Sensors

Sensors register operating states (e.g. engine speed) and setpoint/desired values (e.g. accelerator-pedal position). They convert physical quantities (e.g. pressure) or chemical quantities (e.g. exhaust-gas concentration) into electric signals.

Automotive applications

Sensors and actuators represent the interfaces between the ECUs, as the processing units, and the vehicle with its complex drive, braking, chassis, and bodywork functions (for instance, the Engine Management, the Electronic Stability Program ESP, and the air conditioner). As a rule, a matching circuit in the sensor converts the signals so that they can be processed by the ECU.

The field of mechatronics, in which mechanical, electronic, and data-processing components are interlinked and cooperate closely with each other, is rapidly gaining in importance in the field of sensor engineering. These components are integrated in modules (e.g. in the crankshaft CSWS (Composite Seal with Sensor) module complete with rpm sensor).

Since their output signals directly affect not only the engine's power output, torque, and emissions, but also vehicle handling and safety, sensors, although they are becoming smaller and smaller, must also fulfill demands that they be faster and more precise. These stipulations can be complied with thanks to mechatronics.

Depending upon the level of integration, signal conditioning, analog/digital conversion, and self-calibration functions can all be integrated in the sensor (Fig. 1), and in future a small microcomputer for further signal processing will be added. The advantages are as follows:

- Lower levels of computing power are needed in the ECU
- A uniform, flexible, and bus-compatible interface becomes possible for all sensors
- Direct multiple use of a given sensor through the data bus
- Registration of even smaller measured quantities
- Simple sensor calibration

1 Sensor integration levels

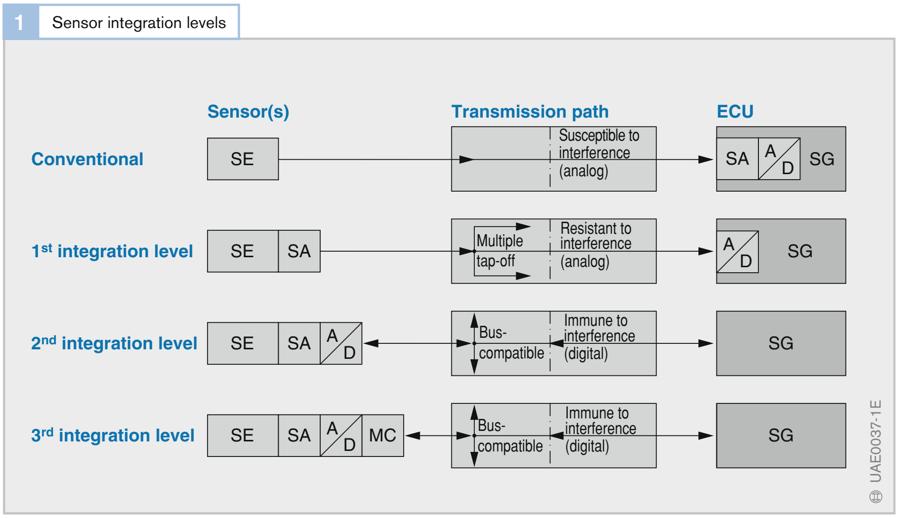

Fig. 1

SE	Sensor(s)
SA	Analog signal conditioning
A/D	Analog-digital converter
SG	Digital ECU
MC	Microcomputer (evaluation electronics)

K. Reif (Ed.), *Gasoline Engine Management*, Bosch Professional Automotive Information,
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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 method of operation

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.

1 Coolant temperature sensor

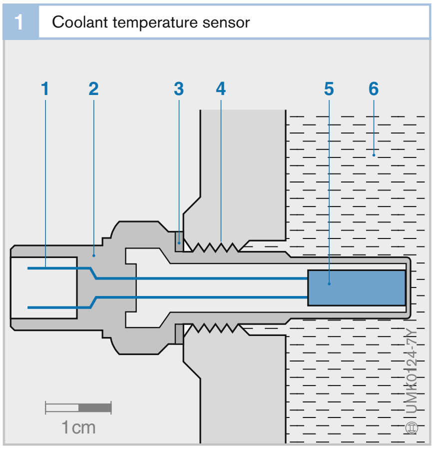
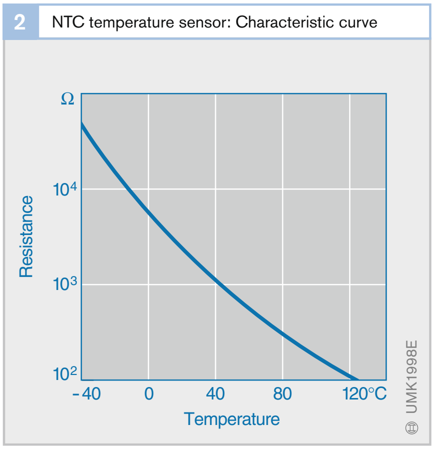


Fig. 1
1 Electrical connections
2 Housing
3 Gasket
4 Thread
5 Measuring resistor
6 Coolant

2 NTC temperature sensor: Characteristic curve



Engine-speed sensors

Application

Engine-speed sensors are used in Motronic systems for

- Measuring the engine speed, and
- Determining the crankshaft position (position of the engine pistons)

The rotational speed is calculated from the internal between the sensor's signals.

