the sensor from the pressure medium has up to now only been achieved at the cost of considerable technical outlay.

DMS[1]) pick-off

Table 1 presents a systematic overview of the proven pressure-measurement techniques which to a great extent have already been used in automotive applications. The list is arranged according to the type of diaphragm material and the applied DMS technology. Those combinations are marked which will be dealt with in the following as examples (x) or whose manufacture or purchase have been considered more closely (fields marked in blue):

Table 1

1 DMS pick-off and diaphragm material

DMS pick-off	Diaphragm material		
	Ceramic	Metal (steel)	Silicon
Foils [1]) (glued)			
Thick-film			
Metal thin-film		X	
Silicon thin-film		X	
Diffusion resistances			X

[1]) Unsuitable for large-batch production, x) Present-day examples ■ Under consideration

With regard to the particular measuring effect's magnitude and type, the DMS techniques listed above have widely varying characteristics. The gauge factor (K)defines the magnitude of the measuring effect of deformation resistors. It gives the relative change in such a resistor's resistance R referred to the relative change in its length l an (Equation 1):

$$K = \frac{\Delta R/R}{\Delta l/l} = 1 + 2 \cdot \upsilon + \frac{\mathrm{d}\rho/\rho}{\varepsilon}$$

Here, the symbol ε (expansion) is often inserted for the relationship $\Delta l/l$, and in multiples of 10^{-6} (ppm) as "micron" or "micro strain".

υ is the material's "transversal-contraction factor", and ρ is its electrical conductivity. υ characterises the reduction of cross-section area of the material upon elongation.

[1]) DMS = Strain gauge or strain-gauge resistor

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In the ideal case of constant volume, $\upsilon = 0.5$ (in reality, $\upsilon = 0.3...0.4$).

Whereas the conductivity term in Equation 1 is of hardly any importance in the case of metallic resistors, with regard to Si resistors it plays a dominant role.

One refers, incidentally, to a *longitudinal gauge factor* when the resistor is expanded in the direction of current and to a *transverse gauge factor* when it is expanded crosswise to the current direction (Fig. 2). Table 2 provides an overview of typical values for the most important gauge factors.

"Creep" (slight mechanical give under the effects of long-term unidirectional loading) is a highly-feared phenomenon which, when it occurs at all, is only encountered on glued foil-DMS. The other DMS techniques all apply non-glued techniques and are not affected by this phenomena.

To be precise, a diaphragm's deformation depends upon the difference in the pressure applied to its top and bottom sides. This means that there are four different basic pressure-sensor types (Table 3):

- Absolute pressure,
- Reference pressure,
- Barometric pressure, and
- Differential pressure.

2 Gauge factor, physical quantities

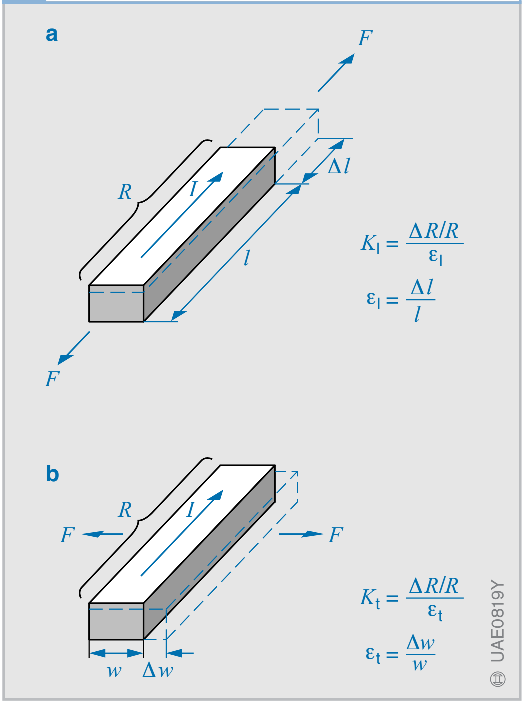

Fig. 2
a Longitudinal
b Transverse
F Force
I Current
R Resistance
l Length
w Width
ε Elongation
K Gauge factor

2 Gauge factors for different materials

Material	*Gauge factors* Longitudinal	Transverse
Foil DMS	1.6 ... 2.0	≈ 0
Thick film	12 ... 15	12 ... 15
Metal thin film	1.4 ... 2.0	–0.5 ... 0
Si thin film	25 ... 40	–25 ... –40
Si monocrystalline	100 ... 150	–100 ... –150

Table 2

3 Basic sensor types for pressure measurement

Pressure on diaphragm bottom side p_U	Pressure on diaphragm top side p_0 Measuring pressure	Ambient pressure	Vacuum
Measuring pressure	Difference pressure	Reference pressure	Absolute pressure
Ambient pressure	Reference pressure	–	Barometric pressure
Vacuum	Absolute pressure	Barometric pressure	–

Table 3

Transfer to a force sensor

Instead of directly using the force taken up by their diaphram, a number of sensors transfer it to a force sensor whose measuring range can remain constant due to the fact that the purely mechanical diaphragm has already performed the adaptation to the pressure-measuring range. Perfect linkage from measuring diaphragm to force sensor (for instance by a tappet) must be ensured though.

Examples of application

- Thick-film pressure sensors,
- Micromechanical pressure sensors,
- Si combustion-chamber pressure sensors, and
- Metal-diaphragm high-pressure sensors.

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Thick-film pressure sensors

Application

As an alternative to micromechanical pressure sensors, thick-film pressure sensors can sometimes be used (for instance in engine-management systems, M and ME Motronic). These are in the form of a module for installation in the ECU or a stand-alone component. They are used as:

- Manifold-pressure or boost-pressure sensor (pressure range 20...400 kPa or 0.2...4.0 bar), and
- Atmospheric-pressure sensor (pressure range 60...115 kPa or 0.6...1.15 bar).

Design and operating concept

The sensor is subdivided into a pressure-measuring cell and a chamber for the evaluation circuit. Both are arranged on a common ceramic substrate (Fig. 1).

The pressure-measuring cell (Fig. 2) comprises a "bubble-shaped" thick-film diaphragm which encloses a reference pressure of 0.1 bar. The diaphragm deforms as a function of the pressure being measured. There are four deformation resistors on the diaphragm which are connected to form a bridge circuit. Two of these active deformation resistors are located in the center of the diaphragm and change their conductivity when mechanical stress is applied (measured pressure). Two passive deformation resistors are situated on the diaphragm's periphery and function primarily as bridge resistors for temperature compensation. They have little effect upon the output signal.

When pressure is applied, the diaphragm deforms and changes the bridge-circuit balance. The bridge's measurement voltage U_M is therefore a measure of the measured pressure p (Fig. 3). The evaluation circuit amplifies the bridge voltage, compensates for the influence of temperature, and linearises the pressure curve. The evaluation circuit's output voltage U_A is inputted to the ECU.

1 Thick-film pressure sensor (for ECU installation)

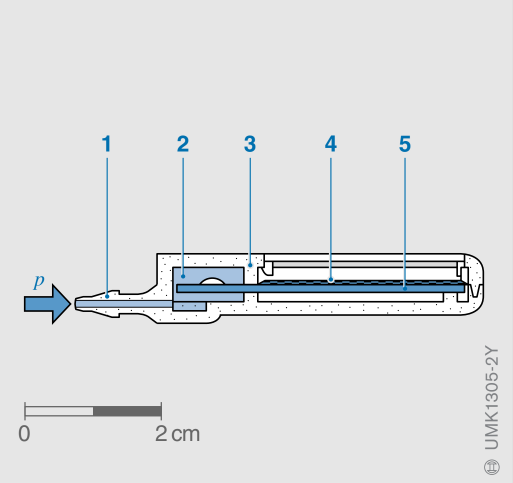

Fig. 1
Measuring range:
1 Pressure connection for the measured pressure p
2 Pressure-measuring cell
3 Sealing web
Signal conditioning:
4 Evaluation circuit
5 Thick-film hybrid on ceramic substrate

2 Thick-film pressure sensor (pressure-measuring cell)

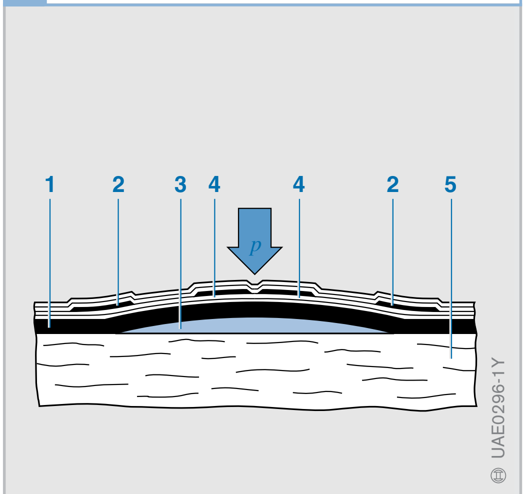

Fig. 2
1 Thick-film diaphragm
2 Passive reference deformation resistor
3 Reference-pressure chamber ("bubble")
4 Active deformation resistor
5 Ceramic substrate
p Measured pressure.

3 Thick-film pressure sensor (circuit)

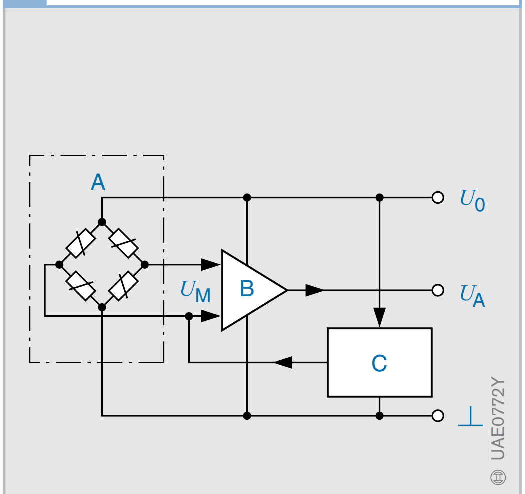

Fig. 3
A DMS pressure-measuring cell
B Amplifier
C Temperature-compensation circuit
U_0 Supply voltage
U_M Measured voltage
U_A Output voltage

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Micromechanical pressure sensors

Application

Manifold-pressure or boost-pressure sensor

This sensor measures the absolute pressure in the intake manifold between the supercharger and the engine (typically 250 kPa or 2.5 bar) and compares it with a reference vacuum, not with the ambient pressure. This enables the air mass to be precisely defined, and the boost pressure exactly controlled in accordance with engine requirements.

Atmospheric-pressure sensor

This sensor is also known as an ambient-pressure sensor and is incorporated in the ECU or fitted in the engine compartment. Its signal is used for the altitude-dependent correction of the setpoint values for the control loops. For instance, for the exhaust-gas recirculation (EGR) and for the boost-pressure control. This enables the differing densities of the surrounding air to be taken into account. The atmospheric-pressure sensor measures absolute pressure (60...115 kPa or 0.6...1.15 bar).

Oil and fuel-pressure sensor

Oil-pressure sensors are installed in the oil filter and measure the oil's absolute pressure. This information is needed so that engine loading can be determined as needed for the Service Display. The pressure range here is 50...1000 kPa or 0.5...10.0 bar. Due to its high resistance to media, the measuring element can also be used for pressure measurement in the fuel supply's low-pressure stage. It is installed on or in the fuel filter. Its signal serves for the monitoring of the fuel-filter contamination (measuring range: 20... 400 kPa or 0.2...4 bar).

Version with the reference vacuum on the component side

Design and construction

The measuring element is at the heart of the micromechanical pressure sensor. It is com-

1 Pressure-sensor measuring element with reference vacuum on the components side

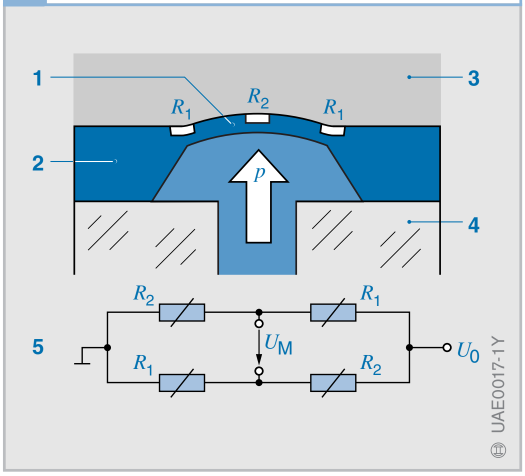


Fig. 1
1 Diaphragm
2 Silicon chip
3 Reference vacuum
4 Glass (Pyrex)
5 Bridge circuit
p Measured pressure
U_0 Supply voltage
U_M Measured voltage
R_1 Deformation resistor (compressed)
R_2 Deformation resistor (extended)

2 Pressure-sensor measuring element with cap and reference vacuum on the components side

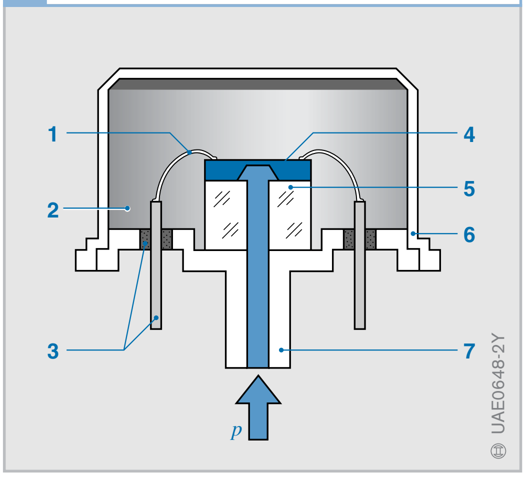
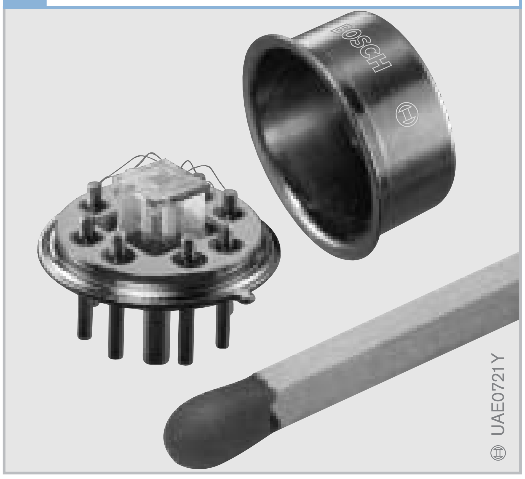


Fig. 2
1, 3 Electrical connections with glass-enclosed lead-in
2 Reference vacuum
4 Measuring element (chip) with evaluation electronics
5 Glass base
6 Cap
7 Input for measured pressure p

3 Pressure-sensor measuring element with cap and reference vacuum on the components side



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prised of a silicon chip (Fig. 1, Pos. 2) in which a thin diaphragm has been etched micromechanically (1). Four deformation resistors (R_1, R_2) are diffused on the diaphram. Their electrical resistance changes when mechanical force is applied. The measuring element is surrounded on the component side by a cap which at the same time encloses the reference vacuum (Figs. 2 and 3). The pressure-sensor case can also incorporate an integral *temperature sensor* (Fig. 4, Pos. 1) whose signals can be evaluated independently. This means that at any point a single sensor case suffices to measure temperature and pressure.

Method of operation

The sensor's diaphragm deforms more or less (10 … 1000 µm) according to the pressure being measured. The four deformation resistors on the diaphragm change their electrical resistances as a function of the mechanical stress resulting from the applied pressure (piezoresistive effect).

The four measuring resistors are arranged on the silicon chip so that when diaphragm deformation takes place, the resistance of two of them increases and that of the other two decreases. These deformation resistors form a Wheatstone bridge (Fig. 1, Pos. 5), and a change in their resistances leads to a change in the ratio of the voltages across them. This leads to a change in the measurement voltage U_M. This unamplified voltage is therefore a measure of the pressure applied to the diaphragm.

The measurement voltage is higher with a bridge circuit than would be the case when using an individual resistor. The Wheatstone bridge circuit thus permits a higher sensor sensitivity.

The component side of the sensor to which pressure is not supplied is subjected to a reference vacuum (Fig. 2, Pos. 2) so that it measures the absolute pressure.

The signal-conditioning electronics circuitry is integrated on the chip. Its assignment is to amplify the bridge voltage, compensate for temperature influences, and linearise the pressure curve. The output voltage is between 0...5 V and is connected through electrical terminals (Fig. 4, Pos. 5) to the engine-management ECU which uses this output voltage in calculating the pressure (Fig. 5).

4 Micromechanical pressure sensor with reference vacuum on the components side

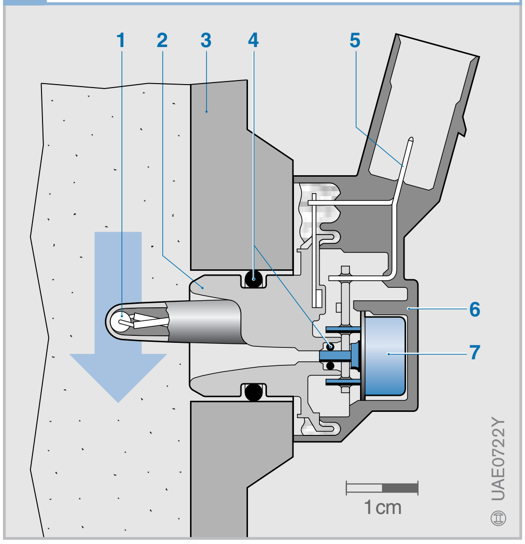
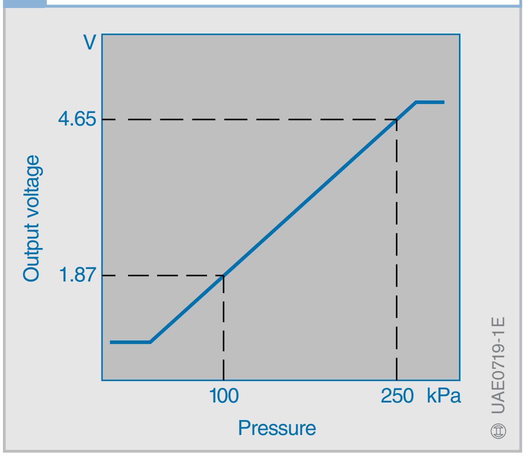


Fig. 4
1 Temperature sensor (NTC)
2 Lower section of case
3 Manifold wall
4 Seal rings
5 Electrical terminal (plug)
6 Case cover
7 Measuring element

5 Micromechanical boost-pressure sensor (example of curve)



Version with reference vacuum in special chamber

Design and construction

The *manifold or boost-pressure sensor* version with the reference vacuum in a special chamber (Figs. 6 and 7) is easier to install

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than the version with the reference vacuum on the components side of the sensor element. Similar to the pressure sensor with cap and reference vacuum on the components side of the sensor element, the sensor element here is formed from a silicon chip with four etched deformation resistors in a bridge circuit. It is attached to a glass base. In contrast to the sensor with the reference vacuum on the components side, there is no passage in the glass base through which the measured pressure can be applied to the sensor element. Instead, pressure is applied to the silicon chip from the side on which the evaluation electronics is situated. This means that a special gel must be used at this side of the sensor to protect it against environmental influences (Fig. 8, Pos. 1). The reference vacuum is enclosed in the chamber between the silicon chip (6) and the glass base (3). The complete measuring element is mounted on a ceramic hybrid (4) which incorporates the soldering surfaces for electrical contacting inside the sensor.

A *temperature sensor* can also be incorporated in the pressure-sensor case. It protrudes into the air flow, and can therefore respond to temperature changes with a minimum of delay (Fig. 6, Pos. 4).

Operating concept

The operating concept, and with it the signal conditioning and signal amplification together with the characteristic curve, corresponds to that used in the pressure sensor with cap and reference vacuum on the sensor's structure side.The only difference is that the measuring element's diaphragm is deformed in the opposite direction and therefore the deformation resistors are "bent" in the other direction.

6 Micromechanical pressure sensor with reference vacuum in a chamber

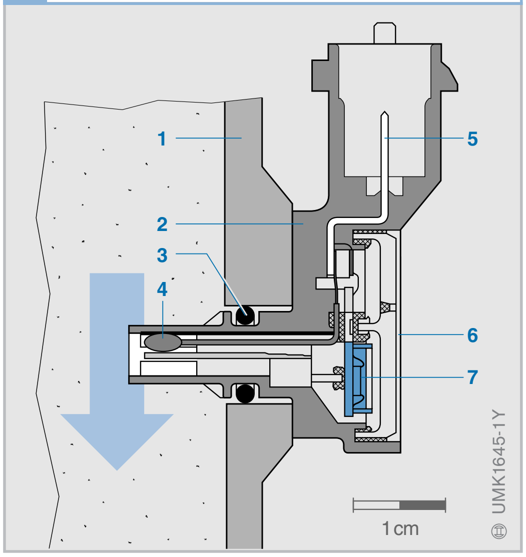

Fig. 6
1 Manifold wall
2 Case
3 Seal ring
4 Temperature sensor (NTC)
5 Electrical connection (socket)
6 Case cover
7 Measuring element

7 Micromechanical pressure sensor with reference vacuum in a chamber and temperature sensor

8 Measuring element of pressure sensor with reference vacuum in a chamber

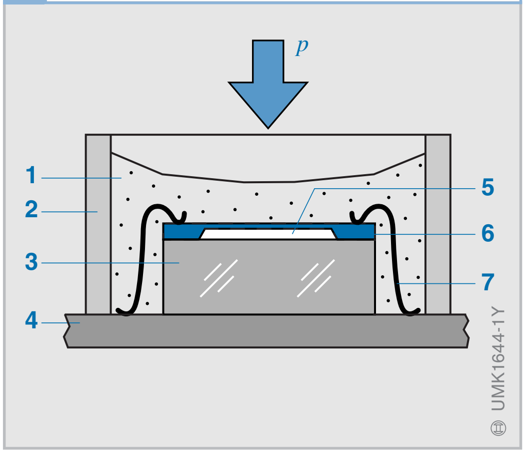

Fig. 8
1 Protective gel
2 Gel frame
3 Glass base
4 Ceramic hybrid
5 Chamber with reference volume
6 Measuring element (chip) with evaluation electronics
7 Bonded connection
p Measured pressure

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High-pressure sensors

Application

In automotive applications, high-pressure sensors are used for measuring the pressures of fuels and brake fluids.

Diesel rail-pressure sensor

In the diesel engine, the rail-pressure sensor measures the pressure in the fuel rail of the Common Rail accumulator-type injection system. Maximum operating (nominal) pressure p_{max} is 160 MPa (1600 bar). Fuel pressure is controlled by a closed control loop, and remains practically constant independent of load and engine speed. Any deviations from the setpont pressure are compensated for by a pressure control valve.

Gasoline rail-pressure sensor

As its name implies, this sensor measures the pressure in the fuel rail of the DI Motronic with gasoline direct injection. Pressure is a function of load and engine speed and is 5...12 MPa (50...120 bar), and is used as an actual (measured) value in the closed-loop rail-pressure control. The rpm and load-dependent setpoint value is stored in a map and is adjusted at the rail by a pressure control valve.

Brake-fluid pressure sensor

Installed in the hydraulic modulator of such driving-safety systems as ESP, this high-pressure sensor is used to measure the brake-fluid pressure which is usually 25 MPa (250 bar). Maximum pressure p_{max} can climb to as much as 35 MPa (350 bar). Pressure measurement and monitoring is triggered by the ECU which also evaluates the return signals.

Design and operating concept

The heart of the sensor is a steel diaphragm onto which deformation resistors have been vapor-deposited in the form of a bridge circuit (Fig. 1, Pos. 3). The sensor's pressure-measuring range depends upon the diaphragm's thickness (thicker diaphragms for higher pressures and thinner ones for lower pressures). When the pressure is applied via the pressure connection (4) to one of the diaphragm faces, the resistances of the bridge resistors change due to diaphragm deformation (approx. 20 µm at 1500 bar).

The 0...80 mV output voltage generated by the bridge is conducted to an evaluation circuit which amplifies it to 0...5 V. This is used as the input to the ECU which refers to a stored characteristic curve in calculating the pressure (Fig. 2).

1 High-pressure sensor

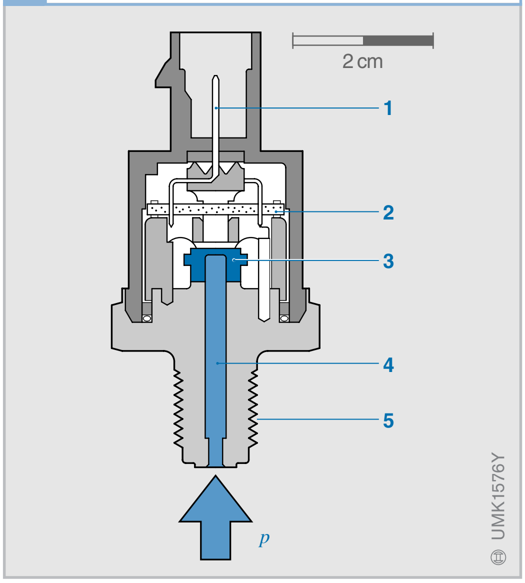
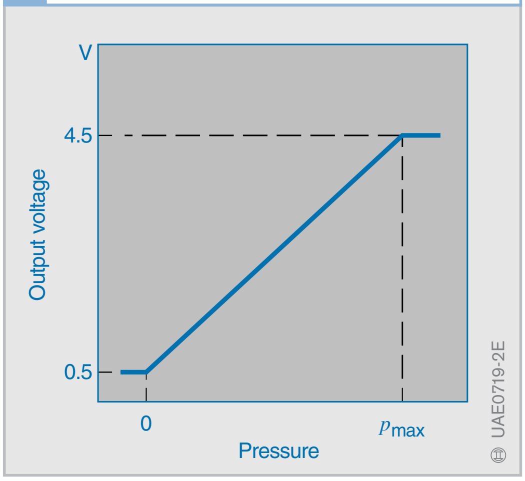


Fig. 1
1 Electrical connection (socket)
2 Evaluation circuit
3 Steel diaphragm with deformation resistors
4 Pressure connection
5 Mounting thread

2 High-pressure sensor (curve, example)



Force sensors and torque sensors

Measured quantities

The following list underlines the wide variety of applications for force and torque sensors in automotive engineering:

- In the commercial-vehicle sector, measurement of the coupling force between the towing vehicle and its trailer or semitrailer for the closed-loop controlled application of the brakes, whereby neither push nor pull forces are active at the drawbar.
- Measurement of the shock-absorber force for use in electronic chassis-control systems,
- For electronically controlled braking-force distribution, measurement of the axle load on commercial vehicles,
- Measurement of the pedal force on electronically-controlled braking systems,
- Measurement of the braking force on electrically actuated, electronically-controlled braking systems,
- Proximity or non-contact measurement of drive and brake torques,
- Proximity or non-contact measurement of steering torque or power-steering torque,
- Finger-clamp protection on power windows and electrically operated sunroofs,
- Force sensors integrated in the wheel bearing,
- Weight measurement of vehicle occupants for occupant-restraint systems.

In many cases, initial developments failed to lead to the expected results since generally the costs involved in achieving the stipulated accuracy were excessive for the systems in which the sensors were to be installed.

Contrary to expectations, it proved impossible to force down the costs for the production of good torque sensors below those for pressure and acceleration sensors. In fact the torque sensors cost more.

Matters are aggravated, and this applies particularly to torque sensors, when the measured quantity has to be transferred using non-contact methods from a *rotating shaft* (e.g. steering spindle or drive shaft) to a sensor mounted on the chassis.

Since any form of measurement of only part of the force or torque is very problematical and can easily lead to false results, force and torque sensors must be directly connected into the *power flux* (in other words, the complete measured variable must pass through them). In other words, there is a direct relationship between the extent of the measuring range and the sensor's size, that is, the wider the measuring range the larger the sensor.

Although, in line with automotive-industry demands, there are compact force and torque sensors on the market, these only measure accurately enough when the forces are introduced to the sensor in a precisely defined manner, a stipulation that normally can only be complied with under laboratory conditions. The tolerances and misalignment normally encountered in practice generally dictate the connection of *homogenisation elements* which in turn then lead to the sensors becoming too large

If force and torque-transfer components must be cut in order for sensors to be fitted, this generally results in an *interface problem.* This can only be solved by close cooperation between the sensor supplier and the suppliers of the parts which must be cut in order to install the sensors. This usually involves a large number of different companies and the automaker as well. Up to now, this problem has not been encountered with other sensor types, at least not with this severity and with such wide-ranging implications.

Even if the force and torque-transfer components do not have to be cut, and mechanical elements are used as measuring springs which only need modifying for installation of the sensor elements, very precise alignment is still necessary.

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Measuring principles

Basically speaking, when considering force measurement, a difference must be made between static and dynamic measuring principles, and between measuring principles based on displacement and mechanical strain.

For the most part, static sensors have been in demand up to now, whereby for force sensors, non-resilient strain-measuring principles were preferred. In the present-day example of steering-torque sensing though, "soft" resilient sensor systems are acceptable which can also incorporate angle-measurement pick-offs. This is possible, particularly because this characteristic proved to be tolerable in earlier hydraulic systems which were not equipped with sensors. At present, being as the use of microstructural elements for mass production has not yet been clarified, magnetic coil systems still dominate in both sectors.

Force sensors

Magneto-elastic principle

The magneto-elastic effect is based on the anisotropic (directional) behaviour of relative magnetic permeability μ_r, (relationship between magnetic induction and magnetic field strength). This has the same value in all directions when no force is applied from the outside, but under the influence of an applied force its value changes. In the (longitudinal) direction of the applied force, this change (μ_{rl}) is different to that in the transverse direction (μ_{rq}).

In fact, the permeability change in the direction of force is a true reflection of the sign of the force. Even though practically all ferromagnetic materials demonstrate this effect, it can be optimized by using a specific alloy composition. Unfortunately though, the materials which have good linearity, low hysteresis, and low temperature sensitivity, are not identical with the ones which have a high measuring effect. Whereas the maximum measuring effects observed up to the present are about 30% (referred to the fundamental isotropic values), and can be utilised without electronics being necessary, the effects displayed by materials which have been optimised from the point of view of measurement techniques is only in an area of a few percent and needs electronic backup.

The advantages of the magneto-elastic effect are to be found in its broad temperature range and the fact that technical applications are possible up to temperatures as high as approx. 300 °C. On the other hand, it represents a marked volume effect. This means that the coils used for detection not only register a local variation of permeability caused by the application of force, but more or less the effects throughout the whole of the coil's cross section. This makes the sensor somewhat less sensitive to the possibility of force being applied asymmetrically.

Since the changes in permeability as a function of applied force are practically always registered with the help of alternating fields, the penetration depth of these fields, which is highly frequency-dependent, must be observed:

Only those mechanical forces can contribute to the measuring effect which are present in the measuring field's effective penetration depth. In order to be able to put the measuring effect to maximum use, the magnetically active air gap should be kept as small as possible. Often, this means that the magnetically active measuring circuit is

1 Magneto-elastic anisotropic effect

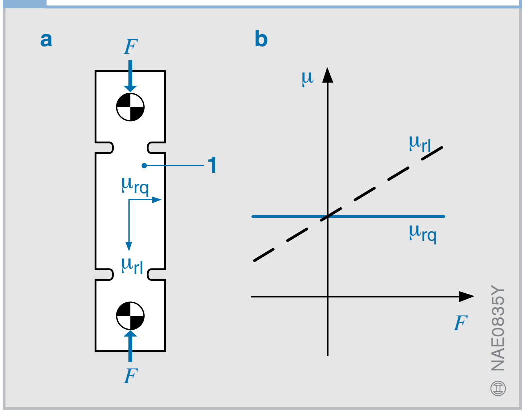

Fig. 1
- a Magneto-elastic measurement structure
- b Measuring effect
- F Force
- μ_r Relative magnetic permeability
- μ_{rq} Transverse to the direction of force
- μ_{rl} In the direction of force

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closed with ferromagnetic material, even when this is not included in the power flux.

Figure 2 shows the two most important possibilities of evaluating the magneto-elastic effect: If a coil is arranged on the measurement structure so that its direction of field coincides with the direction of applied force, the change in inductance L can be picked-off and applied directly. Independent of the magnitude of the applied force, the excitation field strength H and the induction B always have the same direction (Figs. 2a and 3a).

If the field strength H of the supply coil is not axially parallel to the applied force, the effect of the latter not only changes the magnetic induction B, but also its direction (due to the anisotropy of the permeability, Fig. 2b).

Assuming that with no force applied the directions of H and B are superposed one upon the other in the normal manner, these assume increasingly different directions when force is applied and increased. In particular, this can be of advantage in varying the magnetic coupling of two measuring coils (Figs. 3b, 3c, and 4).

2 Influence of the magneto-elastic effect

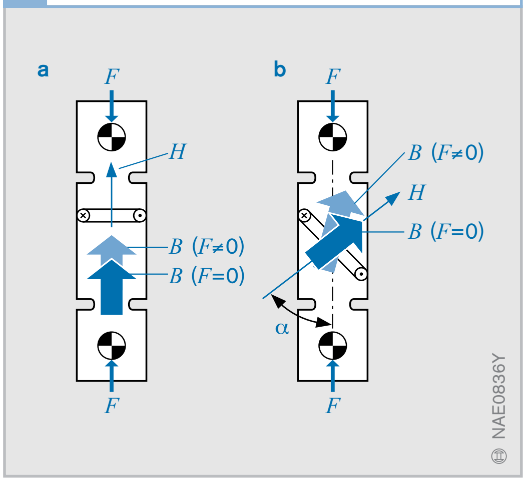

Fig. 2
- a With direction of force parallel to the direction of field
- b For different directions of field strength H and force F
- B Induction
- α Enclosed angle

4 Magneto-elastic tensile-force/compressive-force sensor for measuring braking torque

3 Different forms of magneto-elastic force sensors

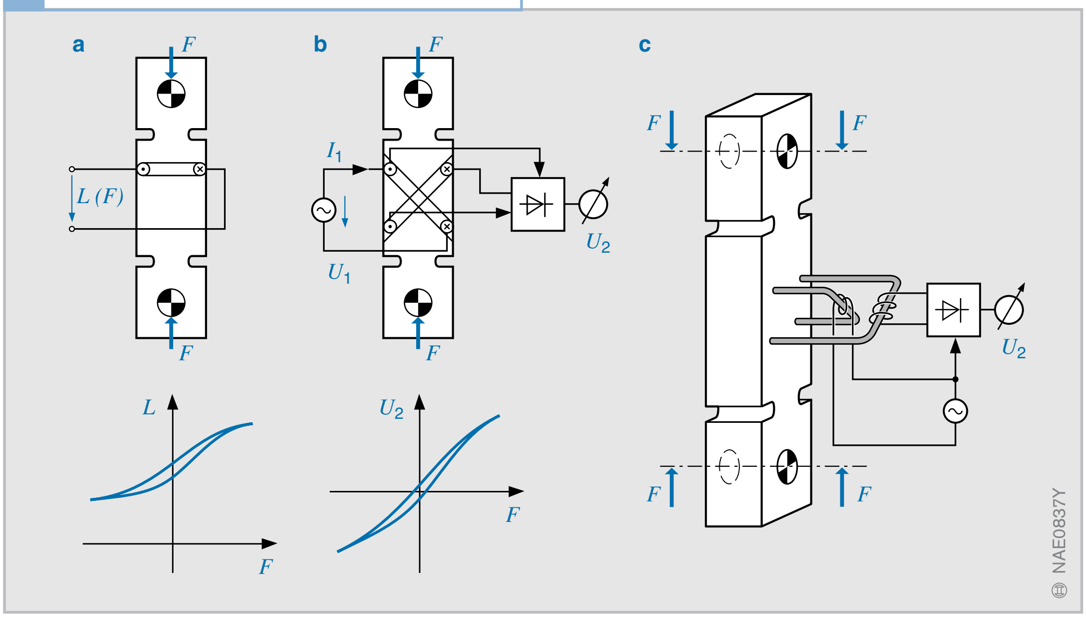

Fig. 3
- a Variable inductance
- b Variable coupling
- c Variable coupling

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Strain-gauge (DMS) principle (piezoresistive)

Strain-gauge measuring resistors represent the most widespread, and probably the most reliable and precise method for measuring force and torque (Fig. 5). Their principle is based on the fact that in the zone of the elastic-member material to which Hooke's Law applies there is a proportional relationship between the mechanical strain σ in the member, caused by the introduction of force, and the resulting deformation ε.

$$\varepsilon = \Delta l/l = \sigma/E$$

whereby E is the modulus of elasticity. Since it does not directly measure the strain resulting from the applied force, but rather the resulting deformation, the strain-gauge method can be regarded as an indirect measuring method. For instance, if the modulus of elasticity decreases by 3% above 100 K, a figure which is normal for metals, then the force indicated by the strain-gauge method is 3% too high.

Strain-gauge resistors in the form of film resistors are so closely bonded to the surface of the selected elastic member that they follow its surface deformation perfectly. The change in resistance resulting from the resistor's deformation is defined by the particular gauge factor K of the resistor in question (refer to "pressure sensors"):

$$\Delta R/R = K \cdot \varepsilon$$

On metal film resistors, the K factor rarely exceeds 2. Strain gauges are designed that as far as possible (in combination with a given elastic material and its thermal expansion) they are temperature insensitive ($TK_R \approx 0$). Any residual temperature sensitivity is usually eliminated by depositing the resistors on the elastic member in the form of a half or full bridge. Since temperature effects result in same-direction changes on the strain gauge this results in no output signal.

The auxiliary bridge resistors can be (but need not be) located within the elastic member's deformation zone. They can also be fitted as purely compensation resistors (Fig. 5c). It must be noted that often the K-factor itself also has a temperature coefficient (TK_K). Usually, this decreases along with increasing temperature, which means that in favorable cases it can compensate for the signal increase caused by the E-module.

5 Starin-gauge force sensors

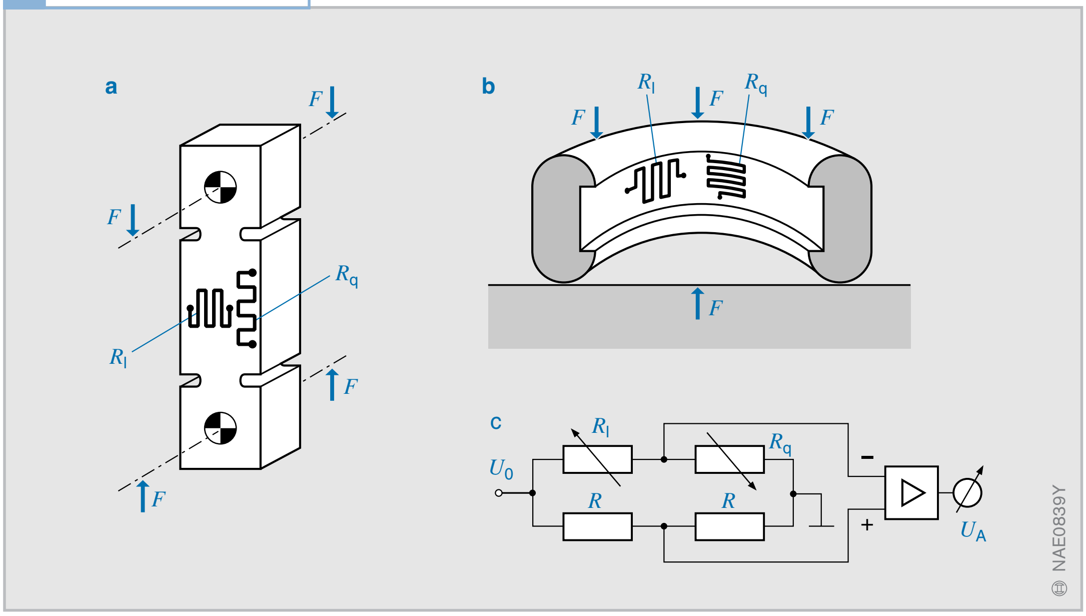

Fig. 5
- a Rod-shaped
- b Toroidal-shaped
- c Electronic evaluation
- F Force
- $R_{l,q}$ Metal film resistors, lengthways, crosswise
- R Auxiliary bridge resistors
- U_0 Supply voltage
- U_A Output voltage

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Apart from this, signal reductions caused by the K-factor are usually compensated for by a bridge supply voltage which increases accordingly.

Disadvantages/Limitations
Notwithstanding their high levels of accuracy and reliability, since the deformation and therefore also the changes in resistance (at least in the case of metal film resistors) are only in the percentage range of the original state, the strain-gauge sensors only generate output voltages in the mV range so that in general local amplification is required. A further disadvantage of small strain-gauge resistors is the fact that they only measure the strain at precisely that point at which it is applied, and no averaging takes place to arrive at a figure which applies to the (larger) elastic member as a whole. This, of course, no longer holds true in cases in which the strain-gauge structure is distributed across the elastic member's complete surface. This necessitates extremely precise and reproducible application of the strain to be measured if measuring errors due to uneven strain introduction is to be avoided.

Applications
As a rule, in order to carry out force measurements, very small strain-gauge resistors must be attached to larger force-carrying elastic members. The traditional method of applying the strain-gauge resistors to the elastic member by means of a foil backing (as applied in such devices as high-precision scales), is not inexpensive enough for large-batch "low-cost" production. First attempts are therefore being made to apply low-cost, large batch film/layer techniques by depositing the strain-gauge resistors on small metal wafers which are then pressed into, or welded onto the elastic element.

Orthogonal printed resistors

Practically all electrical film resistors change their resistance not only under the influence of laterally applied deformation strain but also when compression is applied vertical to the film plane (orthogonal). Here, the so-called "conductive plastic", commonly used in potentiometers, features very high sensitivity. "Cermet" and "carbon layers" are also highly sensitive (Fig. 6). Up to a certain limit, the resistance of the above materials decreases along with increasing compression. The values that can be achieved with-

6 Piezoresistive behaviour of various resistance materials when orthogonal compression is applied

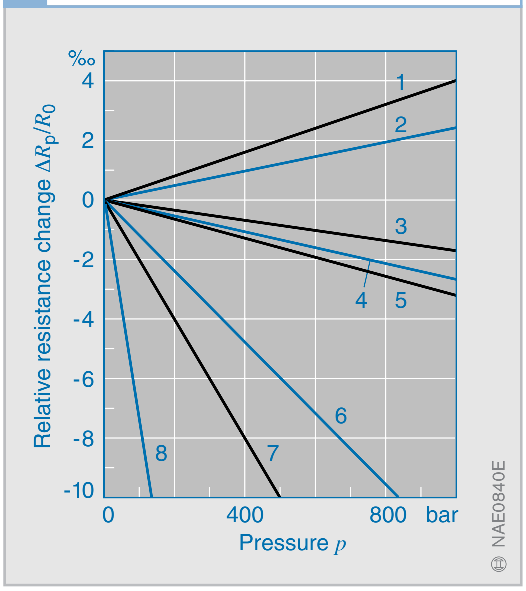


Fig. 6
1 84.5Ag15.5Mn
2 Manganin
3 Cu
4 Au
5 Ag
6 Carbon film/layer
7 Cermet
8 Conductive plastic

7 Force sensor with orthogonally compressed strain-gauge resistors

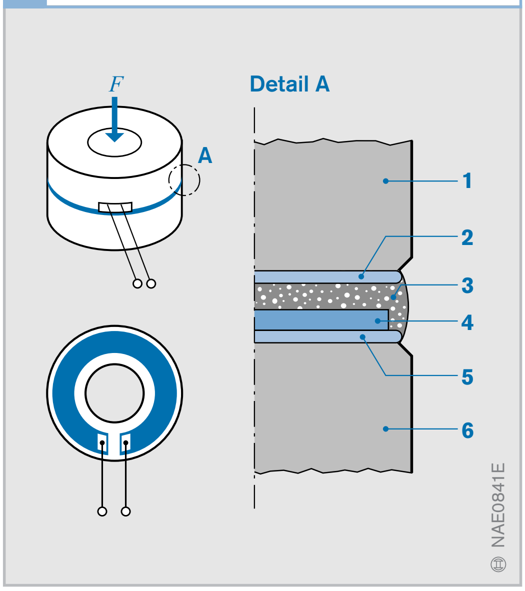


Fig. 7
1 Force-application ring
2 Insulation
3 Adhesive layer/ glass layer
4 Sensor layer
5 Insulation
6 Support ring

out permanent resistance change are similar to those which apply for lateral deformation. In both cases, the limit is a function of substrate strength and not of the resistance material. Of course, sensors of this type are almost only suitable for loading by compression but not by lateral strain.

Unfortunately, the majority of materials feature a relatively high temperature sensitivity referred to their deformation dependency. This makes such sensors unsuitable for static measurements. For bridge circuits, pressure-free zones can be provided on the substrate on which pressure-independent auxiliary bridge resistors or temperature-dependent compensation resistors can be located.

When the measuring resistors are designed as thick-film force-sensing discs, they are deposited on a hard substrate (for instance steel), and joined to form a solid body by means of a force-application ring (overglazed or cemented, Figs. 7 and 8).

The pressure-sensitive resistors though can also be applied on a carrier foil (Fig. 9) which can be located in a space-saving manner between the force-carrying components (for instance in a vehicle seat). Even though such foil-type resistors are not highly precise force sensors, they are very suitable for the construction of multiple sensor configurations ("sensor arrays") with which the load distribution over a given surface area can be measured, or even the shape of an object with a certain weight. Some sensor arrays also use materials which demonstrate a far more pronounced measuring effect together with a practically exponential characteristic curve. Here, the elastic foil often assumes the function of a switch which closes when pressure is applied and switches in the measuring resistor. Unfortunately, there is no foil encapsulation which is 100% sealed against moisture so that long-term stability cannot be counted on with such resistors.

Examples of application for force sensors

- Magneto-elastic bearing-pin sensors,
- Magneto-elastic braking-force sensors, and
- Seat mat (vehicle-passenger weight).

Torque sensors

Basically, the methods used for torque measurement differ from those for angle and strain measurement. In contrast to strain-measurement methods (strain-gauge resistors, magneto-elastic), angle-measurement methods (e.g. eddy-current) require a certain length l of the torsion shaft via which the torsion angle Φ (approx. 0.4...4°) can be

8 Thick-film force-sensing disc

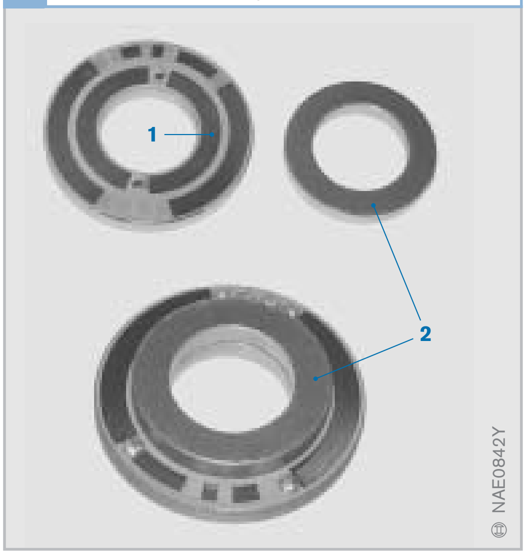
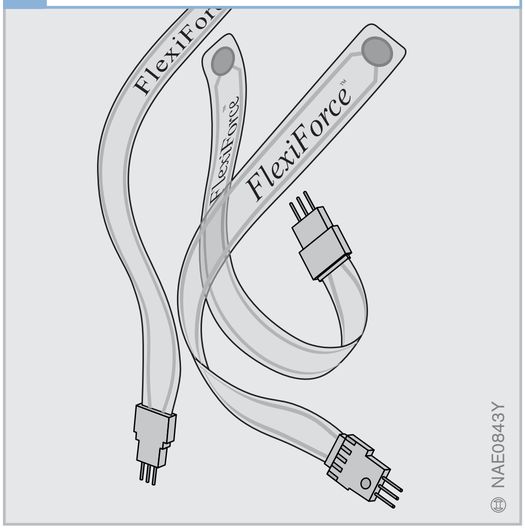


Fig. 8
1 Orthogonally loaded strain-gauge resistors
2 Overglazed force-application ring

9 Orthogonally loaded strain-gauge resistors on foil substrate (commercial name "Flexiforce")



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picked-off. The mechanical tension σ, which is proportional to the torque, is at an angle of less than 45° to the shaft axis (Fig. 10).

The principles described below are all suited for the non-contacting (proximity) transfer of measured values, even from rotating shafts. In the case of steering-torque measurement, it is also desirable for the employed measuring system to measure the steering angle very accurately (through a full rotation of 360°). This is in the sense of modular integration and is to be implemented with only slight modification.

Strain-measuring sensors

Even though *magneto-elastic sensors* which enclose the shaft are available on the market, these involve very high costs. Since it is often impossible to optimise the shaft material with regard to its magneto-elastic properties, a search is being made for methods to coat the measuring shaft with a magneto-elastic layer. Such a coating, which has to exhibit good measuring qualities, has still not been found. The *strain-gauge principle* has therefore also come to the forefront here (Fig. 11):

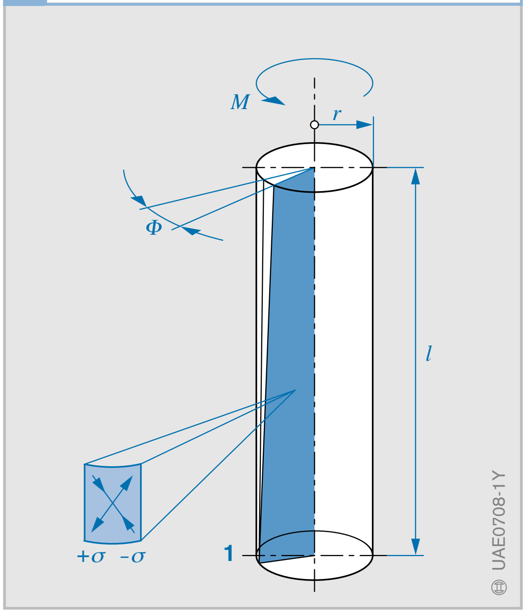
A strain-gauge bridge which is powered using transformer principles (rectifier and control-electronics circuitry on the shaft, independent of the air gap), is used to register the mechanical stress. Further local electronic components on the shaft permit the measured signal to be amplified and converted to an AC form which is independent of the air gap (for instance, frequency-analog) which can then also be outputted using transformer principles. When large-batch quantities are involved, the electronic circuitry on the shaft can be integrated in a single chip. The deformation sensors can be inexpensively formed on a prefabricated steel blank (for instance, using thin-film techniques) which is then welded to the shaft. Considering the fact that such configurations are inexpensive to manufacture, they nevertheless permit high accuracies.

Angle-measuring (torsion-measuring) sensors

Sensors for measuring angular difference

It is a relatively easy matter to define the torsion angle when two mutually-independent incremental rotational-speed sensors, or an absolute-measuring (analog or digital) non-contacting angular-movement pick-off, are

10 Torque measurement: Basic principle



11 Strain-gauge torque sensor with non-contacting (proximity) transformer pick-off

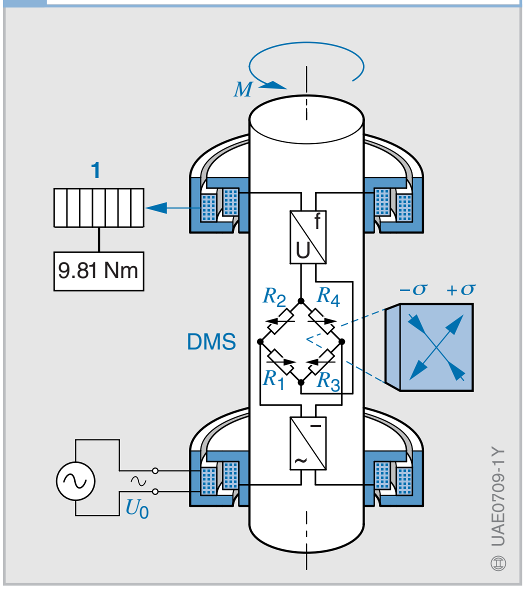


Fig. 10
1 Torque rod
Φ Torsion angle
σ Torsional stress
M Torque
r Radius
l Rod length

Fig. 11
1 Torque-display device
σ Torsional stress
M Torque
U_0 Supply voltage
R_1...R_4 Deformation resistors

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provided at each end of the 5..10 cm-long section subject to torsion measurement (Fig. 12). The difference in their outputs $\varphi_2 - \varphi_1$ is a measure for the torsion angle. Up to now, since adequate accuracy demands extremely precise bearings, together with the necessity to provide correspondingly accurate angular or incremental subdivision around the complete periphery, this method has been regarded as too complicated. Nevertheless work is forcing ahead with solving this problem (magnetically or optically), because such a system would incorporate two distinct advantages:

- Possibility of simultaneous measurement of the angle of rotation with the same system.
- Possibility of measurement without far-reaching modifications to the torsion shaft being necessary, so that essentially the sensor could be in the form of a plug-in sensor providing an efficient interface for a supplier component.

Eddy-current sensors

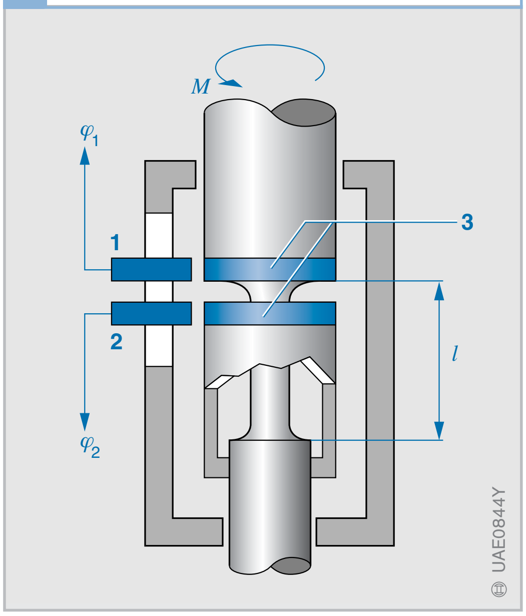
Two slotted sleeves are attached to each end of a sufficiently long section of the measuring shaft. These are inserted one inside the other (Fig 13, Pos. 1). Each sleeve is provided with two rows of slots so that when the shaft is twisted, it becomes increasingly visible through one row of slots, and is hidden more and more by the other row.

This leads to increasing, or decreasing, damping of the two high-frequency coils (approx. 1 MHz) situated above each row of slots so that coil inductance also varies accordingly. The slotted sleeves must be precisely manufactured and assembled in order to achieve the stipulated accuracy. The electronic circuitry is located as close as possible to the coils.

Application examples for torque sensors

- Strain-measuring strain-gauge torque sensors, and
- Angle-measuring eddy-current torque sensors (electric power tools).

12 Defining torque by measuring angular difference



13 Eddy-current torque sensor

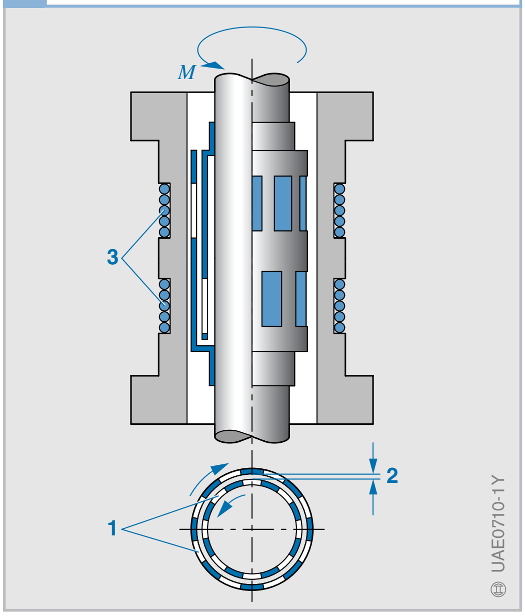


Fig. 12
1, 2 Angle/rotational-speed sensors
3 Angle markings
l Torsion-measurement section
M Torque to be measured
$\varphi_{1,2}$ Angle signals

Fig. 13
1 Slotted sleeves
2 Air gap
3 HF coils
M Torque

Occupant classification (OC) and detection of child's safety seat

Assignment

Following introduction of the airbag for the front-seat passenger, safety and actuarial considerations made it necessary to detect whether the front-seat passenger's seat is occupied or not. Otherwise, when an accident occurs and both front airbags are deployed, unnecessary repair costs result if the passenger seat is unoccupied.

The development of the so-called "Smart Bags" marked an increase in the demand for the ability to detect occupation of the driver-seat and front-passenger seat. The smart bag should feature variable deployment adapted to the actual situation and occupation of the seats. In certain situations, airbag triggering must be prevented when deployment would be injurious to one of the vehicle's occupants (for instance, if a child is sitting in the seat next to the driver, or a child's safety seat is fitted). This led to further development of the "simple" seat-occupation detection to form the "intelligent" **O**ccupation **C**lassification (OC). In addition, the automatic detection of a child's safety seat is integrated as a further sensory function. This can detect whether the seat is occupied or not, provided the seat is equipped with transponders.

Design and construction

A so-called sensor mat and ECU incorporated in the vehicle's front seats (Figs. 1 and 2) registers the information on the person in the seat and sends this to the airbag ECU. These data are then applied when adapting the restraint-system triggering to the current situation.

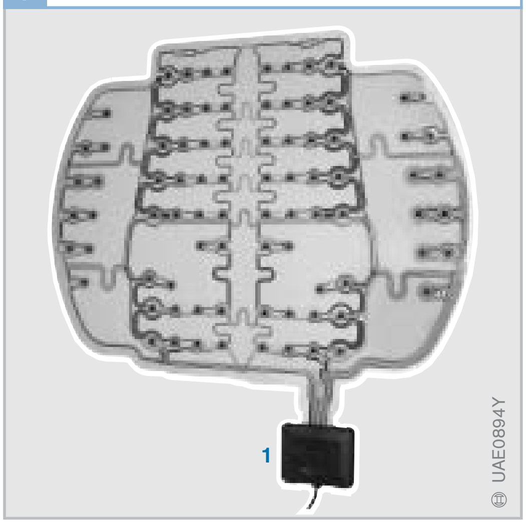
Operating concept

Measuring concept

This relies upon the classification of passengers (OC) according to their physical characteristics (weight, height, etc.), and applying this data for optimal airbag deployment. Instead of directly "weighing" the person concerned, the OC system primarily applies the correlation between the person's weight and his/her anthropometric[1]) characteristics (such as distance between hipbones). To do so, the OC sensor mat measures the pressure profile on the seat surface. Evaluation indicates first of all whether the seat is occupied or not, and further analysis permits the person concerned to be allocated to a certain classsification (Fig. 3).

[1]) The study of human body measurements, especially on a comparative basis.

1 Sensor mat with OC-ECU



2 Installation of the OC sensor mats in the front seats

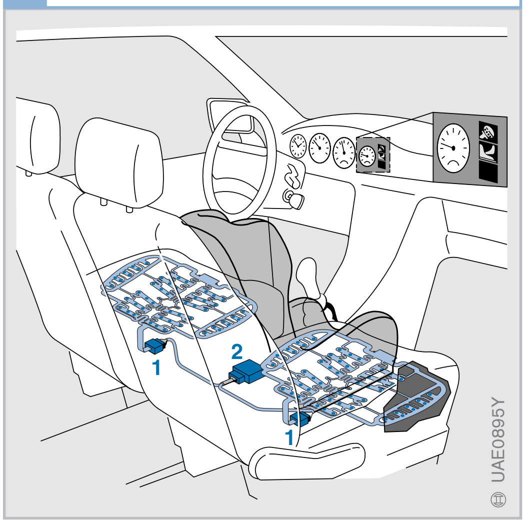


Fig. 1
1 ECU

Fig. 2
1 OC-ECU
2 Airbag ECU

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Sensor technology

Basically, the OC sensor mat comprises pressure-dependent FSR resistance elements (FSR: **F**orce-**S**ensitive **R**esistance), the information from which can be selectively evaluated. A sensor element's electrical resistance drops when it is subjected to increasing mechanical load. This effect can be registered by inputting a measuring current. The analysis of all sensor points permits definition of the size of the occupied seat area, and of the local points of concentration of the profile.

A sensing antenna and two receive antennas in the OC sensor mat serve to implement the child's safety-seat detection function. During the generation of a sending field, transponders in the specially equipped child's seats are excited so that they impose a code on the sending field by means of modulation. The data received by the receive antenna and evaluated by the electronic circuitry is applied in determining the type of child's seat and its orientation.

ECU

The ECU feeds measuring currents into the sensor mat and evaluates the sensor signals with the help of an algorithm program which runs in the microcontroller. The resulting classification data and the information on the child's safety seat are sent to the airbag ECU in a cyclical protocol where, via a decision table, they help to define the triggering behaviour.

Algorithm

Among other things, the following decision criteria serve to analyse the impression of the seating profile:

Distance between hip-bones:
A typical seating profile has two main impression points which correspond to the distance between the passsenger's hip-bones.

Occupied surface:
Similarly, there is a correlation between the occupied surface and the person's weight.

Profile coherence:
Consideration of the profile structure.

Dynamic response:
Change of the profile as a function of time.

3 Seat profile of the human body (a), with assignment of the distance between hip-bones to the person's weight (b)

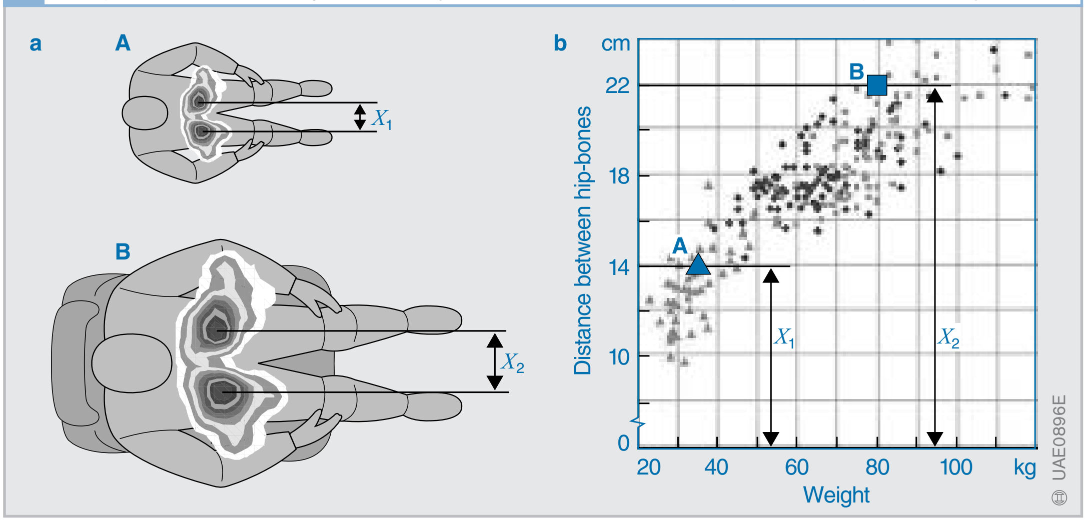

Fig. 3
a Seating profile
b Diagram
A Child with distance between hip-bones X_1
B Adult with distance between hip-bones X_2

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Flow meters

Measured quantities

Flow measurement is only required at a few points on the vehicle:
To register the delivered fuel quantity, and in particular to measure the amount of air drawn in for combustion.

Fuel-flow measurement

On electronically controlled fuel-injection systems, the fuel quantity is metered to the IC engine precisely (without specific flow measurement), either intermittently or continuously. The required fuel quantity is injected precisely thanks to the evaluation of such variable/adjustable parameters as injection duration, setting of the metering unit, injection pressure, fuel temperature etc.

The fuel-flow meters were developed principally during periods of intense fuel scarcity and were used on the IC engines of the time, which were not yet electronically controlled. They indicated the fuel consumption in liters for a given distance of 100 km (60 miles). The difference between the fuel delivered from the tank and the amount of fuel which flowed back to it (whereby, particularly at idle, the amount of fuel returned to the tank was considerable) was applied as the basis for calculating the amount of fuel that had actually been used (Problem: This was the difference between two large quantities).

Since there is presently no actual necessity for such fuel flow meters, and since they are practically no longer in use, no further space will be devoted to them here.

Airflow measurement

As such, the often-used term *"air quantity"* is incorrect because it does not stipulate whether volume or mass is concerned. Since the chemical processes involved in fuel combustion are clearly based on mass relationships, the measurement must apply to the mass of air drawn in or the mass of supercharged air. In other words, the *"air mass"*. At least on IC engines, the air-mass flow rate is the most important load parameter. The sensors which are used for measuring air quantity or gas flows in general are also referred to as "anemometers".

Depending upon engine power, the average maximum air-mass flow rate to be measured is between 400 and 1200 kg/h. Due to the low air requirements at engine idle, the ratio of minimum to maximum flow is 1:90...1:100. The severe emissions and fuel-consumption requirements dictate accuracies of 1...2% of the measured value. Referred to the measuring range, this can easily correspond to a measuring accuracy of 10^{-4}, a figure which is unusually high for the automobile.

The air though, is not drawn in continuously by the engine, but rather in time with the opening of the intake valves. Particularly with the throttle wide open (WOT), this leads to considerable pulsation of the air-mass flow, also at the measuring point which is always in the intake tract between air filter and throttle valve (Fig. 1). Intake-manifold resonance leads to the pulsation in the manifold sometimes being so pronounced that brief return flows can occur. This applies in particular to 4-cylinder engines in which there is no overlap of the air-intake phase and the charge phase. An accurate flow meter must be capable of registering these return flows with the correct direction.

1 Pulsating air-flow mass Q_{LM} in the intake tract of an IC engine

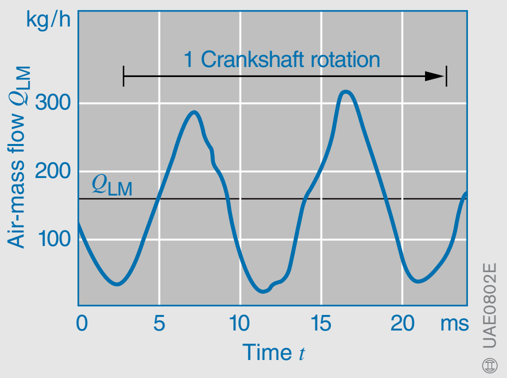

Fig. 1
At WOT and
$n = 3000\ \text{min}^{-1}$;
intake-manifold pressure
$p_s = 0.96$ bar;
mean air-flow rate
$Q_{LMm} = 157.3$ kg/h

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On a 4-cylinder engine, the pulsations are generated at twice the crankshaft speed. This means that they can easily be in the range 50...100 Hz. With an air-mass meter featuring a linear characteristic curve and a narrower frequency bandwidth than above, it would suffice for it to follow the mean value of these rapidly fluctuating air flows. The mean value is in any case positive, so that the meter need not necessarily detect the correct sign.

Practically all of the air-mass meters actually in use feature a characteristic curve which is far from linear, so that the measurement signal must be linearized electronically before it can be evaluated. If averaging takes place before linearisation, this can lead to considerable errors ("mean-value errors"). Being as the pulsations mostly have a pronounced non-sinusoidal characteristic, they therefore also have a considerable harmonic content. This fact means that such air-mass meters must be able to follow the pulsations rapidly enough. This necessitates a *bandwidth* of about 1000 Hz. Apart from this considerable bandwidth, the air-mass meters must also have a high switch-on time constant in order for them to be able to measure correctly during the engine start phase.

Similar to all flow meters, the versions used in the automobile are calibrated for "tubular" flow with a symmetrical flow profile, in other words for a flow whose velocity vector υ at practically every point in the flow cross-section of area A is only a function of the radius to the center line. The flow profile (laminar or turbulent, Fig. 2) is directly related to the Reynolds number R_e.

$R_e = \upsilon \cdot D/\eta$
Where
D = Typical cross-section, and
η = kinematic viscosity of the medium.

Flow is laminar or turbulent when the Reynolds number R is below or above approx. 1200. If the transition is in the center of the measuring range, marked irregularity of the characteristic curve can be expected at this point. As far as automotive applications are concerned, a purely turbulent flow (rectangular profile: $\upsilon = \text{const}_r$) can be reckoned with. This turbulence is sometimes provoked on purpose by means of a special grid element which also serves to protect the measuring system against damage. Assuming a homogeneous density ρ, the flow is simple to calculate as follows:

$Q_V = \upsilon \cdot A$ Volume flow rate
$Q_M = \rho \cdot \upsilon \cdot A$ Mass flow rate

Whereas in measurement techniques, long, straight, advance and overshoot sections of constant cross-section are stipulated in order to guarantee a symmetrical profile, such

2 Flow profiles

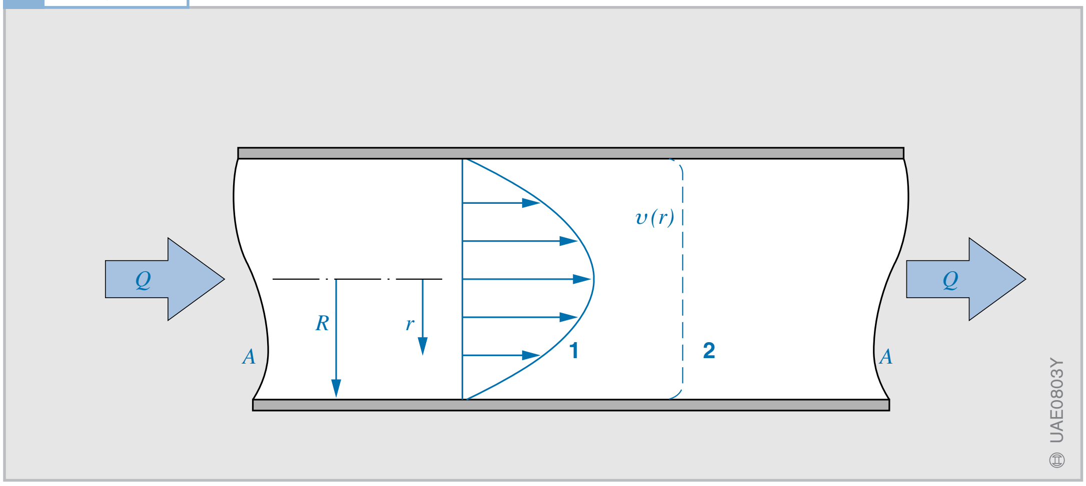

Fig. 2
1 Laminar flow profile
2 Turbulent flow profile
A Cross-section area of the tube
Q Flow
R Tube radius
r Distance from the tube center
$\upsilon(r)$ Flow profile

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conditions cannot be complied with in a vehicle's cramped under-hood installation space. If pronounced asymmetries occur, the flow meter must be calibrated as a function of the actual installation conditions.

Impact pressure gauges, whose function will be dealt in more detail below, react to the pressure drop (Δp) at a special restriction (metering orifice) in the flow cross-section and measure a flow which corresponds neither to the volume flow rate nor the mass flow rate. Instead this flow value is the geometrical mean of the two:

$$Q_{St} = const \cdot \sqrt{\rho} \cdot v = const. \cdot \sqrt{Q_V \cdot Q_M}$$

Whereby, the pressure loss at the flow meter (above all at WOT) is not to exceed 20...30 mbar.

Measuring principles

Up to now, of the practically unlimited variety of flow meters on the market, only those which operate according to the impact-pressure principle have come to the forefront for air-quantity measurement in the vehicle. This principle still depends upon mechanically moving parts, and in principle correction measures are still needed to compensate for density fluctuations.

Today, air-mass meters are increasingly being used which use a thermal method without moving parts. Their "hot-wire" or "hot-film" principle enables them to follow sudden flow changes with a minimum of delay.

Variable orifice plates (sensor plates)

The calculation of the pressure drop across fixed orifice plates is based on two physical laws:

Continuity equation:

$$\rho_1 \cdot v_1 \cdot A_1 = \rho_2 \cdot v_2 \cdot A_2 = const$$

Bernoulli's equation:

$$p_1 + \frac{1}{2} \cdot \rho_1 \cdot v_1^2 = p_2 + \frac{1}{2} \cdot \rho_2 \cdot v_2^2 = const$$

These laws are to be applied for two different measuring cross-sections A_1 and A_2 (Fig. 3).

3 Impact-pressure flowmeter with ring orifice (a) and sensor plate (b)

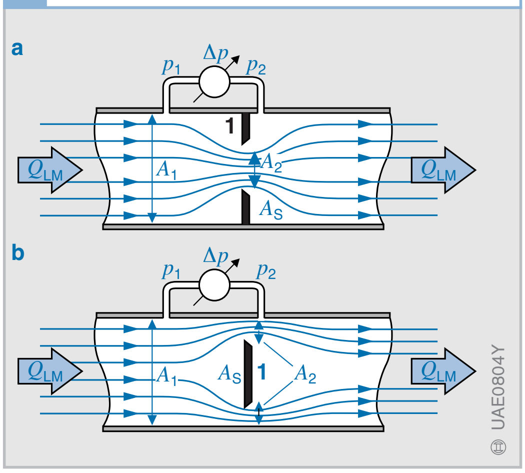

Fig. 3
- a Ring orifice
- b Sensor plate
- 1 Orifice plate
- A_S Plate diameter
- $A_{1,2}$ Measuring cross-section
- $p_{1,2}$ Measurement pressure
- Δ_p Pressure drop
- Q_{LM} Air-mass flow

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Assuming constant density $\rho = \rho_1 = \rho_2$, this results in the pressure drop:

$$\Delta p = Q_V^2 \cdot \rho \cdot \left(\frac{1}{A_2^2} - \frac{1}{A_1^2}\right)$$

This pressure drop can be measured either directly with a differential-pressure flow meter, or by means of the force acting against a so-called sensor plate (Fig. 3).

Due to their r.m.s. relationship to the flow, fixed orifice plates permit only a 1:10 variation of the measured-variable. When larger ranges are to be covered, several orifice plates must be used, or such versions which automatically adapt themselves to the measuring range by opening up a larger flow cross-section A_2 in line with the increasing impact pressure.

With such variable, moving sensor plates it is an easy matter to increase the variation to 1:100. Here, the increasing air flow causes the sensor plate to be deflected (usually against a constant counterforce) into an area whose cross section is specifically shaped so that the resulting deflection/angle relationship complies with the desired characteristic. In other words, linear for K-Jetronic and non-linear for L-Jetronic. The sensor plate's (Fig. 4) setting is then a measure for the air flow which is in relationship to the impact pressure defined above. The limit frequency for such air-mass meters is approx. 10 Hz.

Such sensor plates though are unable to follow the high pulsation frequencies which often occur. From the point of view of the pulsation, they can be regarded as fixed orifice plates with a square-law curve. Under certain load conditions this leads to considerable mean-value errors which can only be compensated for roughly by the use of suitable software.

Here, when the density ρ of the drawn-in air changes due to temperature fluctuations or changes in altitude, the measured signal changes by merely $\sqrt{\rho}$. An air-temperature sensor and a barometric pressure sensor are needed in order to register the density fluctuation in full.

4 Impact-pressure flow meter with variable, moving sensor plate

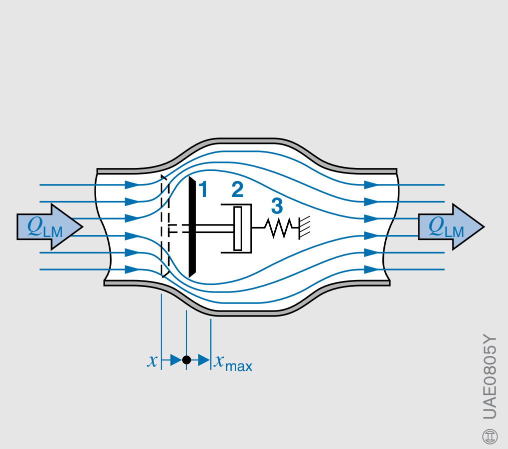

Fig. 4
1 Sensor plate
2 Damping device
3 Soft return spring
Q_{LM} Air-mass flow
x $= x(Q_{LM})$ sensor-plate setting dependent on flow

Hot-wire/Hot-film anemometers

When current I_H flows through a thin wire with electrical resistance R, its temperature increases. If at the same time a medium with density ρ, flows across it at velocity v, a balance is set up between the electrical power input P_{el} and the power P_V drawn off by the air flow, whereby

$$P_{el} = I_H^2 \cdot R = P_V = c_1 \cdot \lambda \cdot \Delta\vartheta$$

Here, the power drawn off by the air flow is proportional to the temperature difference $\Delta\vartheta$ and the coefficient of thermal conductivity λ. The following applies in close approximation:

$$\lambda = \sqrt{\rho \cdot v} + c_2 = \sqrt{Q_{LM}} + c_2$$

Although λ is primarily a function of the mass flow Q_{LM}, with the medium at standstill ($v = 0$) a certain heat loss takes place (convection) represented by the additive constant c_2 This results in the familiar interrelationship

$$I_H = c_1 \cdot \sqrt{(\sqrt{Q_{LM}} + c_2)}\,\sqrt{\frac{\Delta\vartheta}{R}}$$

between the heating current I_H and the mass flow Q_{LM}.

With the application of constant heating power (I_H^2R), which presents no problems, a reciprocal temperature increase $\Delta\vartheta$ would occur which decreases at a rate corresponding to the square root of the air-mass flow Q_{LM}. If on the other hand, the heating current I_H is controlled such that a constant temperature increase (for instance, $\Delta\vartheta$ = 100 K) is maintained even when the flow rate increases, this will lead to a heating current which increases at the fourth root of the mass flow, and at the same time serves as a measure for the mass flow.

The essential advantage of such a control circuit lies in the fact that the electrical heater resistor always remains at the same temperature so that its calorific content need not be changed by means of time-wasting heat transfer. In fact, with a 70 μm platinum wire for instance, it is possible to achieve *time constants* in the 1 ms range for changes in air-flow rate. In cases where closed-loop control is not used the time constants would be 40...100 times higher (Fig. 5).

If the heater temperature were to be maintained constant simply by keeping its (temperature-dependent) resistance constant, with constant mass flow and higher medium temperature, this would result in a current drop and therefore a false measurement. In practice, this error is avoided by using a bridge circuit containing a second high-ohm "compensation resistor" R_K of the same type (e.g. platinum). Here, the heater resistor is kept at a *constant overtemperature* $\Delta\vartheta$ compared to the medium (Fig. 6). In case of a sudden jump in the medium temperature, the sensor reacts with a long time constant since in this case the calorific content of the heater wire must be changed.

The heater resistors in the first air-mass meters (anemometers) used for automotive applications were of very fine *platinum wire.* This wire was mounted in trapezoidal form across the flow cross-section so that it was able take the mean of irregularities in the flow profile. Service lives which were acceptable from the technical viewpoint only became possible when the platinum wire was stabilised by alloy additives so that its resistance no longer changed due to deposits and cracks on its surface. This meant though that the deposits on the heater wire had to be burned-off following every operating phase (approx. 1000 °C).

Notwithstanding a number of functional advantages, this sensor concept was far too costly. Although a *thick-film version* (HFM2) was able to combine all the resistors concerned with the measurement on a single ceramic substrate, this failed to bring the

5 Hot-wire air-mass meter

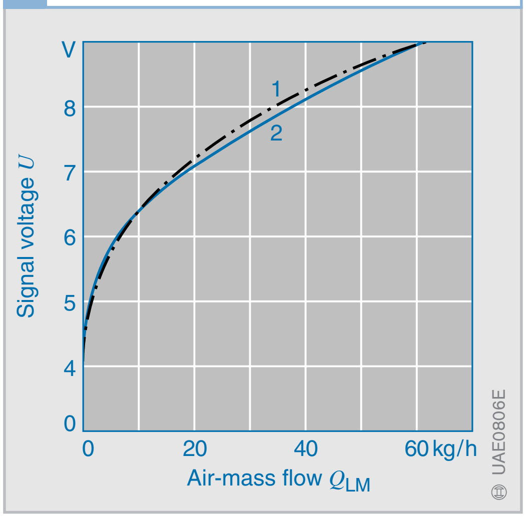

Fig. 5
1 Theoretical characteristic
2 Experimental characteristic

6 Hot-wire air-mass meter (electronic closed-loop control)

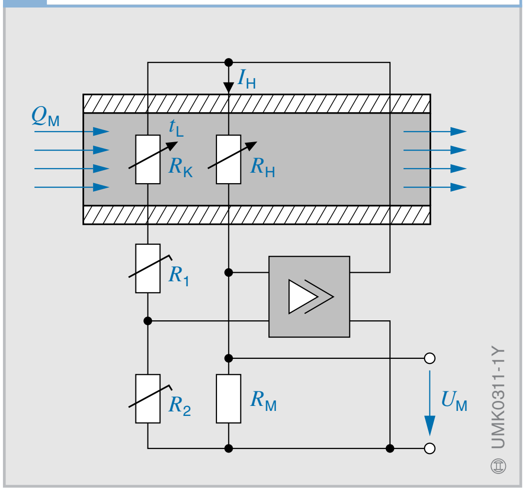

Fig. 6
Q_{LM} Air-mass flow
U_M Measurement voltage
R_H Hot-wire resistor
R_K Compensation resistor
R_M Measuring resistor
$R_{1,2}$ Trimming resistor

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hoped-for advantages with regard to the costs. Due to the substrate's considerable thermal capacity, it was difficult not to exceed the maximum permissible switching constants. Furthermore, a complicated saw cut had to be made to reduce the undesirable heat coupling between heating and compensation resistors. On the other hand though, this version permitted the burn-off process to be dispensed with since the special flow conditions no longer led to unwanted deposits.

In contrast to both its predecessor types, a further *silicon-based micromechanical* version (HFM5) fulfilled practically all expectations. In particular, this version is able to measure in both directions with the correct sign (Fig. 7). This means that the brief return flows that occur as a result of pulsation no longer lead to measuring errors (Fig. 8).

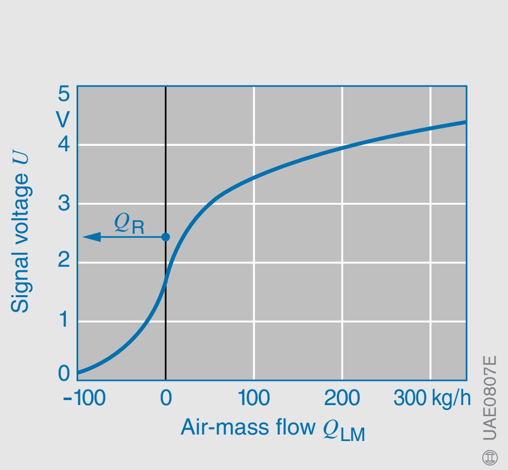
To this end, in addition to the heater control circuit used in the previous versions, a temperature sensor is located on each side of the heater resistor, in other words upstream and downstream. This principle is similar to the "Thomas process" often encountered in literature. When there is no flow ($Q_{ML} = 0$), each of these sensors indicates the same temperature. When flow starts though, since the upstream sensor is cooled by the medium and the other is heated by it, the higher the flow the higher the temperature difference between the two sensors. The output signal derived from the temperature difference has a similar characteristic to the anemometers used up to now, whereby its sign is a clear indication of the flow direction.

Due to its small size, the micromechanical flow meter is only a partial-flow meter. In other words, it is no longer in any way able to average-out any non-homogeneity in the flow velocity as a function of the flow cross-sectional area. Rather, this flow meter must ensure that the partial flow it measures represents the same fraction of the total flow throughout the whole measuring range. This is not always an easy matter.

Examples of application

- Sensor-plate air-mass meter LMM,
- Hot-wire air-mass meter HLM,
- Hot-film air-mass meter HFM2 und
- Hot-film air-mass meter HFM5.

7 Micromechanical hot-film air-mass meter with air-quantity measurement in both directions



8 Pulsating air-mass flow of a 4-cylinder engine

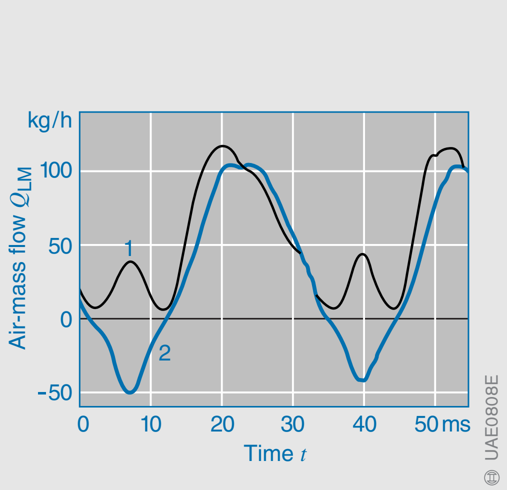


Fig. 7
Q_R Return flow

Fig. 8
At WOT and speed $n = 900\ \text{min}^{-1}$
1 Hot-wire air-mass meter
2 Hot-film air-mass meter

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Sensor-flap (impact-pressure) air-flow sensor LMM

Application

The sensor-flap air-flow sensor is still in operation in a number of engines equipped with certain versions of the L-Jetronic or M-Motronic. It is installed between the air filter and the throttle valve and applies the sensor-flap principle in registering the air flow Q_L drawn in by the engine (Figs. 1 through 3).

Design and operating concept

The air-flow sensor's pivoting sensor flap (Fig. 1, Pos. 1) forms a variable orifice plate. The incoming air Q_L deflects the flap against the constant return force of a spring, whereby the free cross-section area increases along with increasing air flow the more the plate is deflected.

The change of the free air-flow-sensor cross section as a function of the sensor-flap setting has been selected so that there is a logarithmic relationship between the sensor-flap angle and the air quantity drawn in by the engine. This leads to high air-flow sensor sensitivity, a valuable asset in the case of small air quantities which necessitate high measuring accuracy. The stipulated measuring accuracy is 1...3% of the measured value throughout a range defined by $Q_{max} : Q_{min} = 100:1$.

The sensor-plate angle is picked-off by a potentiometer (4) which converts it into an output voltage U_A (Fig. 4) which is used as an input to the ECU. In order to eliminate the effects of potentiometer aging and temperature coefficient on accuracy, the ECU only evaluates resistance ratios.

A further phenomenon which must be taken into account are the intake or induction strokes from the individual cylinders. These generate oscillations in the intake manifold, which the air-flow sensor can only follow up to about 10 Hz. To keep these effects down to a minimum, the measuring flap has a compensation flap attached to it which, in combination with a damping chamber (5), serves to damp the oscillations of the pulsating intake air.

Instead of the desired mass flow which is proportional to the product from $\rho \cdot v$, measurement according to the impact-pressure principle only measures a flow which is proportional to the product $\sqrt{\rho} \cdot v$. This means that density compensation (air temperature, air pressure) is required in order to achieve precise fuel metering.

The intake air's density changes along with its temperature. This fact is taken into account by the ECU calculating a correcting quantity from the temperature-dependent resistance of a temperature sensor integrated in the air-flow sensor (2). M-Motronic versions always feature barometric-pressure compensation. Here, a manifold-pressure sensor is connected pneumatically to the intake manifold so that it can pick-off the absolute manifold pressure. It is either integrated directly in the ECU (connected by hose to the intake manifold), or located in the vicinity of the intake manifold, or attached directly to it.

1 Impact-pressure airflow sensor

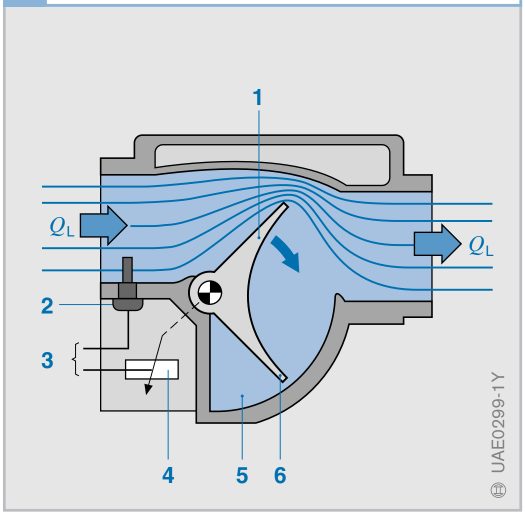

Fig. 1
1 Sensor plate
2 Air-temperature sensor
3 To ECU
4 Potentiometer
5 Damping chamber
6 Compensation flap
Q_L Intake-air flow

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2 Impact-pressure air-flow sensor (air-chamber side)

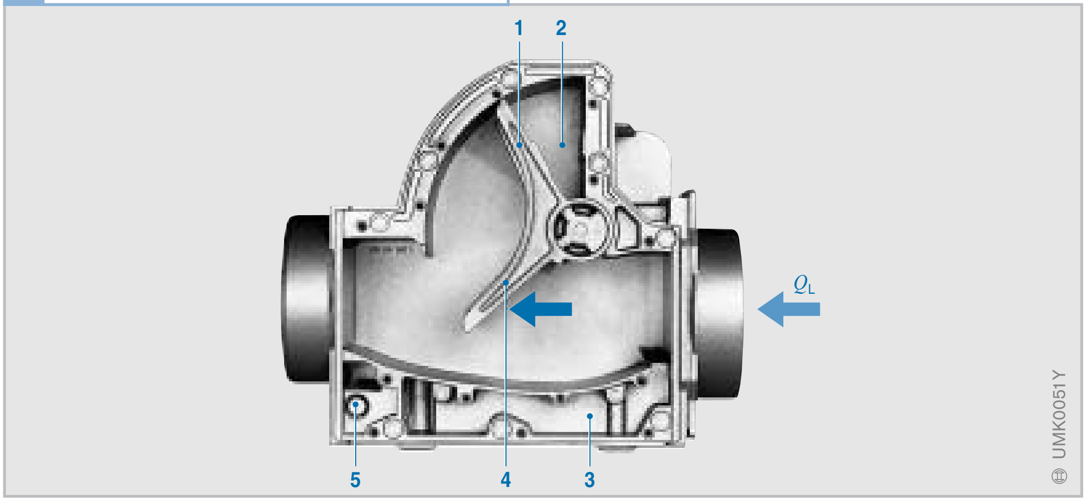

Fig. 2
1 Compensation flap
2 Damping chamber
3 Bypass
4 Sensor plate
5 Idle-mixture adjusting screw
Q_L Intake-air flow

3 Impact-pressure air-flow sensor (connection and components side)

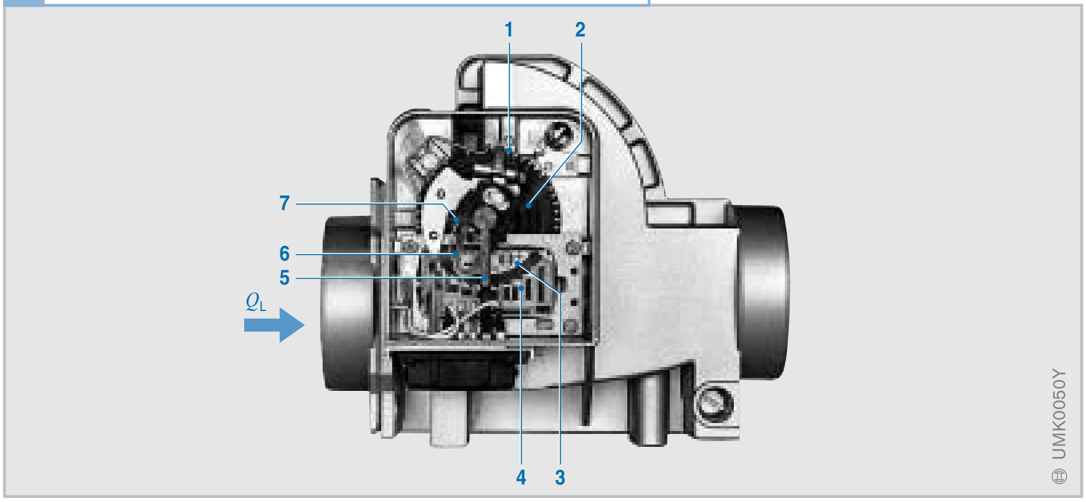

Fig. 3
1 Ring gear for spring preload
2 Return spring
3 Wiper track
4 Ceramic plate with resistors and printed conductors
5 Wiper pick-off
6 Wiper
7 Pump contact
Q_L Intake-air flow

4 Impact-pressure air-flow sensor (potentiometer circuitry and voltage curve)

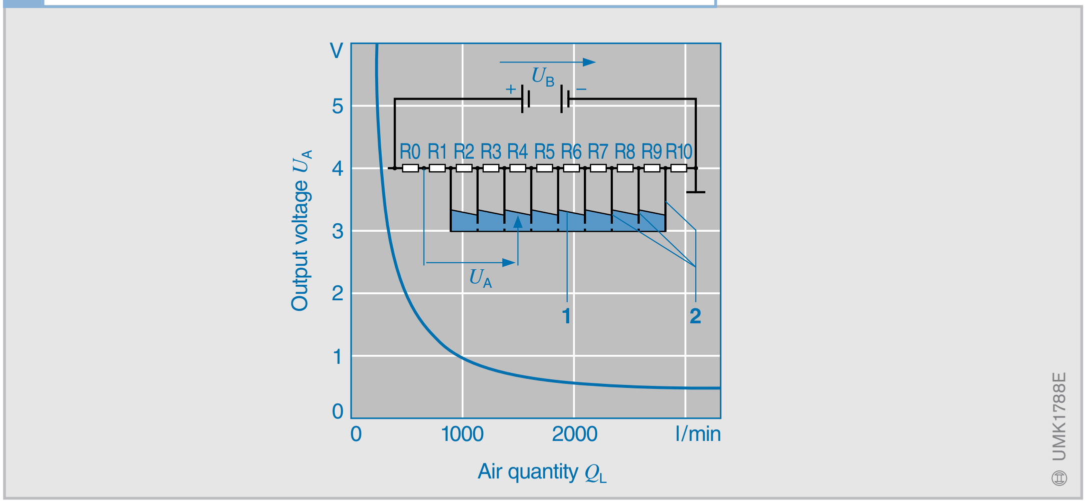

Fig. 4
1 Wiper track
2 Conductor segments (data points)
$U_A \sim 1/Q_L$ applies for the curve

Hot-wire air-mass meter HLM

Application

The HLM hot-wire air-mass meter is installed as a "thermal" load sensor between air filter and throttle plate in a number of LH-Jetronic or M-Motronic gasoline engines. It registers the air-mass flow Q_M drawn in by the engine, and applies this to determine the engine load. Being as it is able to follow average fluctuations of up to 1 Hz, the HLM is the fastest of the air flowmeters at present in use.

Design and construction

The intake air drawn in by the engines flows through the tubular HLM housing which is protected at each end by a wire mesh. A heated, 70 μm thin platinum wire element is suspended across the HLM measuring tube. It is suspended trapezoidally so that in good approximation it is able to cover the whole of the flow cross-section. A temperature-compensation (thin film) resistor projects into the air flow just upstream of the hot wire. Both of these components (hot wire and resistor) are integral parts of a closed-loop control circuit, where they function as temperature-dependent resistors. The control circuit is basically a bridge circuit and an amplifier (Figs. 1 and 2).

Operating concept

Before the air flowing through the HLM cools down the hot wire, its temperature is measured by means of the temperature-compensation resistor. A closed-loop control circuit regulates the heater current so that the hot wire assumes a temperature which is held at a constant level above that of the intake air. Since the air density influences the amount of heat dissipated to the air by the hot wire, this measuring concept must adequately take it into account. The heating current I_H is therefore a measure of the air-mass flow, and across a precision measuring resistor (R_M) it generates a voltage signal U_M, for input to the ECU, which is proportional to air-mass flow. The HLM, on the other hand, cannot detect the direction of air flow.

In order to prevent measurement-result drift due to deposits on the platinum wire, this is heated for about 1 second to a burn-off temperature of approx. 1000 °C every time the engine is switched off. Here, the dirt deposits evaporate or flake off and leave the hot wire in a clean state.

1 Hot-wire air-mass meter (circuit)

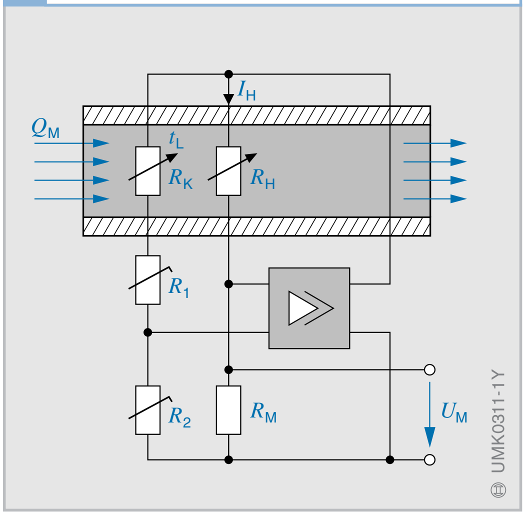

Fig. 1
R_K Temperature-compensation resistor
R_H Hot-wire heater resistor
R_M Measuring resistor
$R_{1,2}$ Bridge balance resistors
U_M Measurement voltage
I_H Heating current
t_L Air temperature
Q_M Air-mass flow

2 Hot-wire air-mass meter

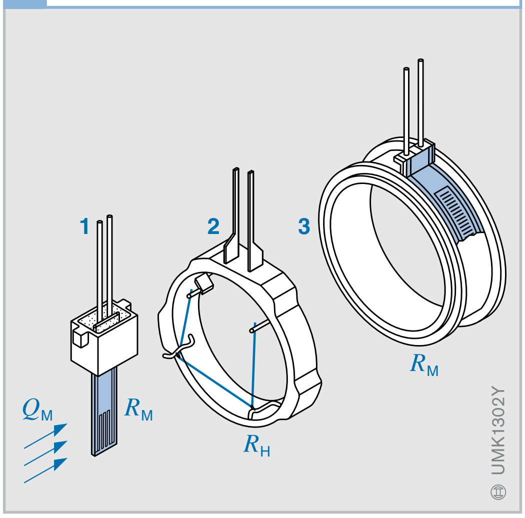

Fig. 2
1 Temperature-compensation resistor R_K
2 Sensor ring with hot wire R_H
3 Precision measuring resistor (R_M)
Q_M Air-mass flow

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Hot-film air-mass meter HFM2

Application

The HFM2 **h**ot-**f**ilm air-mass **m**eter is a thick-film sensor which is installed as a "thermal" load sensor between air filter and throttle plate in a number of LH-Jetronic or M-Motronic gasoline engines. It very accurately registers the air-mass flow Q_M drawn in by the engine, and applies this to determine the engine load.

Design and construction

Together with bridge resistors, the electrically heated HFM2 platinum heater resistor R_H is located on a ceramic chip (substrate, Fig. 1).

The bridge also incorporates a temperature-dependent resistor R_S (flow sensor) which registers the heater temperature. Separation of the heater and the flow sensor is advantageous for the (closed-loop) control circuit. The heater element and the air-temperature compensation sensor (resistor R_K) are decoupled thermally by two saw cuts (Fig. 2).

Since the dirt is deposited mainly on the front edge of the sensor element, the components which are decisive for the heat transition are situated downstream on the ceramic substrate. Furthermore, the sensor is so constructed that air flow around the sensor remains unaffected by dirt deposits.

Operating concept

The electrically heated platinum heater resistor projects into the intake-air flow which cools it down. A closed-loop control circuit regulates the heater current so that the hot wire assumes a temperature which is held at a constant level above that of the intake air. Since the air density, just as much as the flow rate, is decisive regarding the amount of heat dissipated to the air by the hot wire, this measuring concept takes it into account to the appropriate degree. The heating current I_H, and the voltage at the heater, is thus a non-linear measure for the air-mass flow Q_M.

The HFM2 electronic circuitry converts this voltage into the voltage U_M which it adapts to make it suitable for input into the ECU. The computer than uses this to calculate the air mass drawn in by the engine for every working cycle. The HFM2 cannot determine the direction of air flow.

The long-term measuring accuracy of ±4 % referred to the measured value applies even without the burn-off of dirt deposits.

1 Hot-film air-mass meter (circuit)

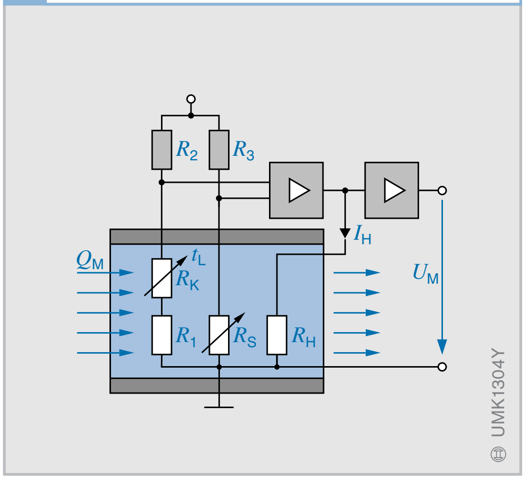

Fig. 1
- R_K Temperature-compensation sensor (resistor)
- R_H Heater resistor
- R_S Sensor resistor
- R_1, R_2, R_3 Bridge resistors
- U_M Measurement voltage
- I_H Heating current
- t_L Air temperature
- Q_M Air-mass flow

2 Hot-film air-mass meter (substrate)

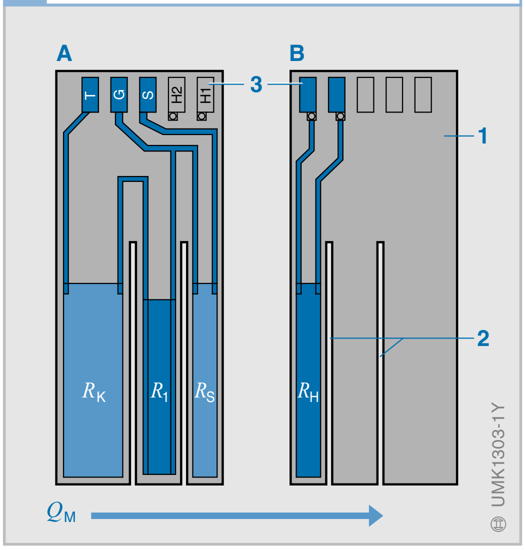

Fig. 2
- A Front side
- B Rear side
- 1 Ceramic substrate
- 2 Two saw cuts
- 3 Contacts
- R_K Temperature-compensation sensor (resistor)
- R_H Heater resistor
- R_S Sensor resistor
- R_1 Bridge resistor

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Hot-film air-mass meter HFM5

Application

For optimal combustion as needed to comply with the emission regulations imposed by legislation, it is imperative that precisely the necessary air mass is inducted, irrespective of the engine's operating state.

To this end, part of the total air flow which is actually inducted through the air filter or the measuring tube is measured by a hot-film air-mass meter. Measurement is very precise and takes into account the pulsations and reverse flows caused by the opening and closing of the engine’s intake and exhaust valves. Intake-air temperature changes have no effect upon measuring accuracy.

Design and construction

The housing of the HFM5 **h**ot-**f**ilm air-mass **m**eter (Fig. 1, Pos. 5) projects into a measuring tube (2) which, depending upon the engine's air-mass requirements, can have a variety of diameters (for 370...970 kg/h). This tube is installed in the intake tract downstream from the air filter. Plug-in versions are also available which are installed inside the air filter.

The most important components in the sensor are the sensor element (4), in the air intake (8), and the integrated evaluation electronics (3). The partial air flow as required for measurement flows across this sensor element.

Vapor-deposition is used to apply the sensor-element components to a semiconductor substrate, and the evaluation-electronics (hybrid circuit) components to a ceramic substrate. This principle permits very compact design. The evaluation electronics are connected to the ECU through the plug-in connection (1). The partial-flow measuring tube (6) is shaped so that the air flows past the sensor element smoothly (without whirl effects) and back into the measuring tube via the air outlet (7). This method ensures efficient sensor operation even in case of extreme pulsation, and in addition to forward flow, reverse flows are also detected (Fig. 2).

1 Hot-film air-mass meter HFM5 (circuit)

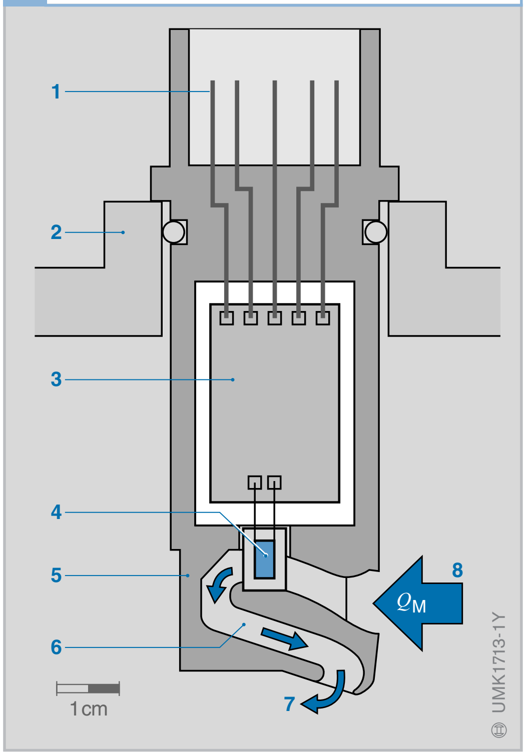

Fig. 1
1 Electrical plug-in connection
2 Measuring tube or air-filter housing wall
3 Evaluation electronics (hybrid circuit)
4 Sensor element
5 Sensor housing
6 Partial-flow measuring tube
7 Air outlet for the partial air flow Q_M
8 Intake for partial air flow Q_M

Operating concept

The hot-film air-mass meter is a "thermal sensor" and operates according to the following principle:

A micromechanical sensor diaphragm (Fig. 3, Pos. 5) on the sensor element (3) is heated by a centrally mounted heater resistor and held at a constant temperature. The temperature drops sharply on each side of this controlled heating zone (4).

The temperature distribution on the diaphragm is registered by two temperature-dependent resistors which are mounted upstream and downstream of the heater resistor so as to be symmetrical to it (measuring points M_1, M_2). Without the flow of incoming air, the temperature characteristic (1) is the same on each side of the heating zone ($T_1 = T_2$).

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As soon as air flows over the sensor element, the uniform temperature distribution at the diaphragm changes (2). On the intake side, the temperature characteristic is steeper since the incoming air flowing past this area cools it off. Initially, on the opposite side (the side nearest to the engine), the sensor element cools off. The air heated by the heater element then heats up the sensor element. The change in temperature distribution leads to a temperature differential (ΔT) between the measuring points M_1 und M_2.

The heat dissipated to the air, and therefore the temperature characteristic at the sensor element is a function of the air mass flow. Independent of the absolute temperature of the air flowing past, the temperature differential is a measure of the air mass flow. Apart from this, the temperature differential is directional, which means that the air-mass meter not only registers the mass of the incoming air but also its direction.

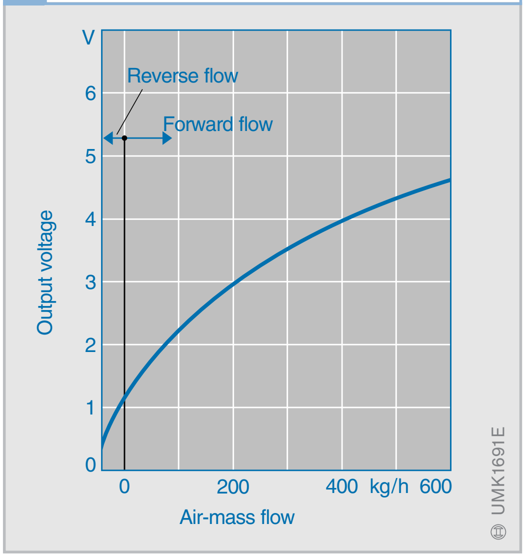
Due to its very thin micromechanical diaphragm, the sensor has a highly dynamic response (<15 ms), a point which is of particular importance when the incoming air is pulsating heavily.

The evaluation electronics (hybrid circuit) integrated in the sensor convert the resistance differential at the measuring points M_1 and M_2 into an analog signal of 0...5 V which is suitable for processing by the ECU. Using the sensor characteristic (Fig. 2) programmed into the ECU, the measured voltage is converted into a value representing the air mass flow [kg/h].

The shape of the characteristic curve is such that the diagnosis facility incorporated in the ECU can detect such malfunctions as an open-circuit line. A temperature sensor for auxiliary functions can also be integrated in the HFM5. It is located on the sensor element upstream of the heated zone.

It is not required for measuring the air mass. For applications on specific vehicles, supplementary functions such as improved separation of water and contamination are provided for (inner measuring tube and protective grid).

2 Hot-film air-mass meter (output voltage as a function of the partial air mass flowing past it)



3 Hot-film air-mass meter: Measuring principle

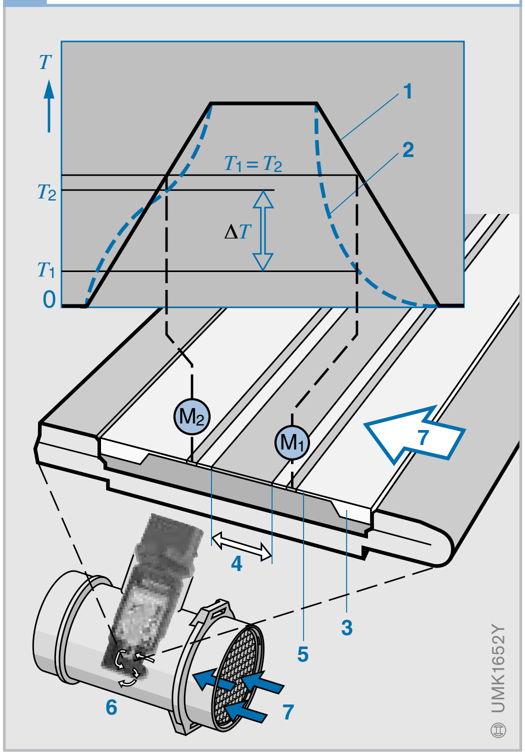


Fig. 3
1 Temperature profile without air flow across sensor element
2 Temperature profile with air flow across sensor element
3 Sensor element
4 Heated zone
5 Sensor diaphragm
6 Measuring tube with air-mass meter
7 Intake-air flow
M_1, M_2 Measuring points
T_1, T_2 Temperature values at the measuring points M_1 and M_2
ΔT Temperature differential

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Gas sensors, concentration sensors

Measured quantities

The concentration of a given material or medium defines the mass or volume percent of a given material in another given material or in a mixture or combination of other materials. With a concentration sensor (also known as a concentration probe), the important thing is that in the ideal case it is sensitive to only one medium, while at the same time practically "ignoring" all other mediums. Of course, in practice, every concentration sensor has its own cross sensitivity to other mediums even though, as is often the case, "temperature" and "pressure" are maintained constant.

In the vehicle, the following parameters must be measured:

- Oxygen content in the exhaust gas (closed-loop combustion control, catalytic-converter monitoring),
- Carbon-monoxide and nitrogen-oxide content, as well as air humidity inside the vehicle (air quality, misting of vehicle windows),
- Humidity in the compressed-air braking system (air-drier monitoring),
- Dampness of the outside air (black-ice warning),
- Concentration of soot in diesel-engine exhaust gas. A still unsolved problem. In contrast to the above-mentioned gas concentrations, this is a particle concentration. The difficulties inherent in the measuring assignment are further aggravated by the possibility of the sensor being blocked by particles so that it no longer functions.

The introduction of the fuel cell as an automotive drive means that further gas sensors will have to be developed, for instance for the detection of hydrogen.

Measuring principles

Measured mediums occur in gaseous, liquid, or solid state, so that in the course of time countless measuring methods have been developed. For automotive applications, up till now only the gas-analysis area, and in particular the measurement of gaseous humidity, has been of any interest. Table 1 presents an overview of the processes applied in general measurement techniques.

Gas measurement in general

Gas sensors are usually in direct unprotected contact with the measured medium (in other words with foreign matter) so that the danger exists of irreversible *damage*. This form of damage is referred to as sensor "contamination". For instance, the lead that may be contained in fuel can make the electrolytic oxygen concentration sensor (Lambda oxygen sensor) unusable.

Moisture measurement

In addition to the outstanding significance of the Lambda oxygen sensor in dealing with exhaust gases, moisture measurement also plays an important role.

Table 1

1 Gas-analysis processes (without particular attention being paid to the moisture-measurement process).
(X) = For automotive applications.

Physical process		Physical-chemical process		Chemical process	
Thermal conductivity		Catalytic effect		Selective absorption	
Magnetic process		Absorption warmth		Selective absorption with prior chemical conversion	
Radiation absorption		Characteristic color reaction			
Gas chromatography		Electrical conductivity	X		
Radioactive process		Electrochemical process	X		

In the broader sense, moisture can be said to be present in gaseous, liquid, or solid form. In the narrower sense, we are dealing here with the gaseous-water (water vapor) content in gaseous mediums – above all in the air.

When a damp gas is cooled in an isobaric process, it reaches its saturation point at a specific temperature (known as the dew point τ).

A number of important definitions are given below in connection with humidity measurement (refer also to Fig. 1):

m_{w} Mass of water
m_{s} Mass of water in the saturation state
m_{tr} Mass of dry gas

M_{w} Mole mass of water
M_{tr} Mean mole mass of the dry gas
p Total pressure of the gas mixture
p_{w} Partial pressure of the water vapor
p_{s} Saturated vapor pressure (vapor pressure of the water at mixture temperature)

Absolute humidity:

$$\chi = \frac{m_{\mathrm{w}}}{m_{\mathrm{tr}}} = \frac{M_{\mathrm{w}}}{M_{\mathrm{tr}}} \cdot \frac{p_{\mathrm{w}}}{p - p_{\mathrm{w}}} \text{ (in \%)}$$

$$f_a = \frac{m_{\mathrm{w}}}{V_{\mathrm{tr}}} \qquad \text{(volume-related)}$$

Relative humidity:

$$\Phi = \frac{p_{\mathrm{w}}}{p_{\mathrm{s}}} \qquad \text{(in \%)}$$

For low-cost applications (for instance in the vehicle), resistive and capacitive sensors are used almost exclusively. They are provided with hygroscopic layers which can store water as a function of the relative humidity (and release it again), and thus trigger a usually drastic change in a resistor's value or in the value of a planar capacitor.

1 Temperature/humidity diagram for air

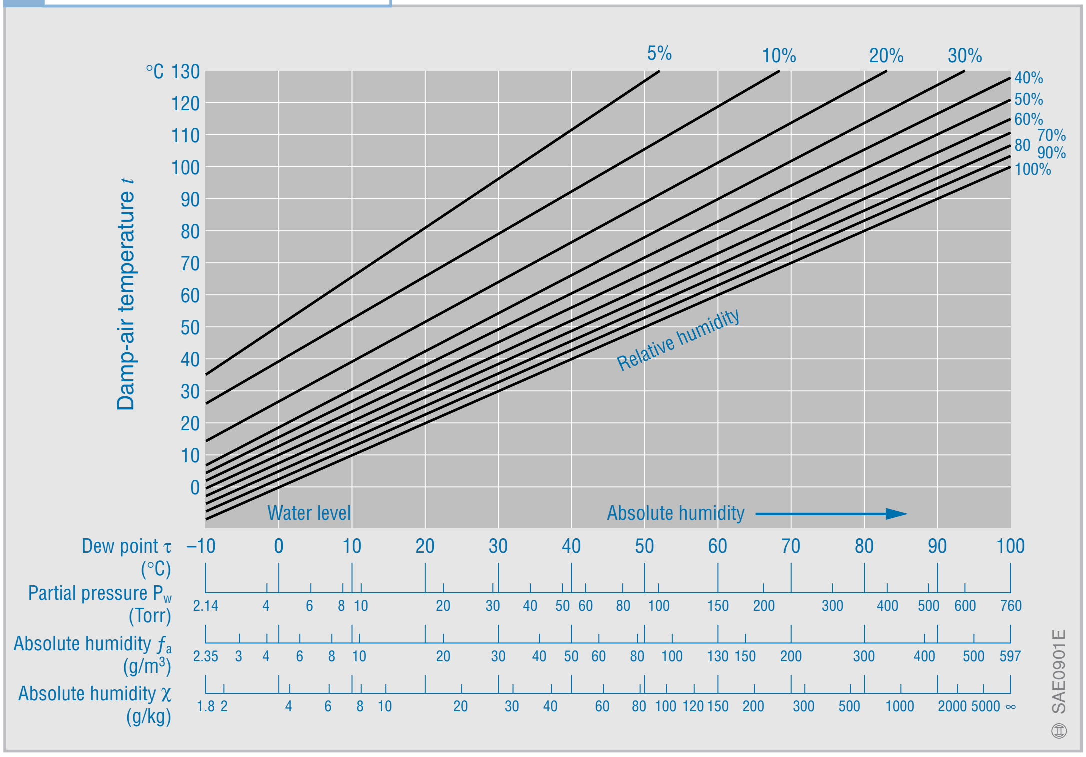

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Table 2

2 Humidity-measurement procedures. X = technologically important

Method/Process	Running number		Measuring instrument	Measuring method
Saturation method	1	X	Dew-point hygrometer	Direct method
	2	X	LiCi dew-point hygrometer	(Measurement of absolute humidity)
Evaporation method	3	X	Psychrometer	
Absorption method	4		Volume hygrometer	
	5	X	Electrolysis hygrometer	
	6		Condensate-quantity hygrometer	
Energy method	7	X	Infrared hygrometer	
	8		Microwave hygrometer	
	9		Electrical-discharge hygrometer	
	10		Diffusion hygrometer	
Hygroscopic method	11	X	Electrical conductive-foil hygrometer	Indirect method
	12	X	Capacitor hygrometer	(Measurement of relative humidity)
	13	X	Hair hygrometer	
	14		Two-strip hygrometer	
	15		Color hygrometer	
	16		Quartz hygrometer	
	17		Gravimetric hygrometer	

2 Capacitive sensor wafer with comb electrodes

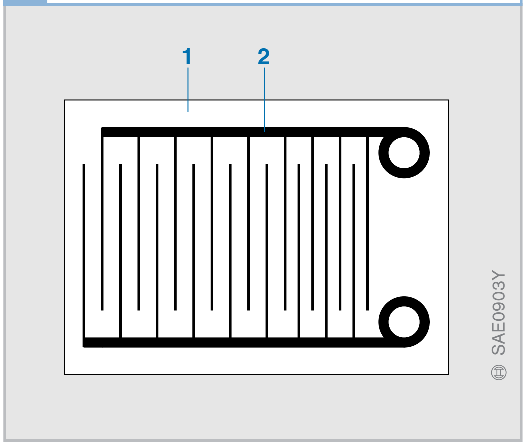
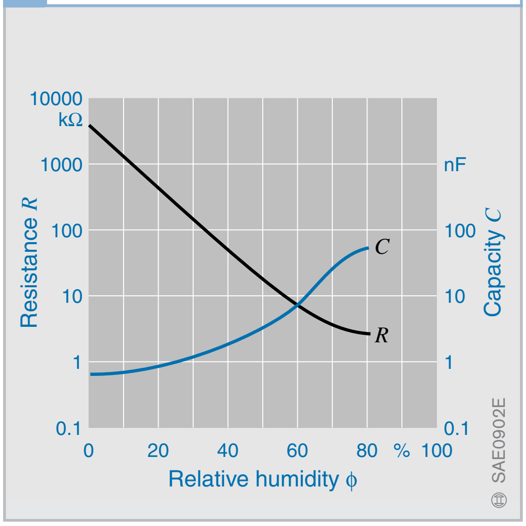


Fig. 2
1 Plastic wafer
2 Comb-shaped, embossed gold-foil electrodes

3 Resistive and capacitive humidity sensor (typical curves)



On *capacitive* humidity sensors, a hygroscopic insulating layer (e.g. Al_2O_3, or a polymer plastic), which can possibly also be the mounting wafer, serves as the dielectric of a capacitor. Either one of the electrodes is permeable to water, or the electrodes have a comb shape (Fig. 2). Along with increasing humidity, the dieeletric absorbs more water and the sensor's capacitance increases considerably (relative dielectric constant of water $\varepsilon_{rW} \approx 81$, Fig. 3).

In the case of the *resistive* sensor, an insulation substrate is coated with a layer of hygroscopic salt (LiCi) held in a paste binder and located between an electrode pair. The layer's conductivity changes drastically along with the relative humidity (Fig. 3). Unfortunately this resistance change is also highly dependent upon temperature so that normally compensation is needed. If the air temperature (NTC) is then measured, the dew point can be defined and with it the absolute humidity. The typical time constants of these sensors are about 30 s.

Table 2 gives an overview of the numerous measurement processes that have been developed in the course of time for humidity measurement.

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Air-quality sensors

Application

Air-quality sensors (Fig. 1) continually monitor air quality at the point where ventilation air enters the vehicle. In particular, these sensors respond to toxic exhaust-gas components such as CO (mainly from gasoline engines) and NO_X (mainly from diesel engines).

A further assignment is to prevent the misting-up of the windows. Here, a humidity sensor registers the air's water-vapor level.

Design and operating concept

The sensors incorporated in the air-quality ECU (Figs. 1 and 2) are comprised of thick-film resistors containing tin oxide. As soon as the measured medium collects there (process is reversible), the resistors in some cases change their electrical resistance drastically (e.g. 1...100 kΩ). The sensor resistors are all grouped on a common ceramic substrate which is heated from the rear to an operating temperature of approx. 330 °C by a heating conductor. Due to the high operating temperature, there is an air gap between components and substrate.

The CO sensor measures concentrations in the 10...100 ppm range (ppm = parts per million) and the NO_X sensor in the 0.5...5 ppm range. As soon as the concentration of pollution gases is excessive (sometimes almost 100 times higher than in clean air), the air-quality ECU closes the fresh-air inlet flaps. This serves to prevent the driver breathing in these gases so that he/she does not tire so quickly. The activated carbon filters also last longer when not loaded by these pollution gases.

Rough protection is provided by a metal cover, underneath which there is a Teflon diaphragm for both sensor chambers which permits passage of the measured gases and gaseous vapors while at the same time holding back fluid humidity. Even though the measured gases must first pass through the Teflon diaphragm, such sensors have a response time of milliseconds.

The latest air-quality ECUs also incorporate a humidity sensor (Fig. 3). Together with the interior temperaure as measured by an NTC resistor, its signal is used for calculating the dew point which is an important factor with regard to the misting-up of the vehicle's windows.

1 Air-quality ECU with sensors

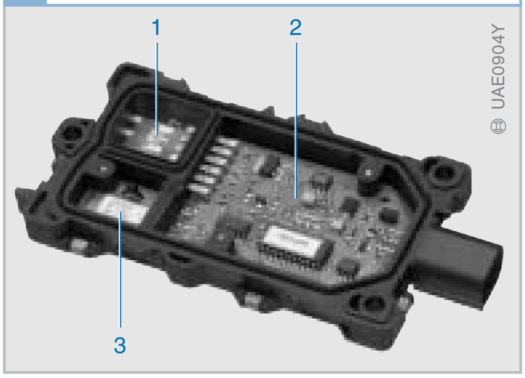

Fig. 1
1 NO_X/CO measuring element
2 Evaluation electronics
3 Humidity sensor

2 Air-quality sensor

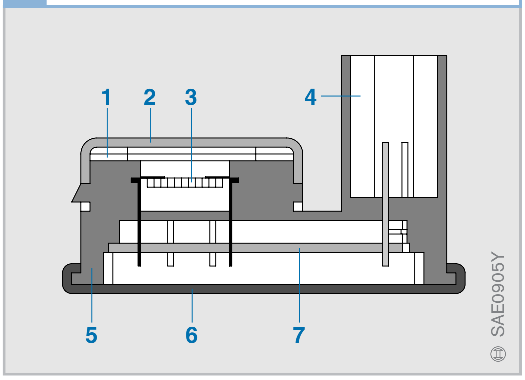

Fig. 2
1 Teflon diaphragm
2 Cover (gas-permeable)
3 NO_X/CO measuring element
4 Plug
5 Housing
6 Cover with gasket
7 pcb

3 Humidity sensor

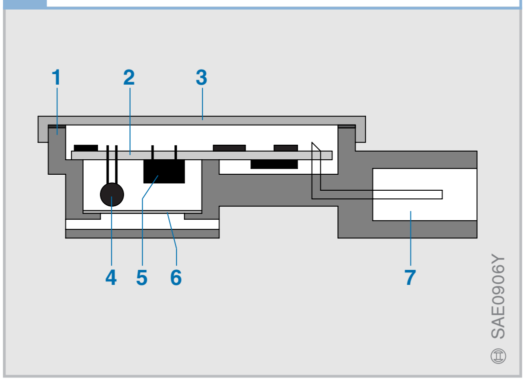

Fig. 3
1 Housing
2 pcb
3 Cover with gasket
4 Temperature sensor
5 Humidity measuring element
6 Teflon diaphragm
7 Plug

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Two-step Lambda oxygen sensors

Application

These sensors are used in gasoline engines equipped with two-step Lambda control. They extend into the exhaust pipe and to the same extent register the exhaust-gas flow leaving each cylinder. Their operating concept is based on the principle of a galvanic oxygen concentration cell with solid-state electrolyte.

"Two-step sensors" indicate whether the A/F mixture in the exhaust gas is "rich" ($\lambda < 1$) or "lean" ($\lambda > 1$). The sudden jump in the characteristic curve of these sensors permits A/F mixture control to $\lambda = 1$ (Fig. 1).

Design and construction

Tube-type (finger) sensors

The solid-state electrolyte is formed from a hollow zirconium-dioxide ceramic body which is impermeable to gas and closed on one end. Yttrium dioxide has been added for stabilisation purposes. The inside and outside surfaces have each been provided with a porous platinum coating which serves as an electrode.

The ceramic body protrudes into the exhaust pipe, and the platinum electrode on its outside surface acts as a catalytic converter in miniature. Exhaust gas which reaches this electrode is processed catalytically and brought to a stoichiometrical balance ($\lambda = 1$). In addition, the outside of the sensor which is in contact with the exhaust gas is provided with a porous ceramic (Spinel) layer to protect it against contamination. The ceramic body is protected against mechanical impact and thermal shocks by a slotted metal tube. The sensor's "open" inner chamber is connected to the surrounding air, which acts as a reference gas (Fig. 2).

Unheated finger sensor LS21

A ceramic support tube and a disc spring serve to locate, fix, and seal-off the active, finger-shaped sensor ceramic in the sensor housing (Fig. 3, design and construction similar to the heated Lambda sensor Fig. 4, but without heater element). A contact element between the support tube and the active sensor ceramic element provides the contact between the inner electrode and the connection cable.

The outer electrode is connected to the sensor housing by the metal seal ring. A pro-

1 Two-step Lambda oxygen sensor (voltage curve for 600°C working temperature)

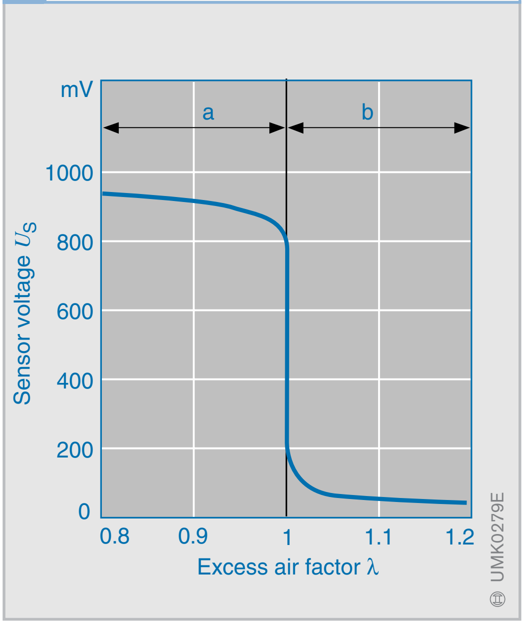

Fig. 1
a Rich A/F mixture
b Lean A/F mixture

2 Configuration of a tube-type Lambda oxygen sensor in the exhaust pipe

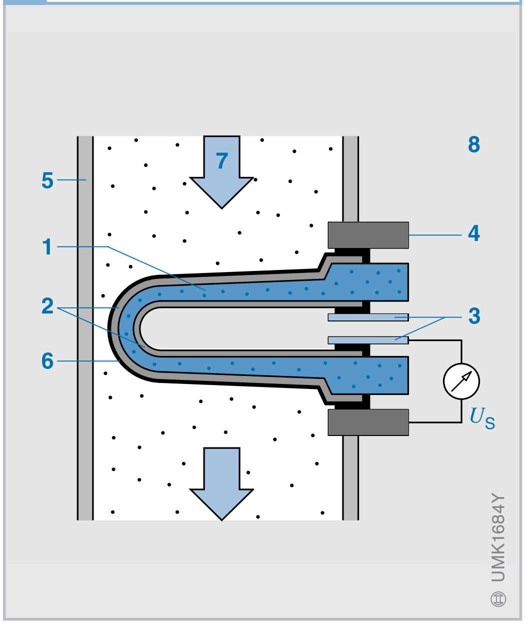

Fig. 2
1 Sensor ceramic element
2 Electrodes
3 Contacts
4 Housing contact
5 Exhaust pipe
6 Ceramic protective coating (porous)
7 Exhaust gas
8 Outside air
U_S Sensor voltage

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tective metal sleeve, which at the same time serves as the support for the disc spring, locates and fixes the sensor's complete inner structure. It also protects the sensor interior against contamination. The connection cable is crimped to the contact element which protrudes from the sensor, and is protected against humidity and mechanical damage by a special high-temperature-resistant cap.

In order to keep combustion residues in the exhaust gas away from the sensor's ceramic element, a specially shaped, slotted protective tube is slipped over the sensor housing at the end exposed to the exhaust gas. The slots are configured so that they provide particularly effective protection against extreme temperatures and chemical loading.

Heated tube-type (finger) sensor LSH24
This heated sensor (Fig. 4) is equipped with a heater element. On this sensor, at low engine loads (e.g. low exhaust-gas temperatures) the ceramic-element's temperature is defined by the electrical heater, and at high loads by the exhaust-gas temperature. This heated tube-type sensor can be installed further away from the engine so that even extended periods of full-load (WOT) driving present no problems. Thanks to the electrical heating, the sensor heats up so quickly that it has already reached operating temperature 20...30 s after the engine has started so that the Lambda closed-loop control can come into operation. The fact that the heated Lambda sensor is always at optimum operating temperature contributes to low and stable exhaust-gas emission figures.

3 LS21 unheated tube-type (finger) Lambda sensor

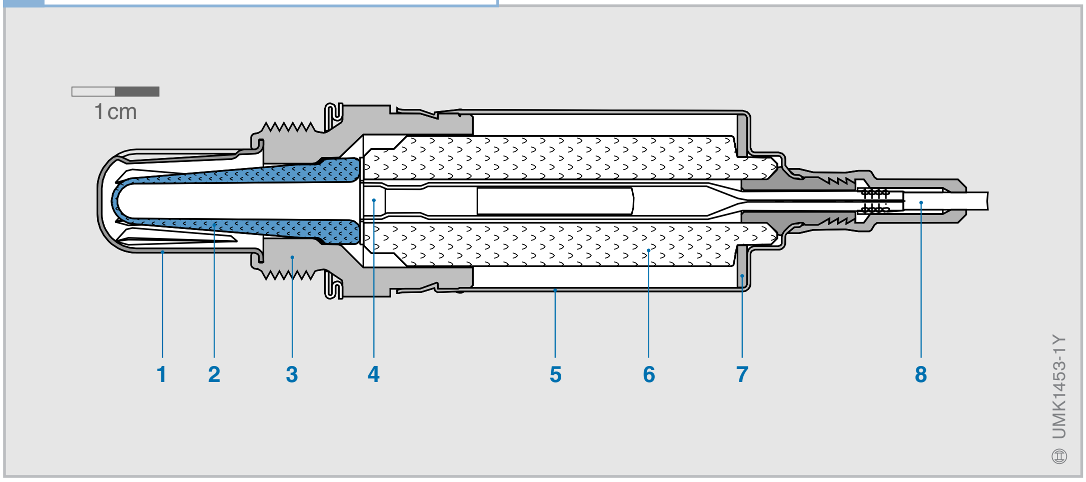

Fig. 3
1 Protective tube
2 Active sensor ceramic
3 Sensor housing
4 Contact element
5 Protective sleeve
6 Ceramic support tube
7 Disc spring
8 Connection cable

4 LSH24 heated tube-type (finger) Lambda sensor

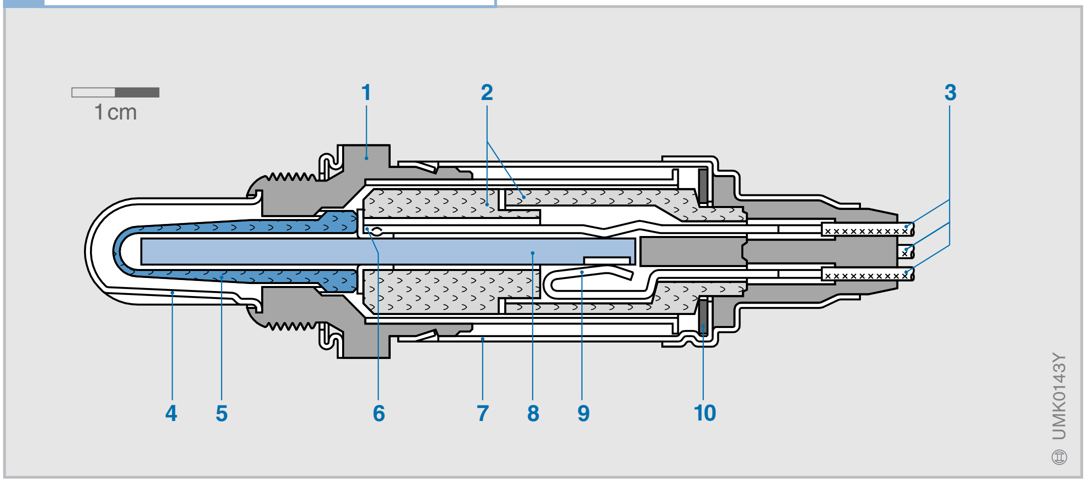

Fig. 4
1 Sensor housing
2 Ceramic support tube
3 Connection cable
4 Protective tube with slots
5 Active sensor ceramic
6 Contact element
7 Protective sleeve
8 Heater element
9 Clamp-type connections for the heater element
10 Disc spring

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Planar Lambda oxygen sensors

Regarding their function, planar Lambda sensors correspond to the heated finger sensors with their voltage-jump curve at $\lambda = 1$. On the planar sensor though, the solid-state electrolyte is comprised of a number of individual laminated foils stacked one on top of the other (Fig. 5). The sensor is protected against thermal and mechanical influences by a double-walled protective tube.

The planar ceramic element (measuring element and heater) is shaped like a long stretched-out wafer with rectangular cross-section. The measuring element's surface is provided with a microporous noble-metal coating, on the exhaust-gas side this also has a microporous ceramic coating to protect it against the erosive effects of the exhaust gas components. The heater is a wave-shaped element containing noble metal. It is integrated and insulated in the ceramic wafer and ensures that the sensor heats up quickly.

Whereas the reference chamber inside the LSF4 sensor (Figs. 6a & 7) has a direct connection to the surrounding air, in the LSF8 sensor (Figs. 6b & 8) it is connected to a sealed oxygen reference chamber.

Operating concept

The two-step sensors operate in accordance with the Nernst principle, and as from about 350 °C their ceramic becomes conductive for oxygen ions. When the engine is operated with excessive fuel, there is residual oxygen in the exhaust gas (e.g. for $\lambda = 0.95$, there is still 0.2... 0.3 percent by volume). This leads to the generation of a voltage between the sensor's boundary layers due to the different oxygen concentration inside and outside the sensor. This means that the exhaust gas's oxygen content can be applied as a measure for the A/F ratio.

The LSF8 sensor's special feature is that it compares the residual oxygen in the exhaust gas with the oxygen contained in a reference chamber inside the sensor which is completely sealed-off to the outside. With the pump voltage U_P applied at the two electrodes a 20 μA current flows which continually pumps oxygen from the exhaust gas through the oxygen-conducting ZrO_2 ceramic and into the reference chamber. From the reference chamber though, which is filled with porous filler material, oxygen permanently diffuses to the exhaust-gas side in accordance with the oxygen content there. This interplay results in the sensor voltage.

5 Planar Lambda sensor (functional layers)

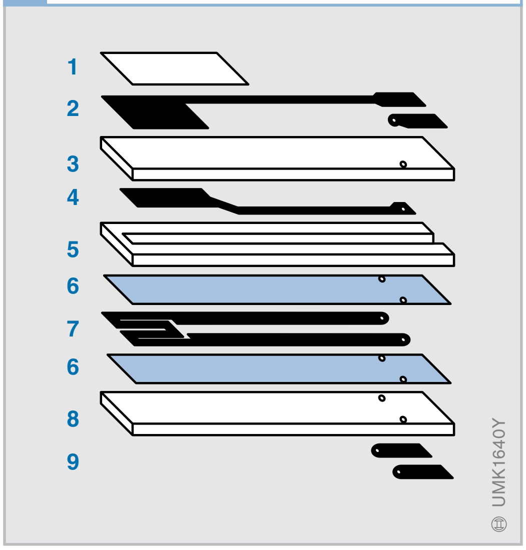

Fig. 5
1 Porous protective layer
2 Outer electrode
3 Sensor foil
4 Inner electrode
5 Reference-air-passage foil
6 Insulation layer
7 Heater
8 Heater foil
9 Connection contacts

6 Planar Lambda sensor (schematic)

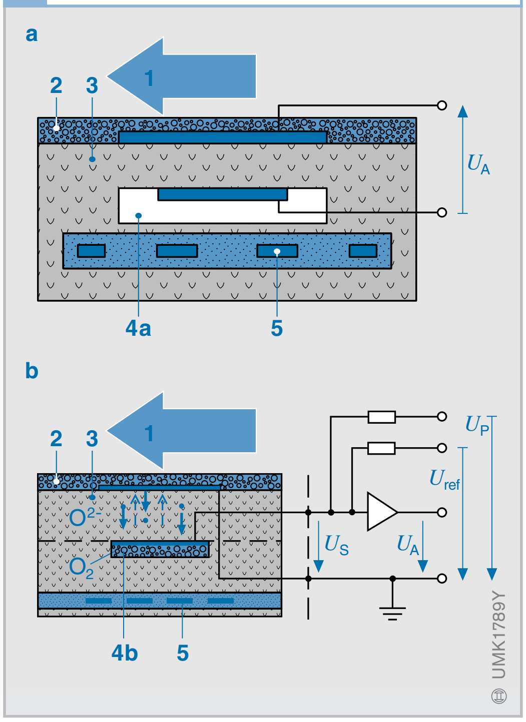

Fig. 6
a LSF4 version
b LSF8 version
1 Exhaust gas
2 Protective porous ceramic layer
3 Measuring element with microporous noble-metal coating
4a Reference-air passage
4b Reference chamber for O_2
5 Heater
U_A Output voltage
U_S Sensor voltage
U_P Pump voltage
U_{ref} Reference voltage

The sensor's output voltage is a function of the oxygen content in the exhaust gas. In the case of a rich mixture ($\lambda < 1$) it reaches 800...1000 mV, and for a lean mixture ($\lambda > 1$) only about 100 mV. The transition from the rich to the lean area is at about 450...500 mV.

The ceramic structure's temperature also influences its ability to conduct the oxygen ions, and therefore the shape of the output-voltage curve as a function of the excess-air factor λ (the values in Fig. 1 apply for about 600 °C). Apart from this, the response time for a voltage change when the A/F mixture changes is also strongly dependent upon temperature.

Whereas response times at ceramic temperatures below 350 °C are in the seconds range, at optimum temperatures of around 600 °C the sensor responds in less than 50 ms. When the engine is started therefore, the Lambda closed-loop control is switched off until the minimum operating temperature of about 350 °C is reached. During this period, the engine is open-loop controlled.

Excessive temperatures reduce the sensor's useful life. This means that the Lambda sensor must be installed so that 850 °C is not exceeded for longer periods during WOT operation. 930 °C are permissible for brief periods.

7 LSF4 planar Lambda sensor

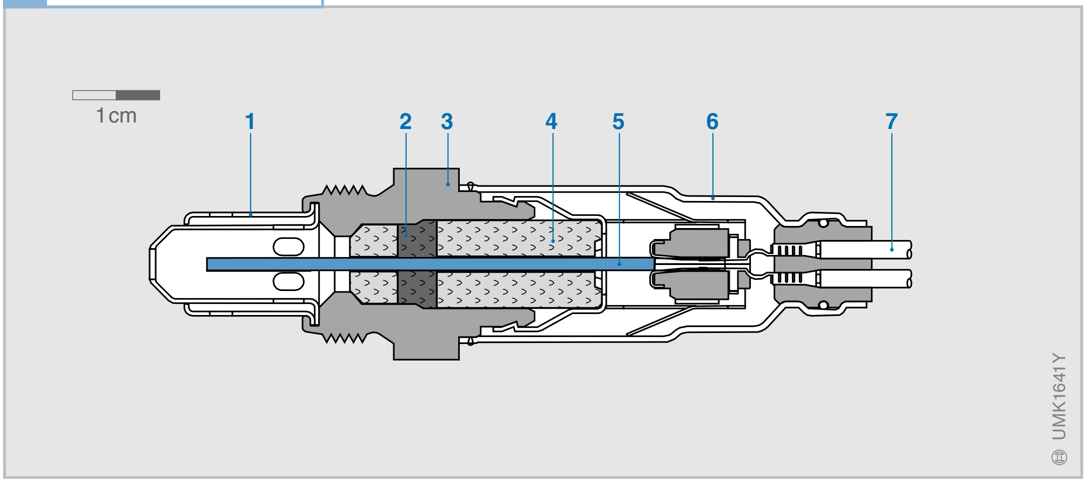

Fig. 7
1 Protective tube
2 Ceramic seal packing
3 Sensor housing
4 Ceramic support tube
5 Planar measuring element
6 Protective sleeve
7 Connection cable

8 LSF8 planar Lambda sensor

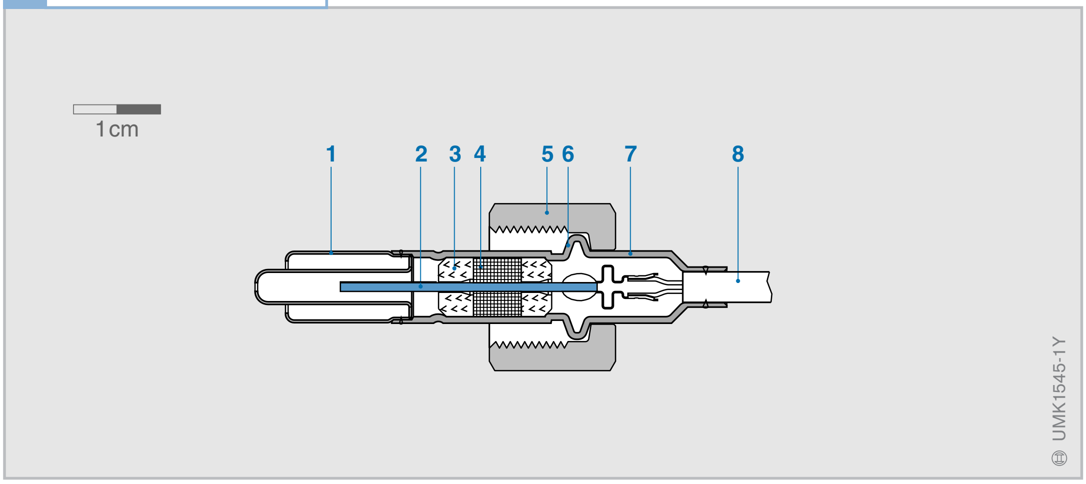

Fig. 8
1 Protective tube
2 Planar measuring element
3 Insulating sleeve
4 Ceramic seal packing
5 Union nut
6 Sealing flange
7 Sensor housing
8 Sheathed-metal cable

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LSU4 planar broad-band Lambda oxygen sensors

Application

As its name implies, the broad-band Lambda sensor is used across a very extensive range to determine the oxygen concentration in the exhaust gas. The figures provided by the sensor are an indication of the air-fuel (A/F) ratio in the engine's combustion chamber. The excess-air factor λ is used when defining the A/F ratio. Broad-band Lambda sensors are capable of making precise measurements not only at the stoichiometric point $\lambda = 1$, but also in the lean range ($\lambda > 1$) and the rich range ($\lambda < 1$). In the range from $0.7 < \lambda < \infty$ (∞ = air with 21% O_2), these sensors generate an unmistakable, continuous electrical signal (Fig. 2).

These characteristics enable the broad-band Lambda sensor to be used not only in engine-management systems with two-step control ($\lambda = 1$), but also in control concepts with rich and lean air-fuel (A/F) mixtures. This type of Lambda sensor is also suitable for the Lambda closed-loop control used with lean-burn concepts on gasoline engines, as well as for diesel engines, gaseous-fuel engines and gas-powered central heaters and water heaters (this wide range of applications led to the designation LSU: Lambda Sensor Universal (taken from the German), in other words Universal Lambda Sensor).

The sensor projects into the exhaust pipe and registers the exhaust-gas mass flow from all cylinders.

In a number of systems, several Lambda sensors are installed for even greater accuracy. Here, for instance, they are fitted upstream and downstream of the catalytic converter as well as in the individual exhaust tracts (cylinder banks).

Design and construction

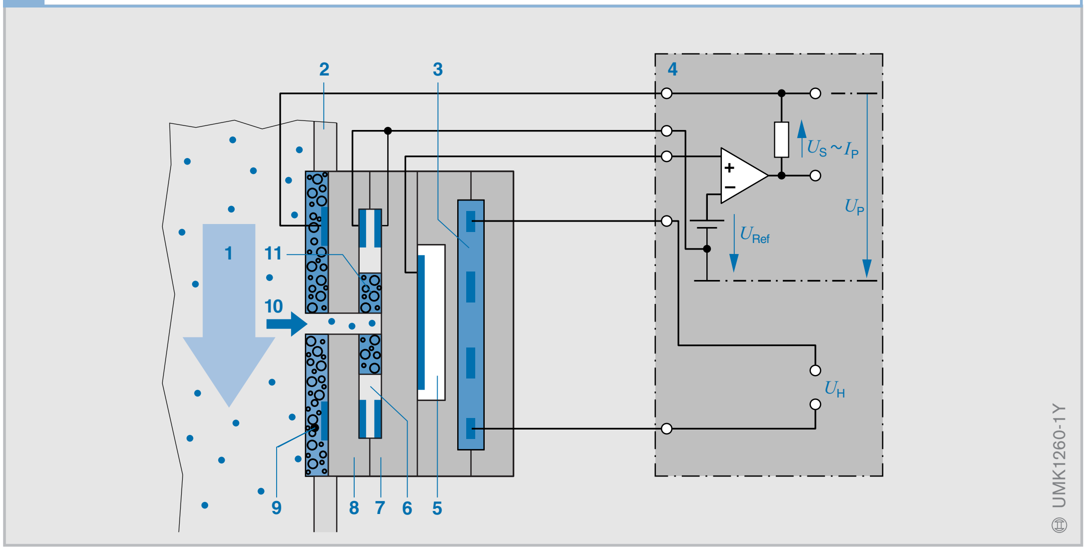
The LSU4 broad-band Lambda sensor (Fig. 3) is a planar dual-cell limit-current sensor. It features a zirconium-dioxide measuring cell (Fig. 1) which is a combination of a Nernst concentration cell (sensor cell which functions the same as a two-step Lambda sensor) and an oxygen pump cell for transporting the oxygen ions.

The oxygen pump cell (Fig. 1, Pos. 8) is so arranged with respect to the Nernst concentration cell (7) that there is a 10...50 μm diffusion gap (6) between them which is connected to the exhaust gas through a gas-access passage (10). A porous diffusion barrier (11) serves to limit the flow of oxygen molecules from the exhaust gas.

Fig. 1
1 Exhaust gas
2 Exhaust pipe
3 Heater
4 Control electronics
5 Reference cell with reference-air passage
6 Diffusion gap
7 Nernst concentration cell
8 Oxygen pump cell with internal and external pump electrode
9 Porous protective layer
10 Gas-access passage
11 Porous diffusion barrier

I_P Pump current
U_P Pump voltage
U_H Heater voltage
U_{Ref} Reference voltage (450 mV corresponds to $\lambda = 1$)
U_S Sensor voltage

1 Planar broad-band Lambda sensor (installation in the exhaust pipe and schematic design of the measuring cell)



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On the one side, the Nernst concentration cell is connected to the atmosphere by a reference-air passage (5), and on the other, it is connected to the exhaust gas in the diffusion gap.

The sensor must have heated up to at least 600...800 °C before it generates a usable signal. It is provided with an integral heater (3), so that the required temperature is reached quickly.

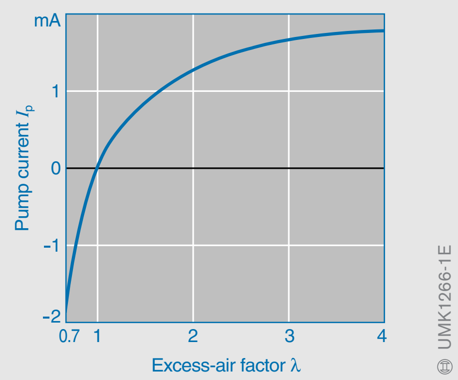
Operating concept

The exhaust gas enters the actual measuring chamber (diffusion gap) of the Nernst concentration cell through the pump cell's gas-access passage. In order that the excess-air factor λ can be adjusted in the diffusion gap, the Nernst concentration cell compares the gas in the diffusion gap with that in the reference-air passage.

The complete process proceeds as follows:

By applying the pump voltage U_P across the pump cell's platinum electrodes, oxygen from the exhaust gas can be pumped through the diffusion barrier and into or out of the diffusion gap. With the help of the Nernst concentration cell, an electronic circuit in the ECU controls the voltage (U_P) across the pump cell in order that the composition of the gas in the diffusion gap remains constant at $\lambda = 1$. If the exhaust gas is lean, the pump cell pumps the oxygen to the outside (positive pump current). On the other hand, if it is rich, due to the decomposition of CO_2 and H_2O at the exhaust-gas electrode the oxygen is pumped from the surrounding exhaust gas and into the diffusion gap (negative pump current). Oxygen transport is unnecessary at $\lambda = 1$ and pump current is zero. The pump current is proportional to the exhaust-gas oxygen concentration and is thus a non-linear measure for the excess-air factor λ (Fig. 2).

2 Pump current I_P of a broad-band Lambda sensor as a function of the exhaust-gas excess-air factor (λ)



3 LSU4 planar broad-band sensor

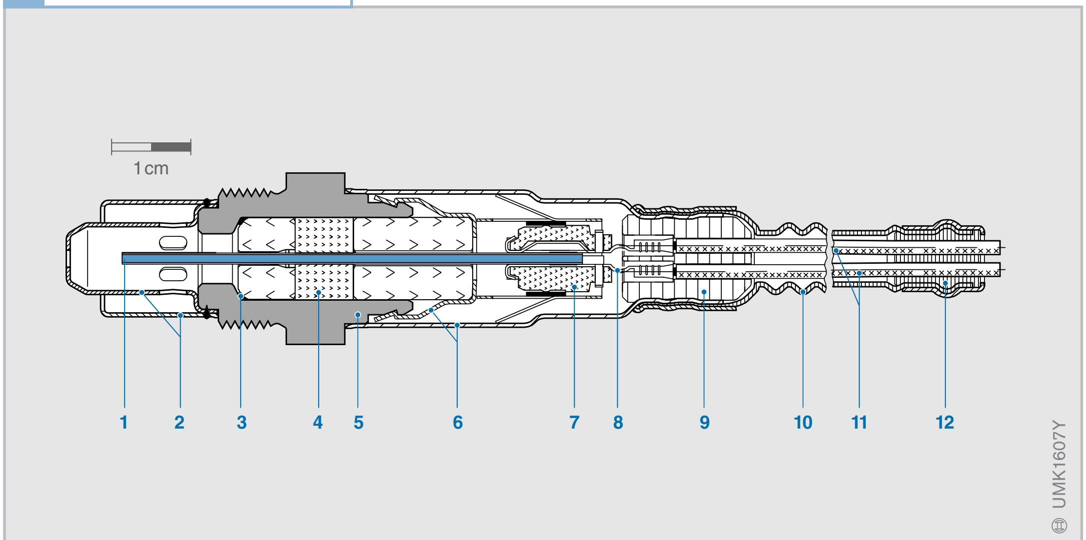


Fig. 3
1 Measuring cell (combination of Nernst concentration cell and oxygen-pump cell)
2 Double protective tube
3 Seal ring
4 Seal packing
5 Sensor housing
6 Protective sleeve
7 Contact holder
8 Contact clip
9 PTFE sleeve (Teflon)
10 PTFE shaped sleeve
11 Five connecting leads
12 Seal ring

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Temperature sensors

Measured quantities

Temperature is defined as a nondirectional quantity which characterises the energy state of a given medium, and which can be a function of time and location:

$$T = T\,(\mathrm{x}, \mathrm{y}, \mathrm{z}, t) \qquad (1)$$

Where x, y, z are the space coordinates, t is time, and T is measured according to the Celsius or Kelvin scale.

Generally speaking, with measured mediums which are in gaseous or liquid form, measurements can be taken at any point. In the case of solid bodies, measurement is usually restricted to the body's surface. With the most commonly used temperature sensors, in order for it to assume the medium's temperature as precisely as possible, the sensor must be directly in contact with the measured medium (direct-contact thermometer). In special cases though, proximity or non-contacting temperature sensors are in use which measure the medium's temperature by means of its (infrared) thermal radiation (radiation thermometer = Pyrometer, thermal camera).

Generally speaking, a temperature sensor should reflect this dependency correctly, in other words, it should reflect as accurately as possible the local distribution of the temperature and its change as a function of time.

In special cases, possibly for functional reasons, this stipulation can be relaxed somewhat. The call for high local resolution and for high-speed response both demand that the sensor should be as small as possible, since it should not falsify the temperature readings by itself absorbing heat. In other words it should have a low thermal capacity.

In order to ensure that the temperature assumed by the sensor remains independent of the usually very different temperature of its mounting, it should be thermally well insulated from it. Since this also falsifies the measurement, the heat developed by the majority of sensors in the active state should be kept to a minimum (e.g. <1 mW).

The temperature sensor's dynamic response is given the time constant τ. This defines the time taken by the sensor to reach 63%, 90%, or 99% of its final reading when subjeted to a jump in temperature. This time depends not only upon the sensor's thermal capacity, but also to a great extent upon the heat-transfer coefficient between the sensor and the medium. The higher it is, the faster the sensor reaches its final reading. Naturally, this figure is far higher for liquid mediums than for gaseous mediums. It must also be taken into account that in case of medium flow, the heat-transfer coefficient is highly influenced by the flow rate v (refer to "hot-film air-mass meter"), and increases by about $\sqrt{v}$. In other words, the time constant of a temperature sensor should always be specified with reference to the defined flow rate of a defined medium.

Temperature measurement in the vehicle makes use almost exclusively of the temperature-dependence of electrical resistance material with positive (PTC) or negative (NTC) temperature coefficient. The direct-contact thermometers apply this phenomena. For the most part, the conversion of the temperature change to an analog voltage takes place by adding a second resistor to form a voltage divider (which also has a linearising effect). The latter can be either neutral with regard to temperature, or temperature-dependent in the other direction. Recently though, non-contacting (pyrometric) temperature sensing has been considered for passenger-protection (passenger-position monitoring for airbag triggering), and for comfort and convenience (climate control in accordance with skin-temperature measurement, prevention of windscreen mist-up). It needed the advent of microsystem technology for this (pyrometric) method to become feasible from the costs viewpoint. Table 1 presents a listing of the temperatures which have to be measured in the vehicle.

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Table 1

1 Temperatures in the vehicle

Measuring point	Temperature range °C
Intake air/Charge air	–40 ... 170
Vehicle surroundings	–40 ... 60
Passenger compartment	–20 ... 80
Fan outlet air/Heater	–20 ... 60
Evaporator (air-conditioner)	–10 ... 50
Coolant	–40 ... 130
Engine oil	–40 ... 170
Battery	–40 ... 100
Fuel	–40 ... 120
Tire air	–40 ... 120
Exhaust gas	100 ... 1000
Brake caliper	–40 ... 2000

Not only the highly differing temperature ranges demand a variety of different sensor concepts and technologies, but also the different accuracies and speeds which are required but not listed in the Table. In many cases, the temperature is measured and applied as an auxiliary quantity in order to be able to compensate for it as a cause of defect or as an unwanted influencing variable.

Measuring principles

Direct-contact sensors

The fact that practically all physical processes are temperature-dependent means that there are almost just as many methods for making temperature measurements. The preferable methods though are those in which the temperature effect is very distinctive and dominant and as far as possible features a linear characteristic. Furthermore, the measuring elements should be suitable for inexpensive mass-production, whereby they should be adequately reproducible and non-aging. Taking these considerations into account, the following sensor techniques have come to the forefront, some of which are also applied in automotive technology:

Resistive sensors

In the form of 2-pole elements, temperature-dependent electrical resistors are particularly suitable for temperature measurement, no matter whether in wire-wound, sinter-ceramic, foil, thin-film, thick-film, or monocrystalline form. Normally, in order to generate a voltage-analog signal they are combined with a fixed resistor R_V to form a voltage divider, or load-independent current is applied (Fig. 1). The voltage-divider circuit changes the original sensor characteristic $R(T)$, to another characteristic $U(T)$:

$$U(T) = U_0 \cdot \frac{R(T)}{R(T) + R_V} \qquad (2)$$

On the other hand, the application of a load-independent current I_0 permits the resistor curve to be reproduced exactly:

$$U(T) = I_0 \cdot R(T) \qquad (3)$$

The measurement sensitivity is reduced more or less depending upon the construction of the voltage-divider circuit. Notwithstanding this fact, in the case of resistance characteristics which display a slightly progressive curve it does have a linearisation influence (an effect which is usually very welcome). Very often, in this connection, the auxiliary resistor is so dimensioned that it equals the measuring resistor at a given reference temperature T_0 (e.g. 20 °C):

$$R_V \approx R\,(T_0) \qquad (4)$$

1 Methods for resistance/voltage conversion

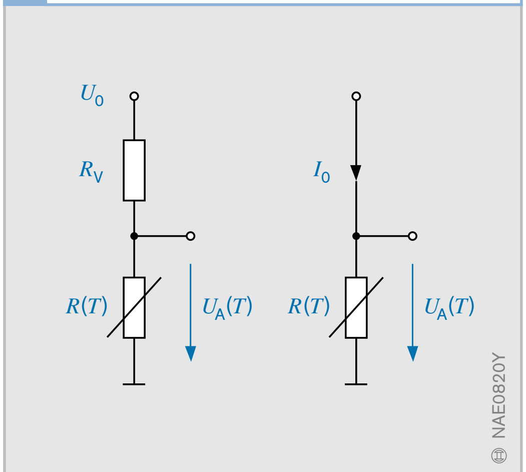

Fig. 1
I_0 Current supply
U_0 Suppy voltage
R_V Temperature-dependent series resistor
$R(T)$ Temperature-dependent measuring resistor
$U_A(T)$ Output voltage

If the precision is inadequate, a resistance sensor can be calibrated to the desired value both with regard to its resistance (referred to a reference temperature), and its temperature coefficient (TK), by means of an adjustable parallel resistor R_P and a series resistor R_S (Fig. 2). Of course, when resistors are added the TK is reduced and the characteristic changes somewhat.

Sintered-ceramic NTC reistors

As a result of their pronounced measuring effects and inexpensive manufacture, the most common semiconductor resistances in use are based on heavy-metal oxides and oxidised crystals. These are sintered in bead form or disc form (Fig. 3) and have a polycrystalline structure. They are often referred to as NTC thermistors. To a good approximation, and by applying the exponential law, their characteristic curve can be defined as follows:

$$R(T) = R_0 \cdot e^{B \cdot (\frac{1}{T} - \frac{1}{T_0})} \quad (5)$$

Where $R_0 = R(T_0)$,
$B = 2000...5000$ K = constant,
T absolute temperature

Here, the characteristic-curve gradient (TK) or the percentage resistance change as a function of temperature, is highly dependent upon the working point. This means that it can only be defined at given points:

$$\text{TK} = -B/T^2 \quad (6)$$

It reduces considerably along with increasing temperature, and often the resistance varies by 4 ... 5 powers of ten. For instance, a typical variation would be from several 100 kΩ to 50...60 Ω. This pronounced temperature-dependence means that applications are restricted to a "window" of about 200 K. This though can be selected in the –40...approx. 850 °C range. Tighter toler-

2 Calibration of a resistor to its desired value

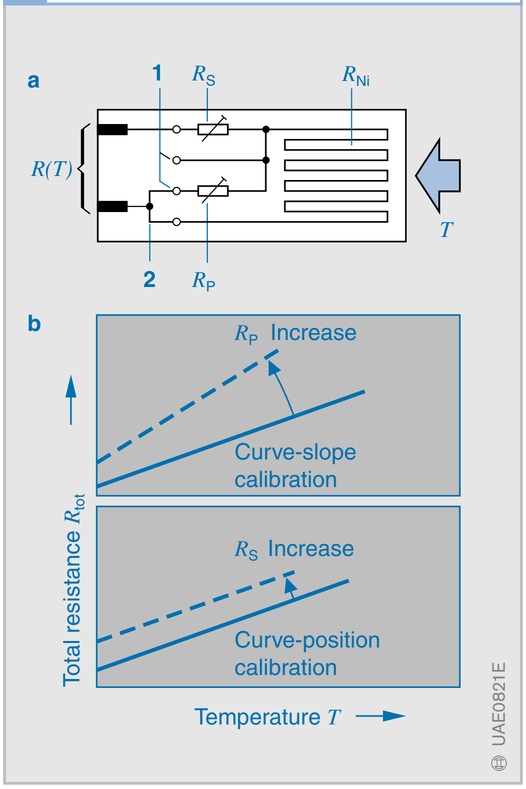

Fig. 2
- a Resistance sensor
- b Characteristic curves
- 1 Auxiliary contacts
- 2 Bridge
- R_{Ni} Nickel film resistor
- $R_{tot}(T)$ Total resistance referred to temperature
- R_P Adjustable parallel resistor
- R_S Adjustable series resistor

3 NTC resistors (examples)

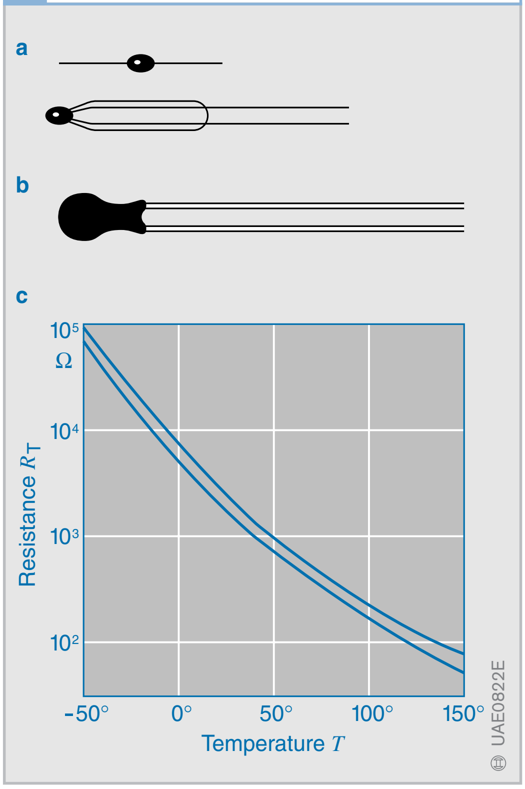

Fig. 3
- a Pearl-form
- b Disc form
- c Characteristc curve with limits of variation

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ances of up to ±0.5 K at a given reference point are complied with by using a selection process, or possibly even by grinding in oil, a method which of course has an affect upon costs. The ageing stability of these sensors has been vastly improved compared to earlier versions which means that it is quite possible for the very close tolerances to apply throughout the sensor's useful life.

PTC thin-film/thick-film metallic resistors

The thin-film metallic resistors are integrated with two additional temperature-neutral trimming resistors on a common substrate chip. Since these resistors have a close-tolerance characteristic curve, can be manufactured with long-term stability, and are suitable for fine trimming using laser cuts (Fig. 4), they feature very high accuracy. Thanks to the film technology applied, it is

4 Thin-film temperature sensor (Ni) with frequency-analog output signal

UAE0234Y

possible to adapt the masking layer as used for protection against the measured medium, and the substrate material, to the particular measuring assignment. The substrate material can be ceramic, glass, or plastic foil, and the masking layer can use plastic moulding, paint, welded foil, glass or ceramic materials. Compared to oxide-ceramic semiconductor sensors, metallic layers feature lower temperature-dependencies, but a more favorable characteristic regarding linearity and reproducibility. The following applies for the computational definition of these sensors:

$$R(T) = R_0\,(1 + \alpha \cdot \Delta T + \beta \cdot \Delta T^2 + ..) \qquad (7)$$

Where $\Delta T = T - T_0$ und
$T_0 = 20\,°C$ (reference temperature),
α = Linear temperature coefficient (TC),
β = Quadratic temperature coefficient.

Even though the β coefficient is very small for metals it cannot be ignored completely. This is why the measurement sensitivity of such sensors is usually characterised by means of a mean TC, the "TC 100". The TC 100 corresponds the mean curve gradient between 0 °C and 100 °C (Table 2 and Fig. 5).

2 Temperature Coefficient TC 100

Sensor material	TK 100 10^{-3}/K	Characteristic curve	Measuring range
Nickel (Ni)	5.1	Slightly progressive	–60 ... 320
Copper (Cu)	4.1	Slightly progressive	–50 ... 200
Platinum (Pt)	3.5	Slightly degressive	–220 ... 850

Table 2

$$\text{Where } TK100 = \frac{R(100\,°C) - R(0\,°C)}{R(0\,°C) \cdot 100K} \qquad (8)$$

Although platinum (Pt) resistors have the lowest TC, they are not only the most precise resistive temperature sensors, but can also boast the best ageing stability. They are available on the market under the designa-

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tion "PT 100" or "PT 1000" (100 Ω or 1000 Ω nominal resistance at a reference temperature of 20 °C) in a variety of different tolerance classes (up to 0.1 °C, Fig. 6). At temperatures up to about 1000 °C, thick-film Pt sensors are suitable whose Pt layer has been stabilized by special additives.

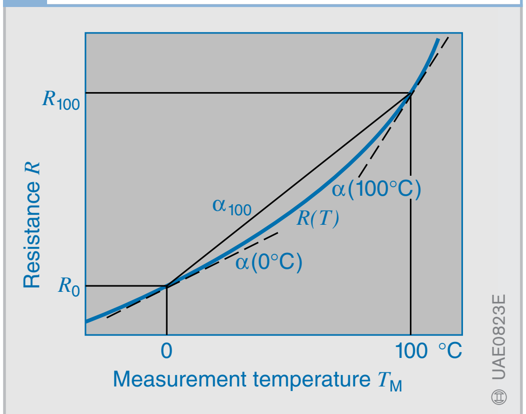
Thick-film resistors (PTC/NTC)

Thick-film pastes with high specific resistance (low surface area), and with positive and negative temperature coefficients are mainly used as temperature sensors for compensation purposes. They have a nonlinear characteristic (which though is not as "bent" as the curve of the solid NTC resistors), and are suitable for laser-trimming. The measuring effect is improved by forming voltage-divider circuits from NTC and PTC materials.

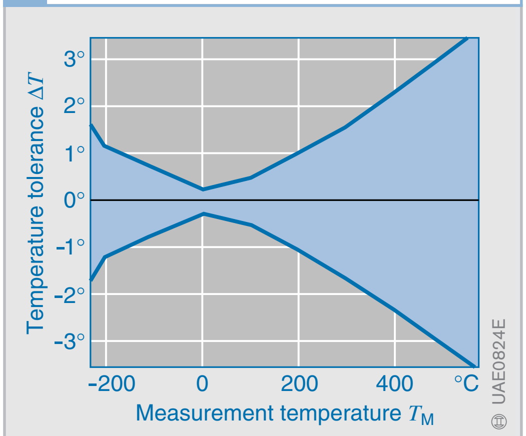
Monocrystalline silicon semiconductor resistors (PTC)

Basically speaking, with temperature sensors of monocrystalline semiconductor materials such as silicon (Si), it is possible to incorporate further active and passive circuit elements on the sensor chip (initial signal conditioning at the measurement point). Due to the close tolerances involved, their production uses the "spreading resistance" principle (Fig. 7a). Current flows through the measuring resistor via a surface point contact and into the Si bulk material from where it spreads in a fan shape to a counter-electrode covering the base of the sensor chip. In addition to the high reproducibility material

5 Definition of the mean temperature coefficient TK 100 = α_{100}



6 Pt resistor (tolerance diagram)



7 Spreading-resistance principle (dual-hole version)

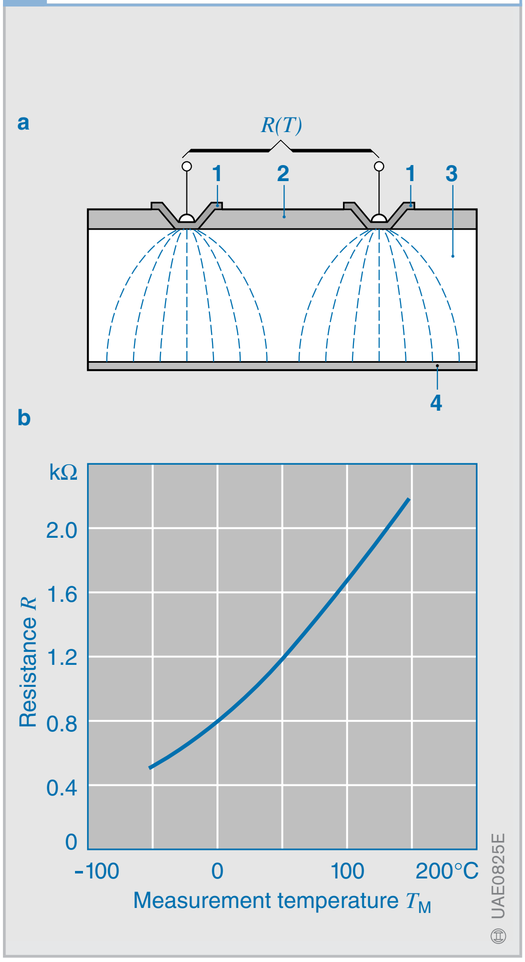


Fig. 7
- a Design
- b Characteristic curve
- 1 Contacts
- 2 Passivation (Nitride, oxide)
- 3 Si substrate
- 4 Counter-electrode without connection
- $R(T)$ Temperature-dependent resistor

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constants, the high current density behind the contact point (high accuracy thanks to photolithographic production) mainly defines the sensor's resistance. In order to make the sensor highly independent of polarity, these sensors are usually series-connected in pairs (dual-hole version, Fig. 7). The base electrode can be in the form of a temperature contact (no electrical function).

Measurement sensitivity is practically double that of a Pt resistor (TK = $7.73 \cdot 10^{-3}$/K). The progressive bend of the temperature curve is more pronounced than on a metallic sensor. The measuring range is limited to approx. +150 °C by the material's intrinsic conductivity (Fig. 7b). There are special versions (Fig. 8) available for operations up to 300 °C.

Thermocouples

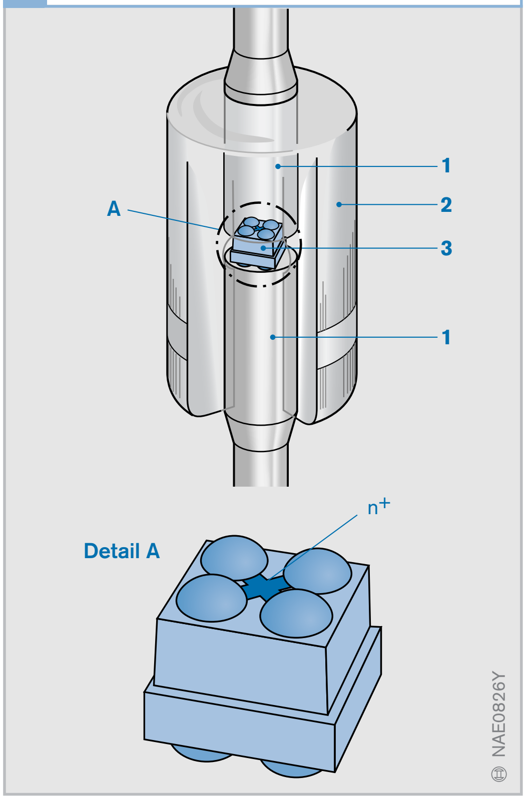
Thermocouples are used in particular for measurement ranges >1000 °C. They rely on the "Seebeck Effect" according to which there is a voltage between the ends of a metallic conductor when these are at different temperatures T_1 und T_2. This "thermovoltage" U_{th} is solely a function of the temperature difference ΔT between the ends of the conductor (Fig. 9). The following applies:

$$U_{th} = c\,(T_2 - T_1) = c\,\Delta T, \qquad (9)$$

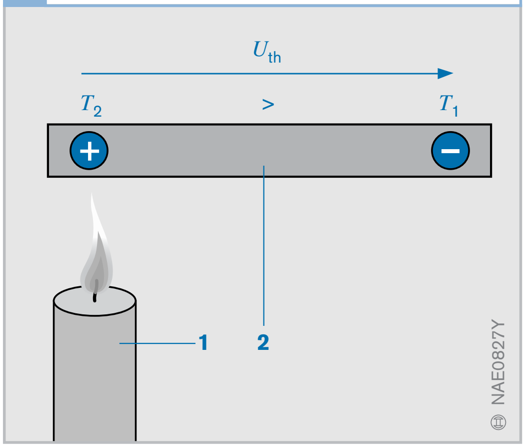
whereby the proportionality constant is material-specific and termed the "Seebeck-Effect".

Since the instrument leads used to measure this voltage across the metallic conductor must themselves be equipped with terminals (for instance made of copper), these are also subject to the same temperature difference, so that unfortunately only the difference between the metallic conductor and the instrument leads is measured. Thermoelectric voltages are always listed based on Platinum as the reference material (Table 3).

8 Spreading resistance sensor (unipolar version for temperatures up to 300 °C)



9 Seebeck effect



3 Thermoelectric voltage U_{th} of a number of metals

Material	Thermoelectric voltage U_{th} mV/100 °C
Constantan	–3.40
Nickel	–1.90
Paladium	–0.28
Platinum	0.00
Copper	+0.75
Manganin	+0.60
Iron	+1.88
Silicon	+44.80

Fig. 9
1 Heat source
2 Metallic conductor
+ High,
– Low thermal velocity of the electrons
T_2 High temperature
T_1 Low temperature
U_{th} Thermoelectric voltage

Fig. 8
1 Metal wire
2 Glass
3 Si crystal

Table 3

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In order that the generated voltages are as high as possible, a number of material pairs have established themselves (Fig. 10, e.g. iron/constantan etc.). It is important that the "limbs" of such a thermocouple are joined at the end to which the heat is applied in such a manner that the joint is electrically conductive (by means of twisting, welding, soldering, etc., Fig. 11).

Thermocouples themselves are usually short, and the extensions up to the point where the signal is picked-off can be made with equalising conductors which use the same material pair as in the thermocouple itself. It is important that both free ends of the thermoelement configuration are at the same (reference) temperature, otherwise the temperature difference at the free ends will also be included in the measurement. Thermocouples, therefore, always measure only the temperature difference to a given reference point. If the measuring point's absolute temperature is to be measured, other devices (such as resistive sensors) must be used to also measure the temperature at the reference point.

The characteristic curve of the thermoelectric voltage against temperature is usually not as linear as that given in Equation (8). The sensor signals are usually small, and IC's are used for their amplification and for their linearisation. In order to increase the measurement voltage, it is common practice to connect a number of identical thermocouples in series. These have their "hot" junctions at the temperature to be measured, and their "cold" junctions at the reference temperature (Fig. 12, thermopile).

Although thermocouples are robust (for instance, high-level EMC due to low internal resistance), they are not particularly accurate as a measuring device. Their deviation can

10 Common thermocouples (characteristic curves)

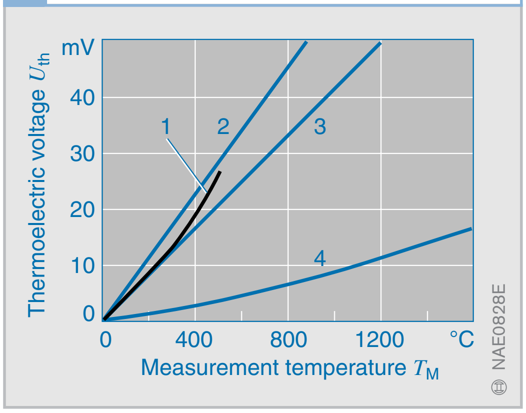

Fig. 10
1 Copper/Constantan
2 Iron/Constantan
3 Nickel-chromium/Nickel
4 Platinum rhodium/Platinum

11 Thermocouple measuring set-up

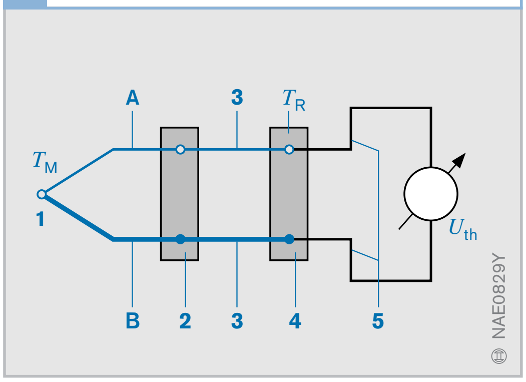

Fig. 11
A/B Material pair (thermocouple legs)
1 Measurement point (electrically conductive junction)
2 Connection head
3 Equalising conductor
4 Reference point
5 Connection cable (Cu)
T_M Measurement temperature
T_R Reference temperature
U_{th} Thermoelectric voltage

12 Thermocouples connected in series

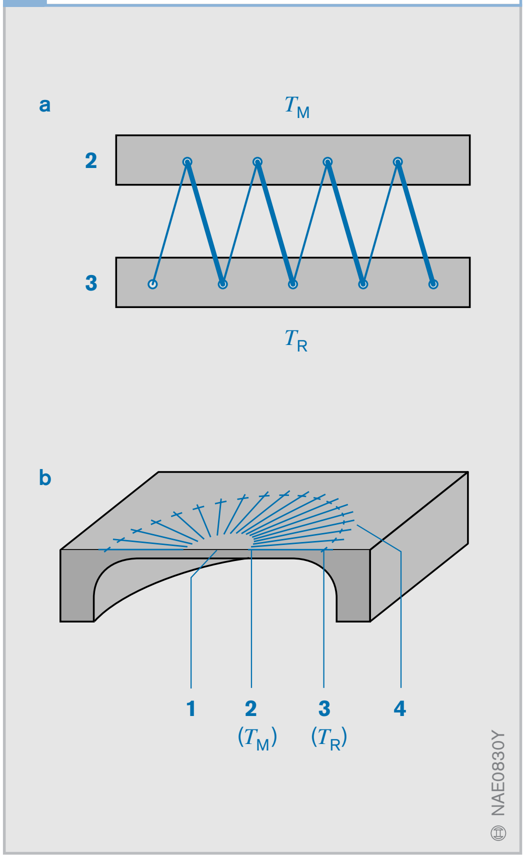

Fig. 12
a Principle of the thermopile
b Example of application
1 Sensitive surface
2 "Hot" junctions at the measurement temperature T_M
3 "Cold" junctions at the reference temperature T_R
4 Thermopile

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easily be in the 5°...15° range, and they are not outstanding regarding their resistance to ageing, which means that individual calibration does not result in a permanent improvement of their accuracy.

Of course, thermocouples can be manufactured using both thin-film and thick-film techniques. Metallic films stacked one on top of the other provide for excellent thermal contact, and extemely small thermocouples can be produced by applying microsystem technology. Thermocouples are particularly suitable for use in thermopiles comprised for instance from 50...100 individual thermocouples. They are used in non-contacting radiation thermometers (pyrometers).

Semiconductor barrier layers

Presuming a constant current, the forward voltage of semiconductor barrier layers (Fig. 13) such as those in diodes and in the basis-emitter path of a transistor, demonstrate very good linearity as a function of temperature:

$$U_F(T) = \frac{k \cdot T}{q} \cdot \ln\left(\frac{I_F}{I_{sat}} + 1\right) \qquad (10)$$

Where:
$I_{sat} = I_{sat}\,(T)$ and I_F = constant,
$q = 1.6 \cdot 10^{-19}$ C (elementary charge),
$k = 1.88 \cdot 10^{-23}$ JK^{-1} (Boltzmann's constant),
T Absolute temperature.

It is advantageous here when the sensor directly outputs a voltage which is a function of the temperature. The two-pole sensor is of course dependent upon polarity. Whereas, for all sensors, the forward voltage decreases by almost exactly 2 mV/°C, the absolute voltage at the barrier layer differs considerably from sensor to sensor, and may necessitate additional calibration elements in order for a precise measurement to be made. Above all, it is the temperature-dependent saturation current I_{sat} which is responsible for the negative temperature coefficient (NTC). This current increases dramatically with rising temperature. Here, the silicon's intrinsic conductivity limits this sensor's application to temperature ranges <150 °C.

Sometimes, emitter-coupled transistor pairs are used in a similar manner for temperature measurement. With this form of temperature measurement, the ratios of the collector currents to each other represent a very good reproducible measure for the temperature. Usually, an integrated supplementary circuit is used for the "on-chip" conversion to an analog output voltage.

Zener diodes operated in the reverse direction can also be used as highly practical temperature sensors. Their voltage changes are highly dependent upon the Zener voltage. Here, the option exists of various levels of voltage reduction at Zener voltages <4.7 V, and voltage increases at Zener voltages >4.7 V.

Such sensors are often used for temperature compensation on the chip itself.

13 Semiconductor barrier layers

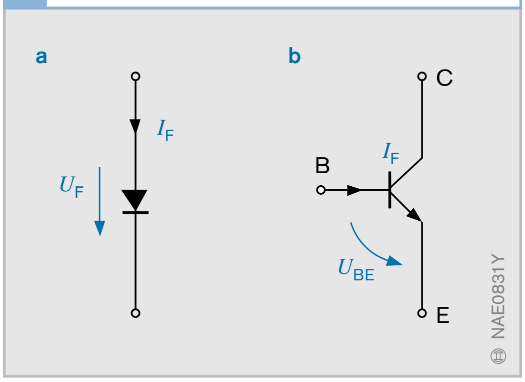

Fig. 13
a Diode
b Transistor
B Base
C Collector
E Emitter
I_F Conducting-state current
U_F Forward voltage
U_{BE} Voltage between base and emitter

Non-contacting temperature measurement, Pyrometry

The radiation emitted by a body is used for the non-contact (or proximity) measurement of its temperature. This radiation is for the most part in the infrared (IR) range (wavelength: 5...20 μm). Strictly speaking, it is the product of the body's radiated power and emission constant. The latter is a function of the material, but for materials which are technically of interest it is usually around 1, although for reflective (applies also to glass) and IR-permeable materials it is far less than 1.

The measuring point is projected onto a heat-sensitive element which, as a result, heats up slightly compared to its surroundings (typically by 0.01...0.001 °C). The element's temperature is a measure for the temperature of the body being measured. A given temperature difference at the object often corresponds to only 1/1000th of this difference at the measuring point. Nevertheless, the object's temperature can be determined with an accuracy of ±0.5 °C.

Bolometer

The Bolometer is a highly sensitive resistance temperature sensor for measuring minute temperature increases (Fig. 14). A further sensor is needed for measuring the temperature of the sensor housing. If this device is to operate efficiently across a wide temperature range, it is necessary though for both these sensors to feature an extremely high degree of synchronism. The Bolometer housing is therefore usually thermostatically controlled (and well-insulated to the housing) so that the primary detecting element (sensor) always operates at the same temperature.

Thermopile sensor

When a very extensive temperature range is concerned, it is more practical for the temperature difference generated by the radiation from the object to be measured using thermocouples. In order to increase the measuring effect, a number of thermocouples are connected in series to form the so-called thermopile. Such a thermopile sensor (Fig. 15) is inexpensive to manufacture micromechanically. All its "hot" junctions are located on a thermally well insulated thin diaphragm, and all its "cold" junctions are in contact with the thicker chip rim (heat

14 Prototype of a bolometer sensor array for automotive applications

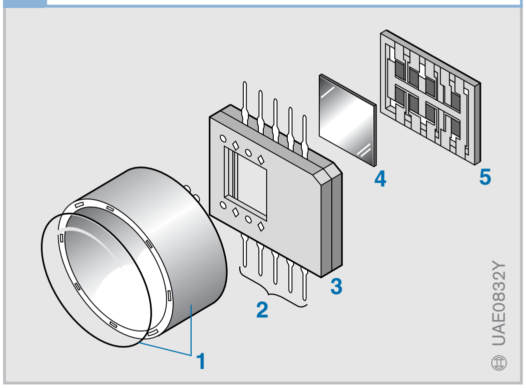

Fig. 14
1 Lens housing with lens
2 Connections
3 Infrared-detector housing
4 Infrared window
5 Detector

15 Pyrometric sensor produced using micromechanical techniques, with thermopile pick-off.

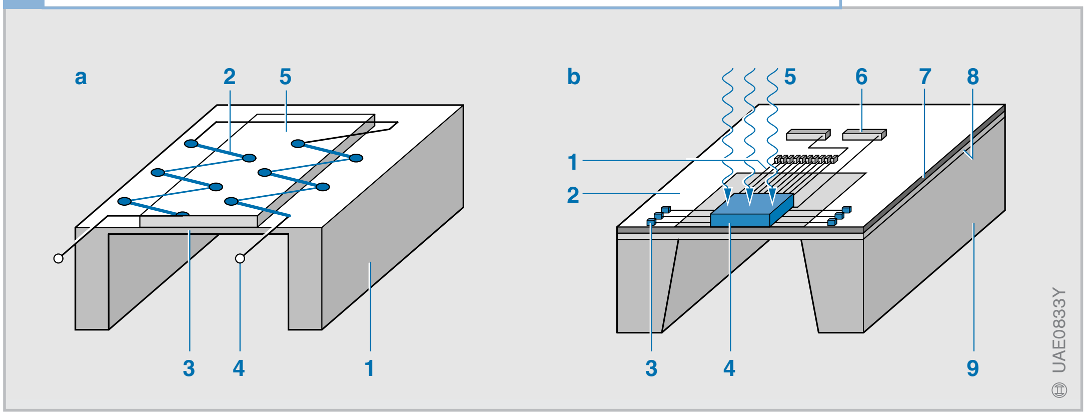

Fig. 15
a Principle of the measuring element
1 Si chip
2 Thermocouples connected in series (i.e. Al/Poly-Si)
3 SiN diaphragm
4 Thermopile junctions
5 Absorber layer

b Sensor configuration
1 Thermocouple
2 "Cold" junction
3 Diaphragm
4 Absorber
5 Heat radiation
6 Electrical connection
7 Si_3N_4 layer
8 SiO_2 layer
9 Heat sink

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sink). Typically, the sensor's response time is approx. 20 ms. Using such a so-called "single-pixel sensor", it is an easy matter to determine the windshield's surface temperature so that measures can be taken to prevent misting-up should the dew point be dropped below.

Single-point sensors, image sensors

If a number of pixels are combined on a single chip (for example, 4x4) to form an array, this provide the basis for a rough form of image analysis (Fig. 16). The pixels must be thermally well insulated from each other, and there must not be too much insensitive surface between them. Due to the fact that each pixel can be electrically addressed, the chip has a large number of connections. On a TO5 casing for example, the ASIC for signal preamplification and series connection of the signal, must be located directly adjacent to the sensor chip. Usually, in the case of thermopile sensors, this ASIC also includes a reference-temperature sensor which measures the pixel's absolute temperature. This permits object temperatures to be measured with an accuracy of approx. ±0.5 K.

An IR imaging-optics system is required for the rough thermal display of an image on the sensor array. The very inexpensive curved mirror is usually ruled out due to it needing too much room. Glass lenses are impermeable for IR light, and plastic lenses are can only be used for operating temperatures of up to approx. 85 °C max. On the other hand, Si lenses are highly suitable for thermal radiation and up to diameters of approx. 4 mm micromechanical techniques can be used to inexpensively manufacture them in the form of a Fresnel or refraction lens. Fitted in the cover of a TO5 casing, these then also serve to protect the sensor against direct damage (Fig. 17). Even though filling the casing with an inert gas improves the crosstalk between the individual pixels, it also negatively affects their response time.

Examples of application

- Intake-air temperature,
- Engine temperature,
- Passenger-compartment temperature control,
- Exhaust-gas high-temperature sensor,
- Infrared image sensor.

16 Micromechanical thermopile array

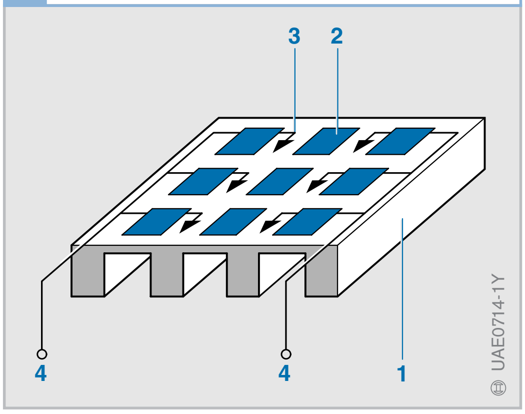


Fig. 16
1 Si chip
2 Pixel
3, 4 Pixel connections

17 Thermal image analysis

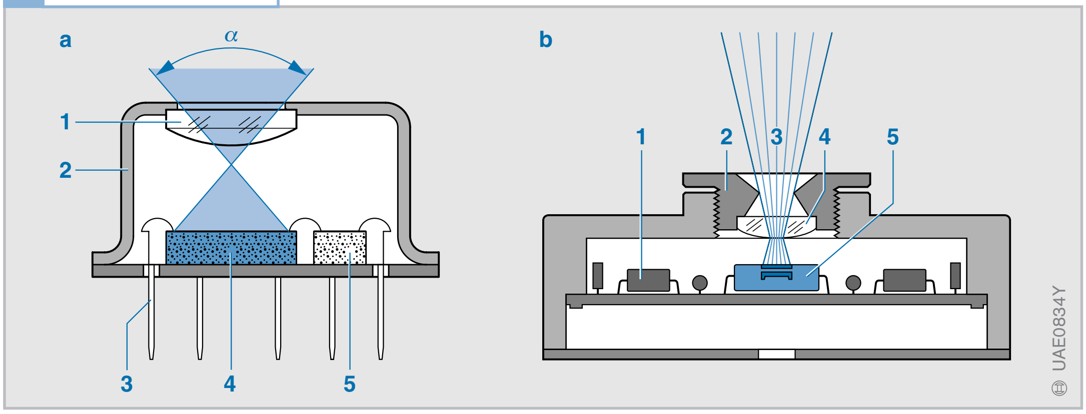


Fig. 17
a IR image sensor
1 Si IR lens
2 TO5 casing
3 Terminal posts
4 Sensor chip
5 Evaluation ASIC
α Viewing angle
b Simple IR camera
1 Electronics
2 Lens system
3 Camera's field of view
4 Si IR lens
5 Sensor array

1 Coolant temperature sensor

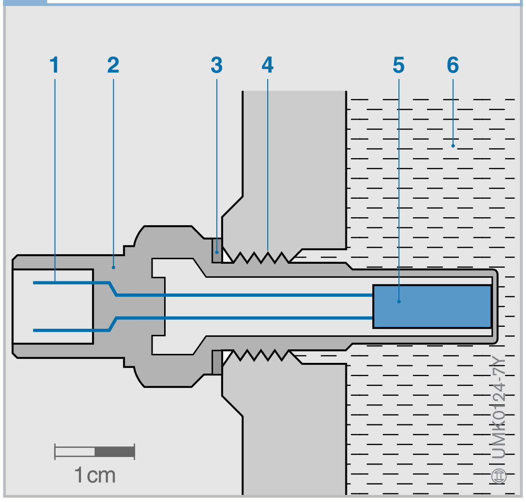
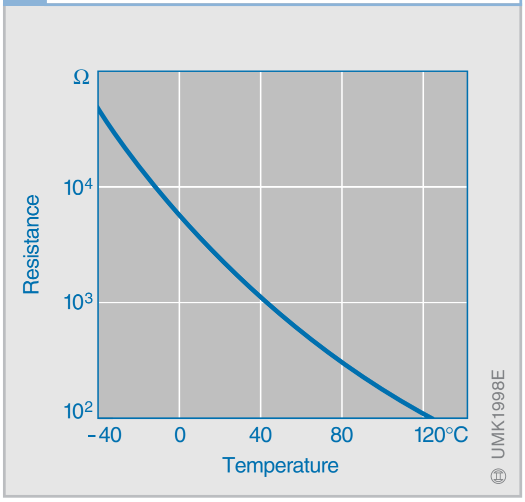


Fig. 1
1 Electrical connections
2 Housing
3 Gasket
4 Thread
5 Measuring resistor
6 Coolant

2 NTC temperature sensor: Characteristic curve



Temperature sensors

Applications

Engine-temperature sensor

This is installed in the coolant circuit (Fig. 1). The engine management uses its signal when calculating the engine temperature (measuring range – 40…+130 °C).

Air-temperature sensor

This sensor is installed in the air-intake tract. Together with the signal from the boost-pressure sensor, its signal is applied in calculating the intake-air mass. Apart from this, desired values for the various control loops (e.g. EGR, boost-pressure control) can be adapted to the air temperature (measuring range –40…+120 °C).

Engine-oil temperature sensor

The signal from this sensor is used in calculating the service interval (measuring range –40…+170 °C).

Fuel-temperature sensor

Is incorporated in the low-pressure stage of the diesel fuel circuit. The fuel temperature is used in calculating the precise injected fuel quantity (measuring range –40…+120 °C).

Exhaust-gas temperature sensor

This sensor is mounted on the exhaust system at points which are particularly critical regarding temperature. It is applied in the closed-loop control of the systems used for exhaust-gas treatment. A platinum measuring resistor is usually used (measuring range –40…+1000 °C).

Design and operating concept

Depending upon the particular application, a wide variety of temperature sensor designs are available. A temperature-dependent semiconductor measuring resistor is fitted inside a housing. This resistor is usually of the NTC (**N**egative **T**emperature **C**oefficient, Fig. 2) type. Less often a PTC (**P**ositive **T**emperature **C**oefficient) type is used. With NTC, there is a sharp drop in resistance when the temperature rises, and with PTC there is a sharp increase.

The measuring resistor is part of a voltage-divider circuit to which 5 V is applied. The voltage measured across the measuring resistor is therefore temperature-dependent. It is inputted through an analog to digital (A/D) converter and is a measure of the temperature at the sensor. A characteristic curve is stored in the engine-management ECU which allocates a specific temperature to every resistance or output-voltage.

Micromechanics

Micromechanics is defined as the application of semiconductor techniques in the production of mechanical components from semiconductor materials (usually silicon). Not only silicon's semiconductor properties are used but also its mechanical characteristics. This enables sensor functions to be implemented in the smallest-possible space. The following techniques are used:

Bulk micromechanics

The silicon wafer material is processed at the required depth using anisotropic (alkaline) etching and, where needed, an electrochemical etching stop. From the rear, the material is removed from inside the silicon layer (Fig. 1, Pos. 2) at those points underneath an opening in the mask. Using this method, very small diaphragms can be produced (with typical thicknesses of between 5 and 50 µm, as well as openings (b), beams and webs (c) as are needed for instance for acceleration sensors.

Surface micromechanics

The substrate material here is a silicon wafer on whose surface very small mechanical structures are formed (Fig. 2). First of all, a "sacrificial layer" is applied and structured using semiconductor processes such as etching (a). An approx. 10 µm polysilicon layer is then deposited on top of this and structured vertically using a mask and etching. In the final processing step, the "sacrificial" oxide layer underneath the polysilicon layer is removed by means of gaseous hydrogen fluoride. In this manner, the movable electrodes for acceleration sensors (Fig. 3) are exposed.

Wafer bonding

Anodic bonding and sealglass bonding are used to permanently join together (bonding) two wafers by the application of tension and heat or pressure and heat. This is needed for the hermetic sealing of reference vacuums for instance, and when protective caps must be applied to safeguard sensitive structures.

1 Structures produced by bulk micromechanics

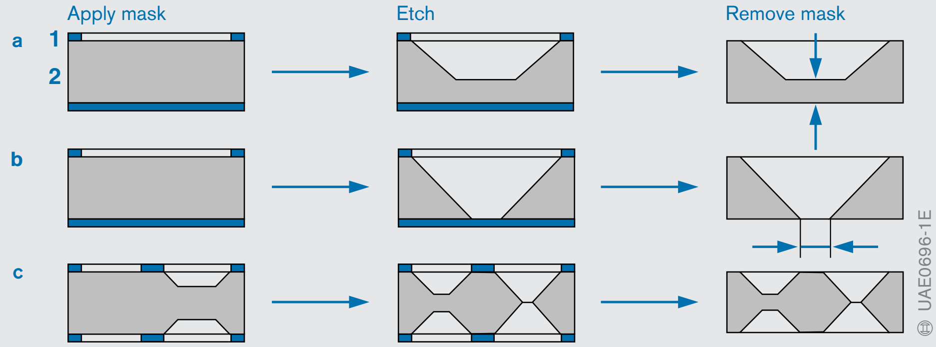
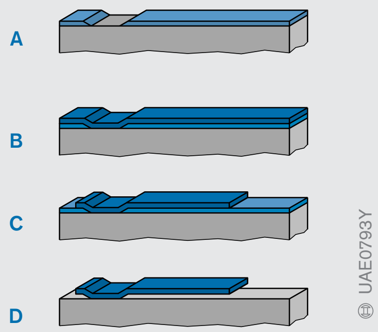


Fig. 1
- **a** Diaphragms
- **b** Openings
- **c** Beams and webs
- 1 Etching mask
- 2 Silicon

2 Surface micromechanics (processing steps)



3 Surface micromechanics (structure details)

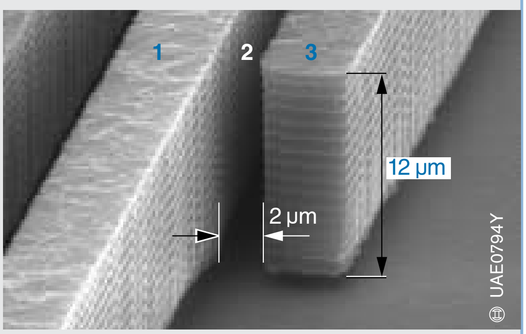


Fig. 2
- **A** Cutting and structuring the sacrificial layer
- **B** Cutting the polysilicon
- **C** Structuring the polysilicon
- **D** Removing the sacrificial layer

Fig. 3
- 1 Fixed electrode
- 2 Gap
- 3 Spring electrodes

Prospects

Development trends

In future, it is to be expected that considerably more automotive sensors will be developed for the vehicle's immediate and more remote surroundings (Fig. 1) than for its drivetrain. These developments include the sensor technology which measures the vehicle's movement (kinematics), both as an entity on its own and as a moving component in the flow of traffic. Also included are sensors which directly register the contact of the vehicle's wheels with the road surface. Of decisive importance here are a number of extensive, new assignment areas:

- Guiding and steering the vehicle to a destination (navigation),
- Reliable, safe vehicle guidance and steering by means of electronic assistance systems (up to the limits of physical possibilities),
- Extended passenger protection systems with higher intelligence levels and preemptive effects, up to as far as the total prevention of collision as the optimum objective,
- Safeguarding the vehicle by way of theft-deterrent systems using biometric sensors (e.g. passenger recognition by way of fingerprint).

Such sensors also form the basis for semi-autonomous (partially independent) vehicle driving, with full autonomy being the long-term objective.

Sensor examples

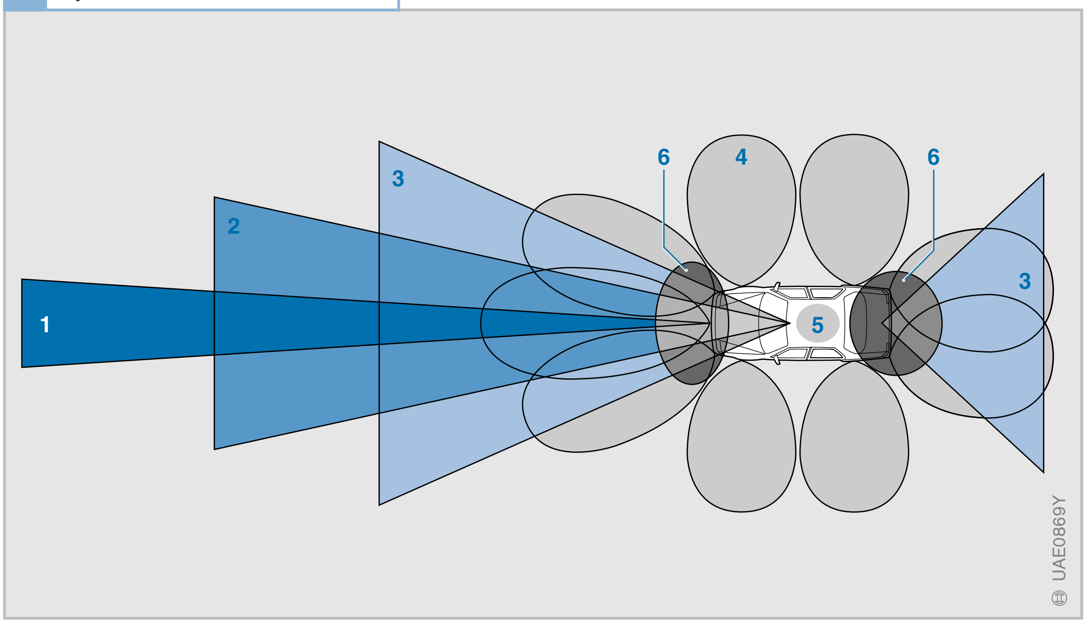
Image sensors (video)

In particular those sensors which generate images on the basis of visible light or infrared light will come to the forefront in ever increasing numbers. These will serve for passenger-compartment monitoring, and for observation outside the vehicle will be aligned to the vehicle's surroundings.

All of these sensors have one objective in view, and that is the simulation of the superior capabilities of the human eye and its mental recognition capabilities (of course, only to a very modest degree at first). It is certain that in the foreseeable future, the costs for image sensors, and the associated very-high-performance processors needed for the interpretation of a given scene, will become interesting from the automotive-applications viewpoint.

Fig. 1
1 Distant-zone radar 77 GHz, series production (distant zone: ≤120 m)
2 Distant-zone/near-range infrared viewer (nightviewing)
3 Video coverage of the vehicle's immediate vicinity (nightviewing, mid-range ≤40 m)
4 Near-range radar 24 GHz (near range: ≤10 m)
5 Passenger-compartment video
6 Ultrasonic, series production (very near range ≤1.5 m)

1 Systems for vehicular all-round vision



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In contrast to the human eye, common image sensors are sensitive in the near IR range (wavelength approx. 1 μm). With appropriate non-visible IR illumination, therefore, all imaginable applications in the vehicle become feasible, including nighttime operation.

In future, image sensors will be able to play a highly variegated role for the observation of the vehicle's interior (seating position, forward shift in case of a crash, size of seat occupants etc.), and of the vehicle's surroundings (vehicle tracking, collision prevention, parking and back-up aids, traffic-sign recognition).

Image sensors are a special case of "multi-sensor structures" formed from light-sensitive elements (pixels) which are arranged as matrix or line arrays and which receive their light through a conventional imaging-optics system. With the Si image sensors (CCD Charge-Coupled Devices, Figs. 2 and 3) available at present, the light entering through a transparent electrode generates charge carriers proportional to the light intensity and the exposure time. These are collected in a "potential layer" (Si-SiO_2 boundary layer). Further electrodes are used to transfer these charges into an opaque zone

3 CCD principle (Charge-Coupled Device)

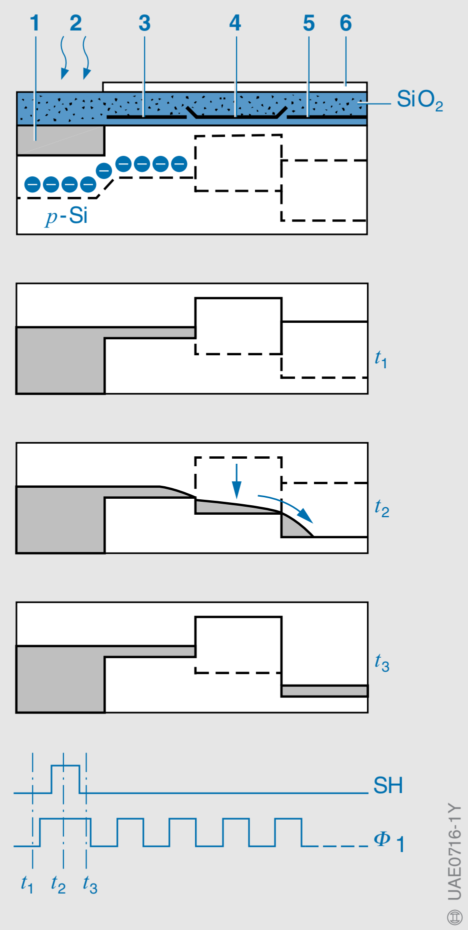

Fig. 3
1 Photodiode
2 Light
3 Storage elecrode
4 Shift gate
5 Transfer electrode
6 Optical masking

2 Image-sensor structure

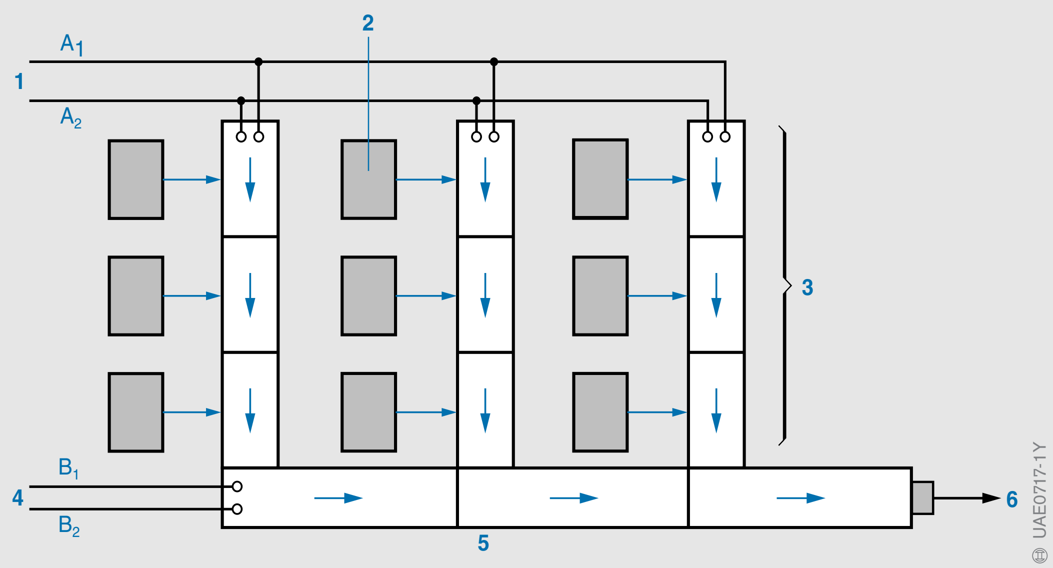

Fig. 2
1 Column clock pulse A_1/A_2
2 Photosensors
3 CCD array
4 Line clock pulse B_1/B_2
5 Output register
6 Video output

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and by means of "analog" shift registers (bucket-brigade principle) are then transferred line by line into an output register which is then read out serially at a high clock-pulse rate.

Whereas, due to their limited dynamic light/dark response (50 dB), their read-out time, and their temperature range (<50 °C), CCD sensors are unsuitable for use in the automobile, innovative "smart" image sensors based on CMOS technology are apparently 100% suitable for such applications. Here, as well as having a dynamic response of 120 dB, the logarithmic light/signal curve which is possible corresponds to that of the human eye. This, for instance, not only makes an aperture control superfluous, but also provides for constant contrast resolution throughout the complete brightness range. These sensors permit random access to the individual pixels while at the same time permitting higher levels of sensitivity (higher readout rate). The first steps in preprocessing the signals on the image-sensor chip have already been implemented.

Optical sensors

Simple, optical sensors for contingency-triggered automatic cleaning of the vehicle's windshield or of the headlamp lenses are also aligned to the environment outside the vehicle.

Rain sensors

The rain sensor detects rain drops on the vehicle's windshield and triggers the operation of the windshield wipers. The relieves the driver of a number of operations that are needed with conventional wiper systems, and thus enables him/her to concentrate better on the road. Nevertheless, manual control is retained as an additional intervention. If the automatic control is required, the driver must activate it after starting the vehicle.

The rain sensor comprises an optical transmit/receive path (similar to the dirt sensor). An LED emits light which is coupled into the windshield at a given angle. This light is reflected from the dry outside surface (total reflection) and reaches the receiver (photodiode) which is also aligned to the windshield at an angle. If there are water droplets on the windshield, a considerable portion of the light is refracted from them and is lost so that the signal received by the photodiode is correspondigly weaker. As from a certain level, the wiper also switches on automatically when there is dirt on the windshield. On newer sensor versions, infrared light is used instead of the visible light commonly employed.

The sensor controls the speed of the windshield wipers as a function of the amount of rain measured on the windshield. Together with the electronically controlled wiper drive, infinitely-variable wiper speeds are possible during interval operation. For instance, if the windshield is suddenly deluged by a gush of water when passing a truck, the system automatically switches on at top speed.

The rain sensor can also be used for closing the windows and the sunshine roof. Provided a second sensor is fitted, it can also control the vehicle headlights. When there is insufficient light, or when the vehicle enters a tunnel, it automatically switches on the headlamps without the driver having to do anything. It is even conceivable that the rain sensor's signals can be used to inform traffic telematics systems about the actual weather situation on a particular stretch of road.

4 Rain sensor for windshields

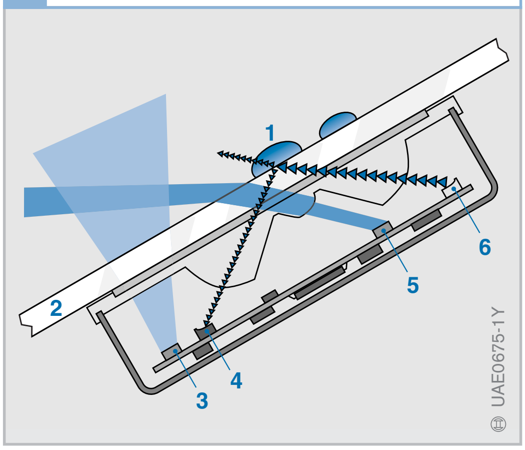

Fig. 4
1 Raindrops
2 Windshield
3 Ambient-light sensor
4 Photodiode
5 Light sensor, aligned to far distance
6 LED

Dirt sensors

The dirt sensor (Fig. 5) detects the degree of dirt on the headlamp lenses and triggers an automatic cleaning process for them. The sensor's reflected-light barrier comprises a light source (LED) and an opto-receiver (phototransistor). It is located on the lens inner surface inside the cleaning area traversed by the headlamp-wiper blade, but not within the direct beam path of the light from the bulb. When the headlamp lens is clean or covered by raindrops, the measuring light (which is in the near IR range) passes through the headlamp lens practically unhindered, and only a negligible portion is reflected back to the opto-receiver. On the other hand, if the transmitted light hits dirt particles on the outside lens surface it is caused to scatter and reflects back to the opto-receiver. The degree of scatter is proportional to the degree of dirt, and above a certain level automatically triggers the headlamp wipers.

Near-range radar (24 GHz)

In case of broadside collisions, and frontal collisions on compact-class automobiles, the time available for triggering the safety and restraint systems is extremely short (≤5 ms), and there is very little space between the passengers and the intruding vehicle. And in contrast to frontal collisions on larger vehicles there are very few vehicle components available for distortion and for absorbing the crash energy. It would therefore be of considerable advantage to be able to reliably forecast the severity of the collision from the very first moment of impact. To this end, near-range radar sensors are being worked on which will be installed all round the vehicle to provide 100% coverage of its surroundings.

5 Dirt sensor for the headlamp lens

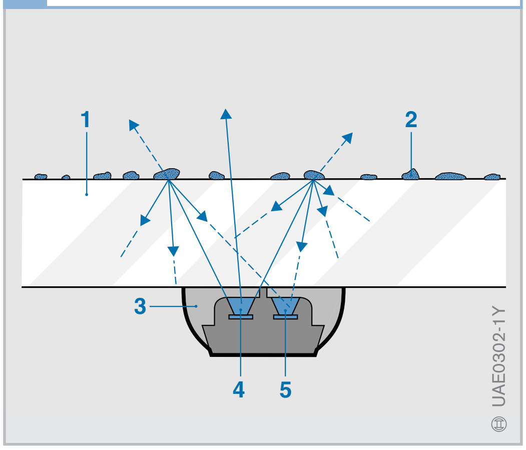

Fig. 5
1 Lens
2 Dirt particles
3 Sensor housing
4 Transmitter
5 Receiver

Further sensor systems

For the new assignments dealt with above, work is proceeding on the following sensor systems:

- Steering-torque sensing (electromotive power steering, "steer-by-wire" system),
- Drive-torque sensing (misfire detection, load signal),
- Braking-force sensing (electromotive braking systems, "brake-by-wire"),
- Passenger protection (AOS **A**utomotive **O**ccupancy **S**ensing, **O**ut **of** **P**osition sensing (OOP), passenger weight),
- Deformation sensors for broadside-collision sensing,
- Pedestrian detection for triggering of engine-hood protective systems,
- Registration of wheel forces (e.g. force-sensor technology integrated in the wheel bearing, and friction-coefficient potential),
- Liquid-measurement sensors (liquid levels, condition/quality of engine oil etc.)
- "Autonomous", that is 100% non-contacting sensors which can in some cases be scanned by radio, and which need no contacts for energy supply (plug-in contacts are still the most frequent causes of malfunction in the vehicle).

It is therefore obvious that the multiplicity of new electrical and electronic systems being introduced in the vehicle necessitates the development of a wide variety of new sensors. Of course, it still remains the objective that once they have completed an economically acceptable service life, existing sensors are replaced with new, more cost-efficient and better sensors produced using new technologies.

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Sensor-signal processing

Signal conditioning (Evaluation IC)

The sensor signals must be conditioned before they can be evaluated digitally (refer to the Section "Data Processing"). As far as required, this signal conditioning can include the following functions:

- Amplification (AC, DC),
- Rectification (also phase-synchronised),
- Threshold-value evaluation (also variable thresholds, pulse-shaping),
- Voltage/frequency conversion, pulse-duration modulation (pdm),
- Frequency filtering including interference-protection measures,
- Analog/digital (AD) and digital/analog (DA) conversion,
- Calibration of offset and amplification (characteristic curve in general), analog, digital (including E^2PROM),
- Linearisation,
- Calibration of temperature compensation (analog, digital),
- Automatic zero reset, possibly also with calibration during operation
- Self-monitoring (On-Board-Diagnosis (OBD), diagnosis output) and test functions,
- Control of the servo-controlled sensors (compensation method),
- Generation of AC voltage for carrier-frequency sensor systems,
- Power-supply stabilisation,
- Short-circuit-proof/overvoltage-proof output and driver stages,
- Signal multiplexers, analog and/or digital serialisation of the signals, coding, including fault detection,
- Bus interface (e.g. CAN) etc.

These functions are all available in the form of ASICs (Application-Specific Integrated Circuits). These circuits are tailor-made for the particular sensor application, and can either be installed locally (at the sensor) or at the ECU. In some cases, the functions are divided between both sides as far as this is expedient. Local integration of the circuit at the sensor (Fig. 1, integration stages 1 to 3) has the advantage that sensor and signal conditioning can be calibrated and compensated together. These then form an inseparable unit which is highly interference-proof and which must be replaced completely if one of the stages should fail.

Whereas previously, the functions described above were in some cases implemented as separate circuits (e.g. CMOS-IC for signal processing, bipolar IC as the interference-proof driver stage), present-day "mixed" technologies (e.g. BICMOS, BCD) also permit the integration on a single chip of the complete function including any digital, programmable memory-location cells which might be necessary (PROM). Basically, in practically all cases, monolithic integration of the sensor and the signal processing is possible (for instance Si manifold-pressure sensors and Hall-effect sensors). The euphoria which initially accompanied this integration has now given way to more sober considerations which take economic aspects more into account. At present, therefore, other state-of-the-art integration methods are in use which are more cost-effective (e.g. thick-film hybrids, combined "Lead frame" and combined chip housing). Such a concept, which in effect can be regarded as being modular, is also considerably more flexible since it can be more easily adapted to new assignments.

Considering the fact that the majority of sensors need an ASIC in order for them to operate correctly, and for their defined characteristics to apply, the wide variety of such signal-processing ASICs that have been created at Bosch represents a "treasure" of immense value. When sensors are produced not only for "in-house" use but also for sale outside, they should as far as possible only be marketed together with these signal-processing circuits.

1 Sensor integration stages (signal-conditioning stages shown in blue)

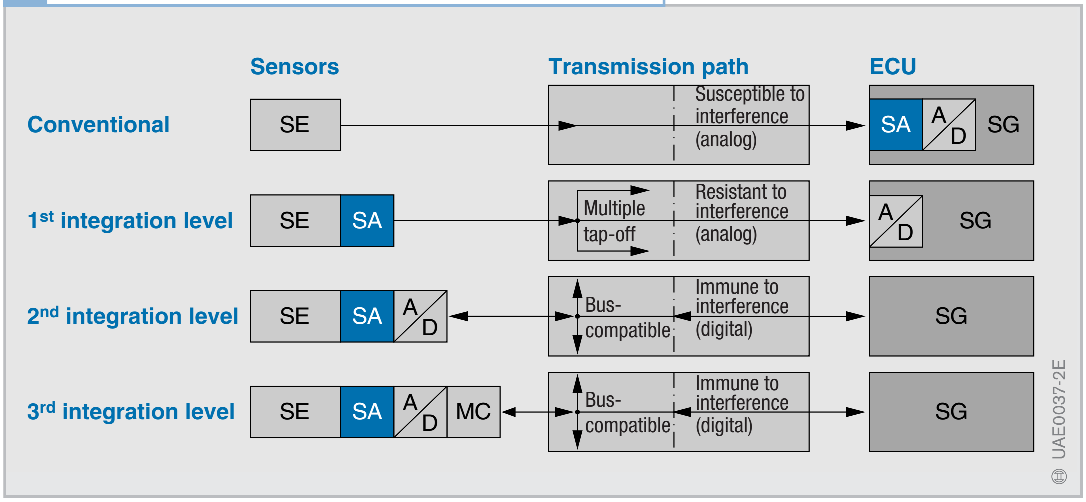

Fig. 1
SE Sensor(s)
SA Signal conditioning (analog)
A/D Analog/digital converter
SG ECU (digital)
MC Microcomputer

Examples of application

Originally, ASICs were conceived primarily for installation in the ECU. This meant though, that requirements which in part were based on special, and in some cases individual, sensor features could not be taken into account. As a rule, the ASICs are therefore now designed for direct installation on the sensor, and are able to store individual parameters for calibration and compensation, and use these to implement corrective measures in the sense of an "intelligent" sensor. Below, we deal with just a few examples of these ASICs.

ASIC CC212

The CC212 is an ASIC for the short-circuiting-ring sensor (for instance, the half-differential version) used for the measurement of displacement, travel, and angle. Due to their considerable measuring effect and their moderate operating frequency (5...50 kHz) short-circuiting-ring sensors do not necessarily need local electronic circuitry. The ASIC CC212 is therefore installed in the ECU where it combines all electronic functions as needed in the ECU, for instance, for the triggering and evaluation of the sensors for Electronic Diesel Control (EDC).

Since this ASIC is already installed in the ECU, the advantages of individual curve and temperature compensation aligned to the special sensor version were dispensed with on purpose. This electronic circuitry could have been installed directly on the sensor and could have simplified the sensor as a result (refer to ASIC CC400). This automatically detects short circuits and cable breaks in and at the sensor, and suppresses any interference peaks which might be present on the sensor output lead.

The ASIC drives a half-differential short-circuiting-ring sensor as an AC voltage divider (10 kHz), whereby the end of the divider is fed with a constant amplitude. Phase-opposed voltage is applied to the other end of the divider, the amplitude of which is regulated (closed-loop controlled) until the output at the divider's pick-off reduces to zero. The closed-loop-controlled output voltage is at the same time the analog output signal (Fig. 2, next page).

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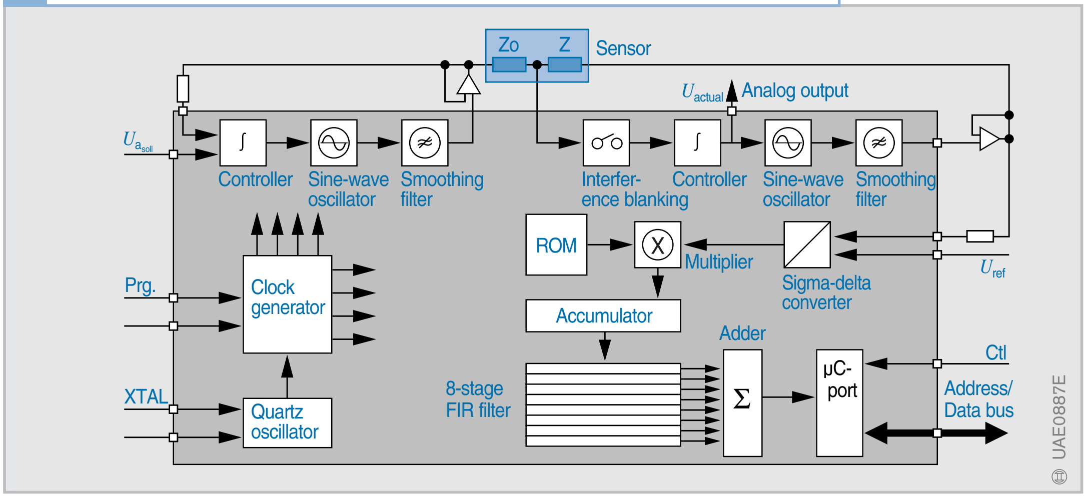
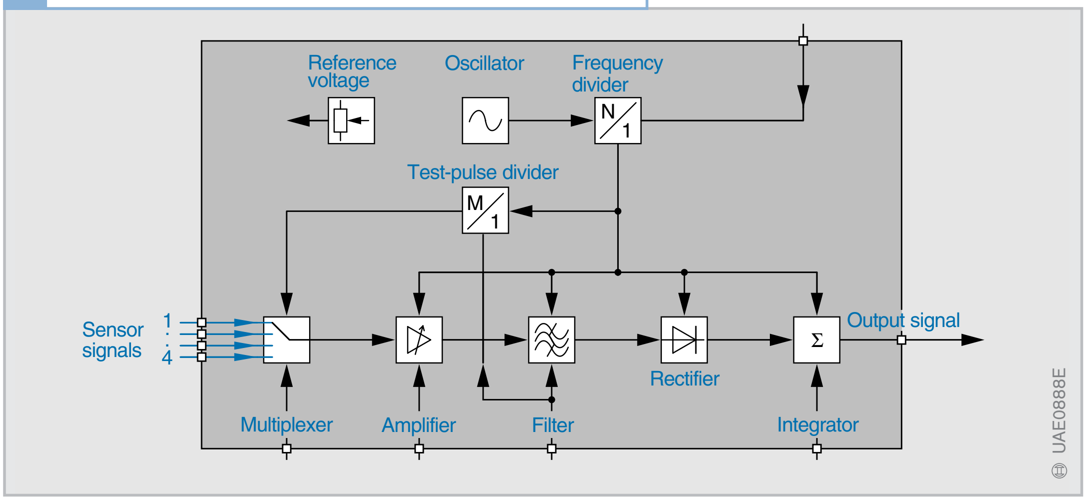
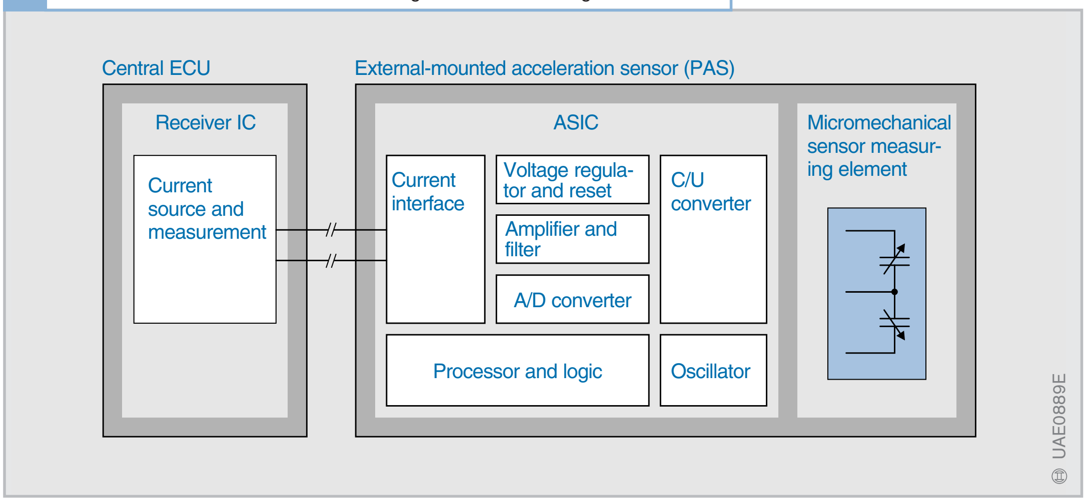
2 ASIC CC212 for the signal evaluation on short-circuiting-ring sensors (installed in ECU)



3 ASIC CC195 for knock-sensor signal evaluation (installed in ECU)



4 ASIC interface for acceleration-sensor signal evaluation (integrated in ECU)



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ASIC CC195

The CC195 is a knock-sensor ASIC. Knock sensors are mounted directly on the engine where they detect acceleration signals in the form of structure-borne noise. The combustion-knock signals are typically in the 5...15 kHz range, and must be filtered out. A time-window control suppresses precisely that phase of the working cycle during which the signal can theoretically occur and allocates this to a given cylinder. The signal occurring in the critical frequency range is rectified and averaged and then evaluated by the ECU. As a result, the ECU shifts the ignition point until knock stops. The ASIC which is responsible for the above functions is inside the ECU and is able to evaluate the signals from up to 4 knock sensors (Fig. 3).

Interface ASIC

In case of a *frontal* collision, acceleration sensors trigger the vehicle's restraint systems in order to protect the passengers. They are located directly in the airbag ECU which is usually installed in the vehicle's console.

The triggering of the protection system for *side-on* collisions must be much faster, and it is therefore necessary to locate the respective acceleration sensors at the vehicle's periphery (for instance at the chassis cross member). From here, the sensors transmit their signals digitally to the central ECU through a two-wire connection.

As its name implies, the PAS (Peripheral Acceleration Sensor) is located at the periphery of the vehicle, and in a two-chip concept contains the capacitive acceleration sensor itself as well as its triggering circuitry and evaluation electronics (Fig. 4). The ASIC used here, incorporates not only the sensor-triggering circuitry and sensor-signal evaluation, but also triggering for the output interface and sensor self-monitoring.

ASIC CC340

The CC340 is a universal, digitally controllable signal amplifier (Fig. 5, three-chip concept). This module applies CMOS technology and is in fact an analog DC difference amplifier. Depending upon a temperature signal, it can simultaneously control the offset and the amplification by means of a correction circuit.

Using this ASIC therefore, and provided that the bridge operating temperature *t* is precsiely monitored, it is possible to precisely amplify the output voltage of the pressure-sensor DMS bridge. Here, on the one side the advantages of simple broad-band, no-delay analog amplification are retained, and on the other, temperature correction takes place in a fully digitised circuit stage which need not be subjected to any demands

5 Combination of sensor, signal amplifier CC340 and EEPROM in one sensor housing (three-chip concept)

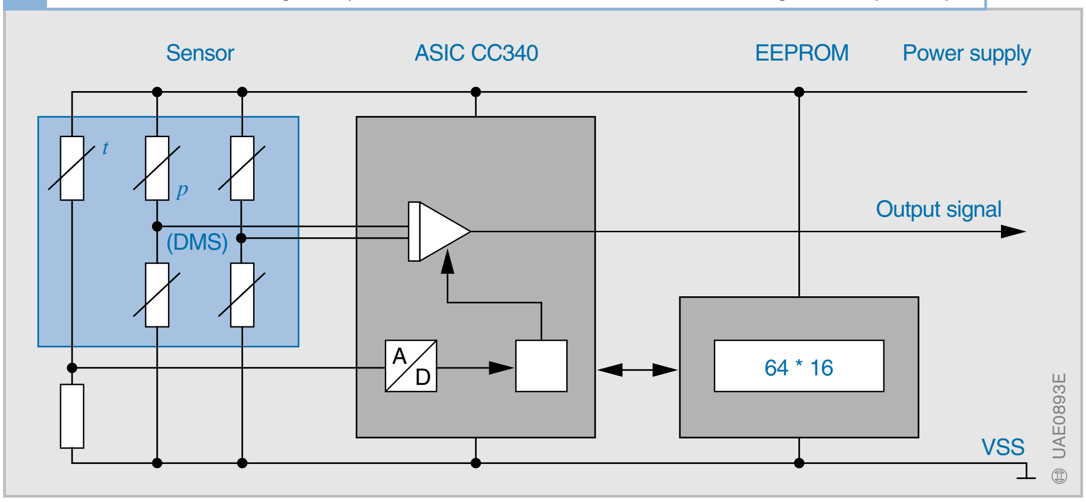


Fig. 5
p Pressure
t Temperature

at all regarding high working speeds and high resolution.

Using 6 bits (64 stages), the temperature signal is roughly digitised. With this digital word, an offset factor and an amplification factor are read out of an EEPROM. These each comprise 8 bits, and can be applied to the amplifier so that extremely non-linear temperature responses can be corrected across a wide range. A selectable basic amplification and a basic offset are also stored in the EEPROM.

When the design of this ASIC is updated, both the EEPROM and the bipolar protective circuit could be integrated in a single chip (Fig. 6). In the first versions of this ASIC, these had to be separated in the three-chip concept in line with the state-of-the-art at that time.

ASIC CC400

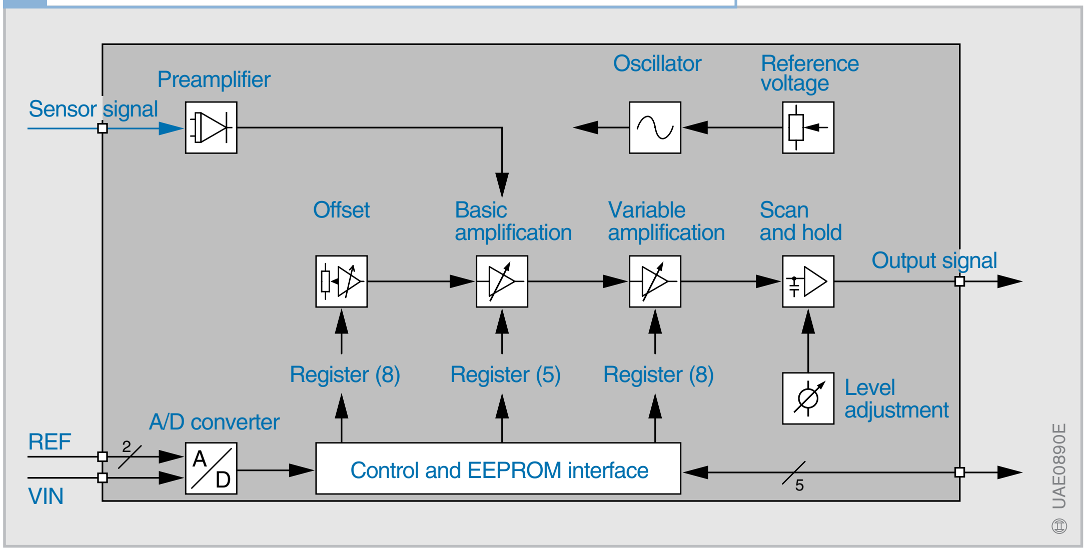
Using the CC400, it is possible to digitally evaluate inductive sensors using calibration and correction functions that have been specifically aligned to the special sensor design (Fig. 7). With this ASIC, it is possible to vastly improve the characteristics not only of micromechanical sensors but also of macromechanical versions (for instance, inductive or capacitive sensors). This takes place by integrating the electronics, a step which at the same time leads to sensor simplification.

In the measuring systems, using a simple self-oscillating circuit, the inductance *L* of a travel or angle sensor, and its operating-temperature as registered by an NTC temperature sensor, are converted into an easily digitised period of oscillation. By means of these two values, the relevant practically faultless measurement values are then read out of a two-dimensional "look-up table".

Only a few values are stored on the ASIC in order to get by with very little memory space. When necessary, the ASIC performs a linear interpolation between these values. The values in the "look-up table" are calculated in a once-only calibration process and stored in the (EE)PROM of the ASIC. Total measure and calculation time is less than 0.5 ms.

Thanks to the measured-value correction as described above, on short-circuiting-ring sensors for instance, the linearisation contour for the laminated iron core can be dispensed with as can a second, fixed-adjusted reference system. This serves to simplify the sensor somewhat. Nonetheless, the CC400

6 Future ASIC with EEPROM and bipolar protective circuit all on a single chip



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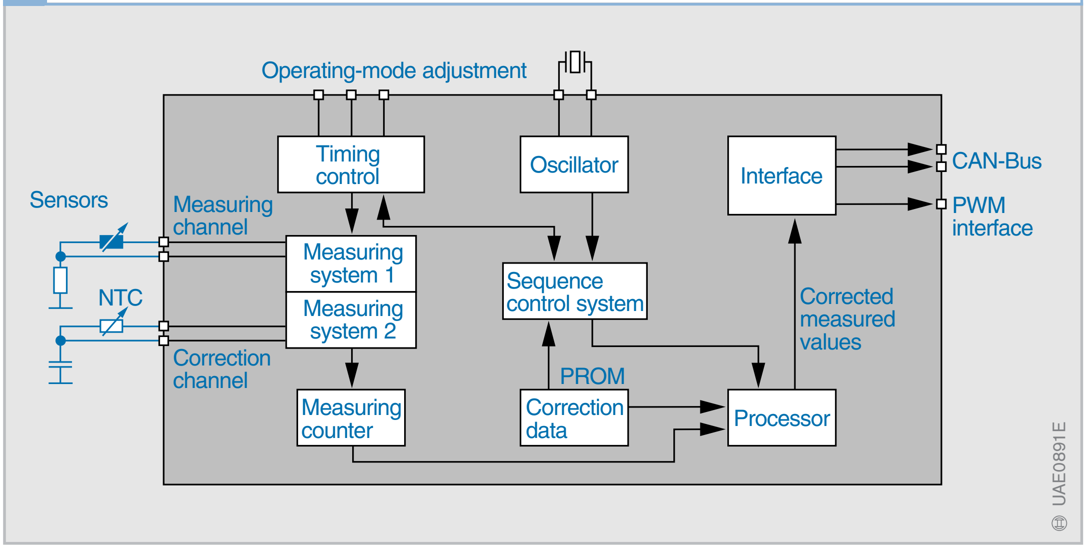
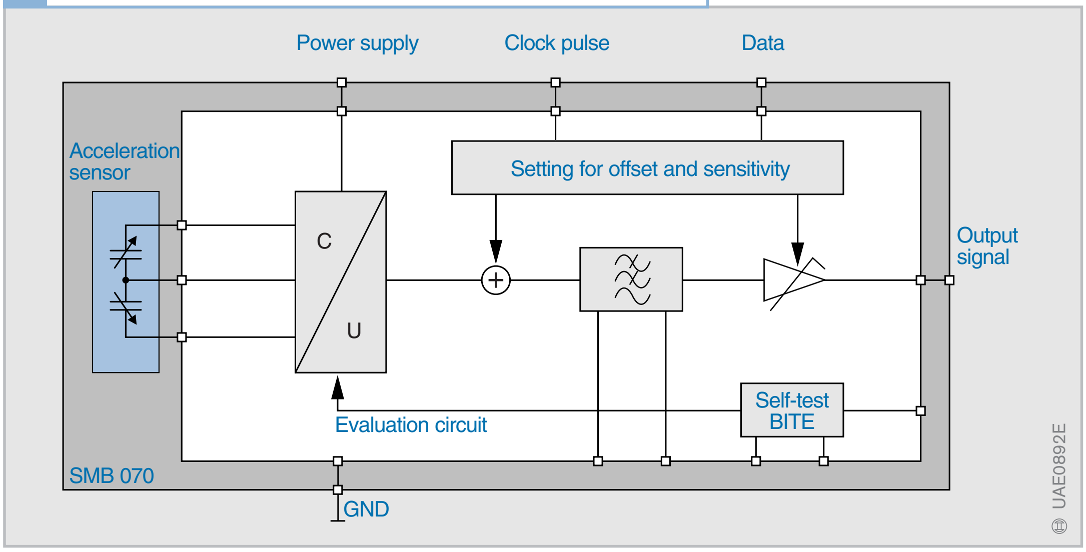
permits a considerable increase in sensor accuracy compared with conventional evaluation. Across the complete temperature range, this applies up to 0.1% of the measuring range. The only principle limitation here is the ageing stability of the travel/angle sensors and of the temperature sensor used.

Fig. 8 shows an example of a capacitive acceleration sensor with evaluation circuit.

7 Full-digital circuit of the ASIC CC400 for the high-speed evaluation of inductive sensors, including the individual correction of characteristc curves and temperature errors, with digital or pwm output signal



8 Capacitive acceleration sensor with evaluation circuit SMB070 (Example)



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Data processing in the vehicle

Requirements

Highly sophisticated state-of-the-art open-loop and closed-loop control concepts are essential for meeting the demands for function, safety, environmental compatibility and comfort associated with the wide range of automotive subsystems installed in modern-day vehicles. Sensors monitor the reference and controlled variables, which an electronic control unit (ECU) then converts into the signals required to adjust the final controlling elements/actuators. The input signals can be analog (e.g. voltage characteristic at pressure sensor), digital (e.g. switch position) or pulse-shaped (i.e. information content as a function of time; e.g. engine-speed signal). These signals are processed after being conditioned (filtering, amplification, pulse shaping) and converted (analog/digital); digital signal-processing methods are preferred.

Thanks to modern semiconductor technology, powerful computer units, with their accompanying program and data memories, and special peripheral circuitry, designed specifically for real-time applications, can all be integrated on only a few chips.

Modern vehicles are equipped with numerous digital control units (ECUs), e.g. for engine management, ABS, and transmission-shift control. lmproved performance and additional functions are obtained by synchronizing the processes controlled by the individual control units, and by adapting (in real time) their respective parameters to each other. An example of this type of function is traction control (TCS) which reduces the driving torque when the drive wheels spin.

Up to now, data between the control units (in the example cited above, ABS/TCS and engine management) has been exchanged mostly through separate lines. However, this type of point-to-point connection is only suitable for a limited number of signals. The data-transmission potential between the individual ECUs can be enhanced by using a simple network topology designed specifically for serial data transmission in automotive applications.

Microcomputer

The microcomputer comprises both the central processing unit (CPU) for processing arithmetic operations and logical relationships, and special function modules to monitor external signals and to generate the control signals for external servo elements. These peripheral modules are largely capable of assuming complete control of real-time operations. The program-controlled CPU could only discharge these at the price of both additional complication and curtailment in the number of functions (e.g. determining the moment at which an event occurred).

Computing power

Apart from the architecture (e.g. accumulator, register machine) and the word length (4 ... 32 bits), the product of the internal clock frequency and the average number of clock pulses required per instruction determines the CPU’s power:

- Clock frequency: 1 ... 40 MHz (typical),
- Clock pulses per instruction: 1 ... 32 pulses (typical), depending on the CPU's architecture and the instruction (e.g. 6 pulses for addition, 32 pulses for multiplication).

Electronic control unit (ECU)

Digital input signals

Register a switch position or digital sensor signals (e.g. rotational-speed pulses from a Hall-effect sensor),
Voltage range: 0 V to battery voltage.

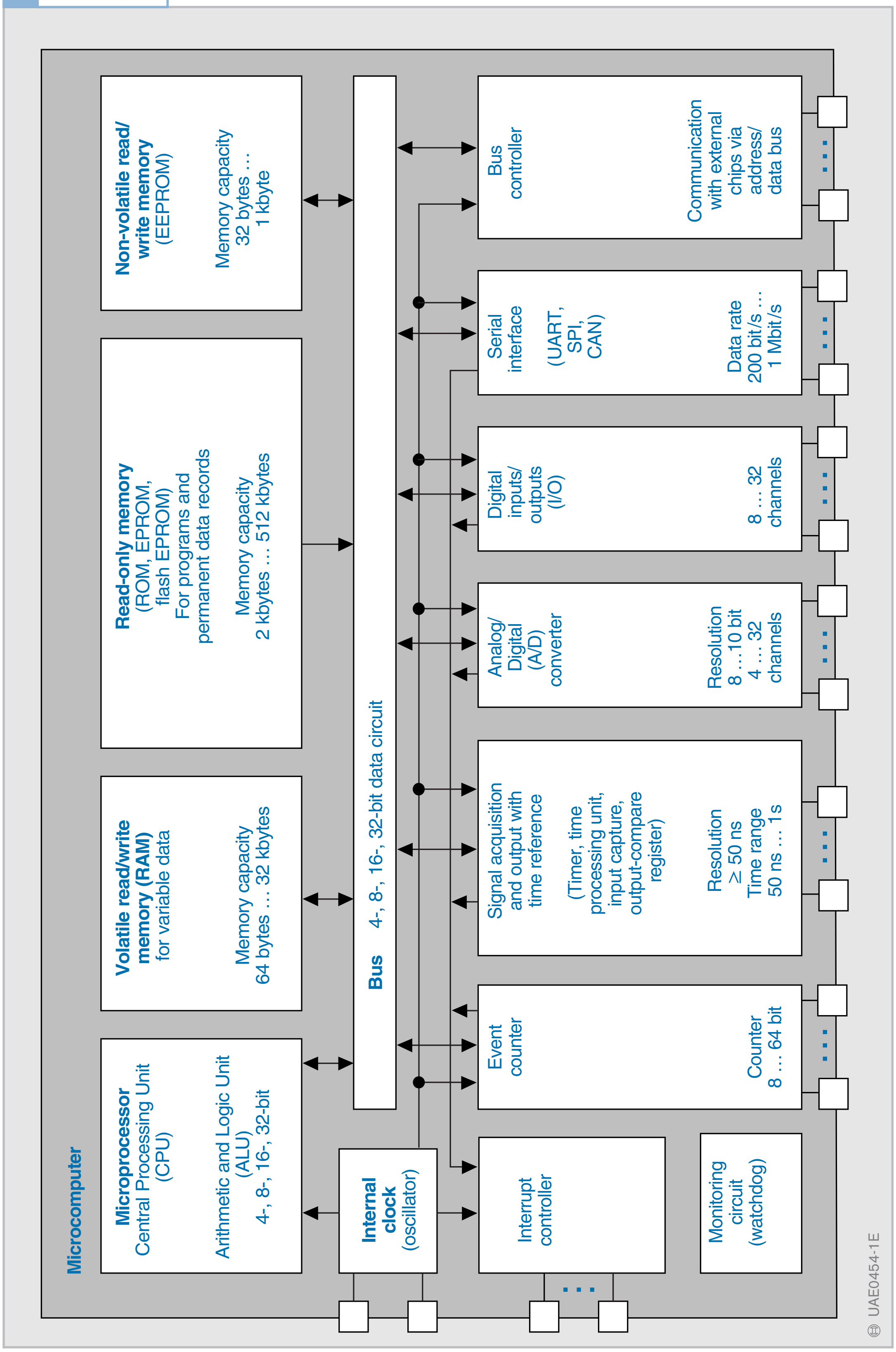
Analog input signals

Signals from analog sensors (lambda sensor, pressure sensor, potentiometer). Voltage range: Several mV up to 5 V.

Pulse-shaped input signals

Signals from inductive rpm sensors. After signal conditioning, they are further processed as digital signals.
Voltage range: 0.5 V to 100 V.

1 Microcomputer



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Signal conditioning

Protective circuits (passive: R and RC circuits; active: special surge-proof semiconductor elements) are used to limit the voltage of the input signals to acceptable levels (microcomputer operating voltage). Filters remove most of the superimposed noise from the useful signals, which are then amplified to the microprocessor's input voltage. Voltage range: 0 V to 5 V.

Signal processing

ECUs usually process signals in digital form. Rapid, periodic, real-time signals are processed in hardware modules specifically designed for the particular function. Results, e.g. a counter reading or the time of an event, are transmitted in registers to the CPU for further processing. This procedure substantially reduces the CPU's interrupt-response requirements (μs range).

The amount of time available for calculations is determined by the open-loop or closed-loop control system (ms range).

The software contains the actual control algorithms. Depending on the data, an almost unlimited number of logic operations can be established and data records stored and processed in the form of parameters, characteristic curves and multidimensional program maps.

Output signals

Power switches and power-gain circuits amplify the microprocessor's output signals (0 V .. 5 V, several mA) to the levels required by the various final-controlling elements/actuators (battery voltage, several A).

2 Signal processing in ECU

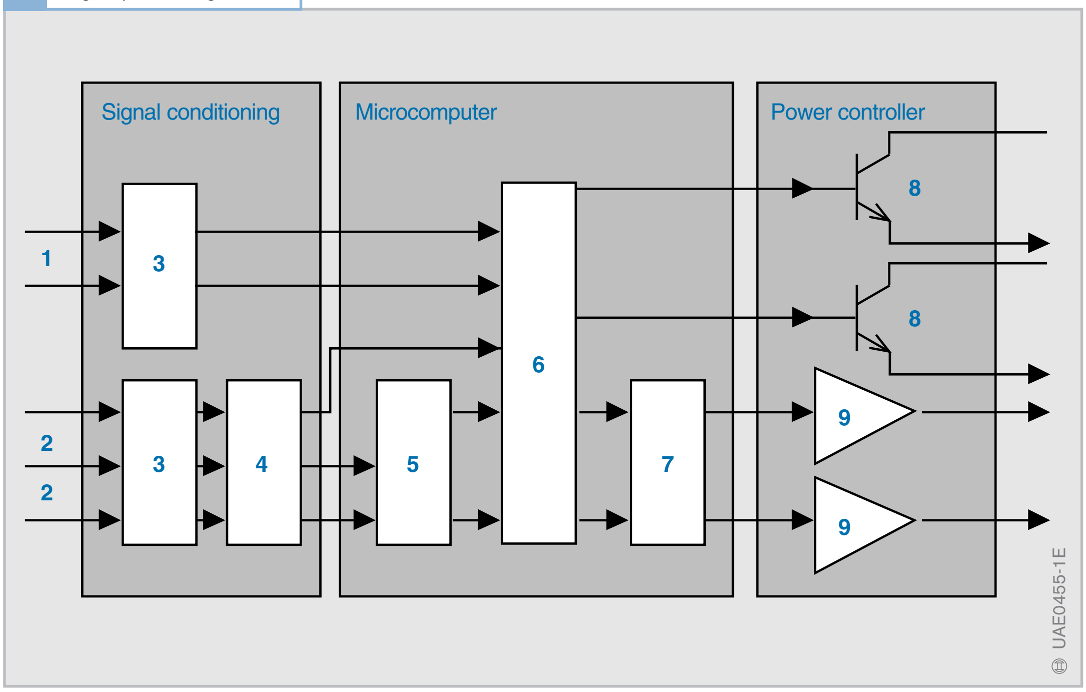

Fig. 2

1 Digital input signals
2 Analog input signals
3 Protective circuit
4 Amplifier, filter
5 A/D converter
6 Digital signal processing
7 D/A converter
8 Circuit-breaker
9 Power amplifier

Complete system

Logistical concept (CARTRONIC)

This concept divides the vehicle's complete electrical system into conveniently dimensioned subsystems. Units with closely-coupled functions (that is, units with high rates of mutual data exchange) are combined in a sub-network. Although this logistical concept results in sub-networks with varying requirements on transmission capacity, demands on data exchange do not vary.

Topology

At the logical level, all the known communications systems developed for automotive applications are based on a single serial connection of the ECUs. The physical layout employs one-wire or differential two-wire interfaces in bus form to interconnect the control units.

Protocol

The protocol consists of a number of a specific collection execution statements which are used to control data communications between the individual control units. Procedures have been laid down for bus access, message structure, bit and data coding, error recognition and response, and the identification of faulty bus users (CAN).

Transmission speed

Multiplex bus: 10 kbit/s...125 kbit/s,
Drivetrain bus: 125 kbit/s...1 Mbit/s,
Telecommunications bus:
10 kbit/s...125 kbit/s.

Latency time

Latency time is defined as the time that elapses between the transmitter's send request and the target station's receipt of the error-free message.
Multiplex bus: 5 ms...100 ms,
Drivetrain bus: 0.5 ms...10 ms,
Telecommunications bus: 5 ms...100 ms.

3 Bus-system interfacing

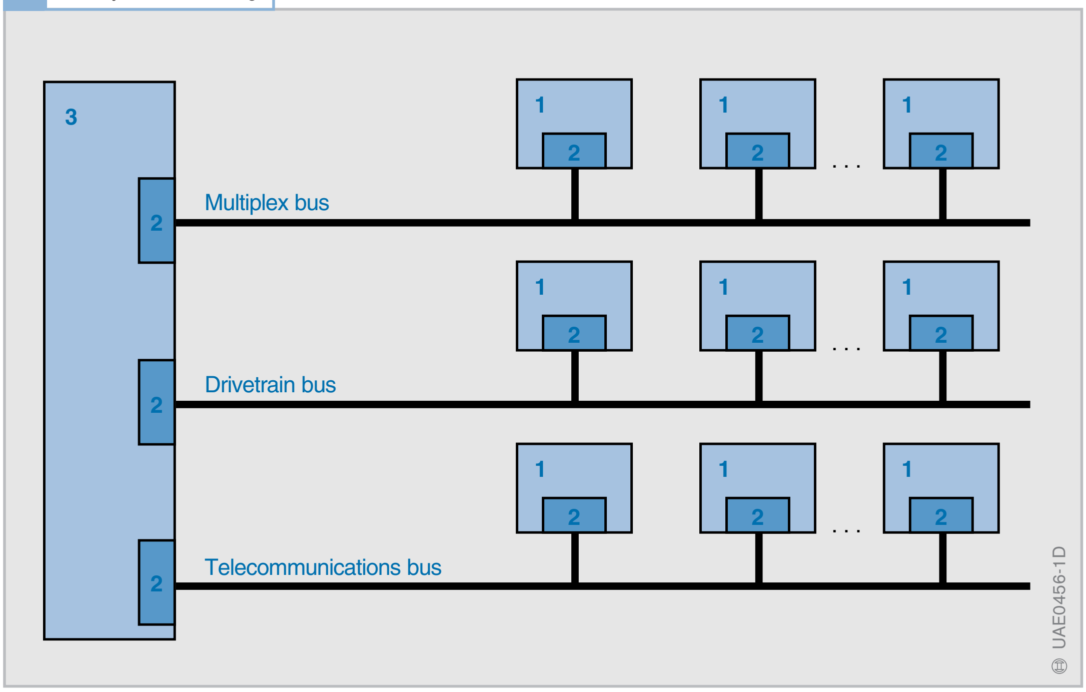

Fig. 3
1 ECU
2 Bus controller
3 Gateway

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Index of Technical Terms

An arrow → indicates a term in italics (e.g. → *Electromagnetic sensors*) which is a synonymous or related term.

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Abbreviations

A
ABS: Antilock Braking System
AC: Alternating Current
ACC: Adaptive Cruise Control
AKSE: Automatic detection of child safety seat
ALU: Arithmetic and Logic Unit
ALWR: Automatic headlight leveling control
AMR: Anisotropic Magneto Resistive
AOS: Automatic Occupancy Sensing
ARS: Angle of Rotation Sensor
ASIC: Application-Specific Integrated Circuit
ASR: Traction Control System **(TCS)**
ASG: Automatic Shift Transmission **(AST)**
AT: Automatic gearbox
ATF: Automatic Transmission Fluid

B
BITE: Built-In Test (self-test)

C
CAN: Controller Area Network
CCD: Charge-Coupled Device
CMOS: Complementary Metal-Oxide Semiconductor
CPU: Central Processing Unit
CSWS: Compact Seal With Sensor
CVT: Continuously Variable Transmission

D
DC: Direct Current
DF: rpm sensor
DMS: Strain gauge/ Strain-gauge measuring resistor
DRO: Dielectric Resonance Oscillator
DRS-MM: Yaw-rate sensor, micromechanical
DWS: Angle-of-rotation sensor

E
ECU: Electronic Control Unit
EEPROM (E^2PROM): Electrically Erasable Programmable Read-Only Memory
EMC: Electromagnetic compatibility
EPROM: Erasable Programmable Read-Only Memory
ESP: Electronic Stability Program
EV: Electric Vehicle
EW: Final value of the measuring range

F
FIR-F: Finite Impulse Response filter
Flash-EPROM: Flash-Erasable Programmable Read-Only Memory
FLL: Frequency-Locked Loop
FMCW: Frequency Modulated Continuous Wave
FSR: Force-Sensitive Resistance

G
GMR: Giant Magneto Resistive

H
HDK: Half-differential short-circuiting-ring sensor
HFM: Hot-film air-mass meter
HLM: Hot-wire air-mass meter

I
IC: Integrated Circuit

K
KS: Knock Sensor

L
LED: Light-Emitting Diode
LMM: Air-flow sensor
LS: Lambda (oxygen) sensor, unheated (two-step tube-type (finger) sensor)
LSF: Lambda (oxygen) sensor, solid electrolyte
LSH: Lambda (oxygen) sensor, heated (two-step tube-type (finger) sensor)
LSU: Lambda (oxygen) sensor, Universal (planar broad-band Lambda (oxygen) sensor)
LWS: Steering-wheel-angle sensor

M
MC, µC: Microcontroller
MM: Micromechanics
MOS: Metal-oxide semiconductor (insulation-layer field-effect transistor (FET))

N
NBF, NBS: Needle-motion sensor
NTC: Negative Temperature Coefficient

O
OC: Occupant Classification
OFW: Surface wave
OMM: Surface micromechanics

P
PAS: Peripheral Acceleration Sensor
PC: Personal Computer
PROM: Programmable Read-Only Memory
PTC: Positive Temperature Coefficient
PTFE: Polytetrafluoroethylene

R
RADAR: Random Detecting and Ranging
RAM: Random-Access Memory
REM: Scanning Electron Microscope **(SEM)**
ROM: Read-Only Memory
RS: Rotational-speed Sensor
RWG: Rack-travel sensor

S
SAW: Surface Acoustic Wave
SCU: Sensor & Control Unit
SMD: Surface-Mounted Device
SMT: Surface-Mount Technology

T
TCS: Traction Control System
TC: Temperature Coefficient
TI: Transistorized Ignition

U
UV: Ultraviolet light

V
VHD: Vertical Hall Devices

W
WOT: Wide-Open Throttle