Inductive speed sensors

Design and method of operation

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, Pos. 4), which is enclosed by a 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 coil depends on whether the sensor is opposite a trigger-wheel tooth or gap. Whereas the magnet's leakage flux is concentrated by a tooth, and leads to an increase in the working flux through the coil, it is weakened by a gap. When the trigger wheel rotates, these magnetic-flux changes induce a sinusoidal output voltage in the coil which is proportional to the rate of change of the flux and thus the engine speed (Fig. 2). The amplitude of the alternating voltage increases sharply along with increasing trigger-wheel speed (several mV...>100 V). At least about 30 rpm are needed to generate an adequate amplitude.

The number of teeth on the trigger wheel depends on the particular application. In Motronic systems, 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 gap where the missing teeth would be situated is allocated to a defined crankshaft position and serves as a reference mark for synchronizing the ECU.

The geometries of the trigger-wheel teeth and the pole pin must be matched to each other. An evaluation circuit 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.

Active speed sensors

Active speed sensors operate according to the magnetostatic principle. The amplitude of the output signal is not dependent on the rotational speed. This makes it possible for very low speeds to be sensed (quasistatic speed sensing).

1 Inductive speed sensor (design)

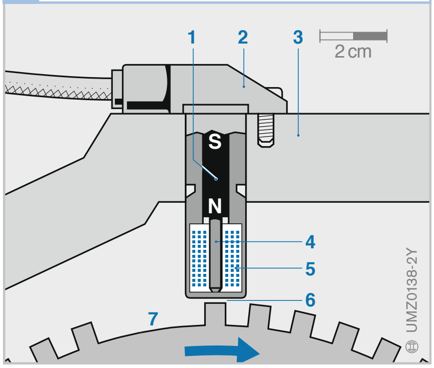


Fig. 1
1 Permanent magnet
2 Sensor housing
3 Crankcase
4 Pole pin
5 Winding
6 Air gap
7 Trigger wheel with reference mark

2 Signal from an inductive speed sensor

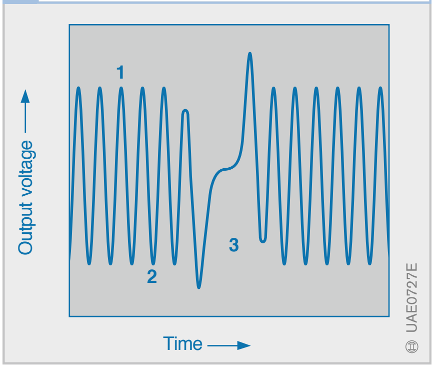


Fig. 2
1 Tooth
2 Tooth gap
3 Reference mark

Differential Hall-effect sensor

A voltage U_{H} proportional to the magnetic field (Hall voltage) can be picked off horizontally to the current direction at a current-carrying plate which is permeated vertically by a magnetic induction B (Fig. 3). In a differential Hall-effect sensor, the magnetic field is generated by a permanent magnet (Fig. 4, Pos. 1). Two Hall-effect sensor elements (2 and 3) are situated between the magnet and the trigger wheel (4). The magnetic flux by which these are permeated depends on whether the sensor is opposite a tooth or a gap. By establishing the difference between the signals from the two sensors, it is possible to

- Reduce magnetic interference signals, and
- Obtain an improved signal-to-noise ratio

The edges of the sensor signal can be processed without digitization directly in the ECU.

Multipole wheels are used instead of the ferromagnetic trigger wheel. Here, a magnetizable plastic is attached to a non-magnetic metallic carrier and alternately magnetized. These north and south poles adopt the function formerly performed by the teeth of the trigger wheel.

AMR sensors

The electrical resistance of magnetoresistive material (AMR, Anisotropic Magneto Resistive) is anisotropic, i.e., it depends on the direction of the magnetic field to which it is exposed. This property is utilized in an AMR sensor. The sensor is located between a magnet and a trigger wheel. The field lines change direction when the trigger wheel rotates (Fig. 5). This generates a sinusoidal voltage, which is amplified in an evaluation circuit in the sensor and converted into a square-wave signal.

3 Hall-effect sensor element (Hall vane switch)

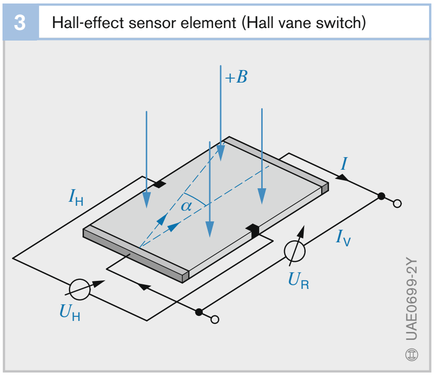


Fig. 3

I	Plate 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

4 Principle of differential Hall-effect sensor

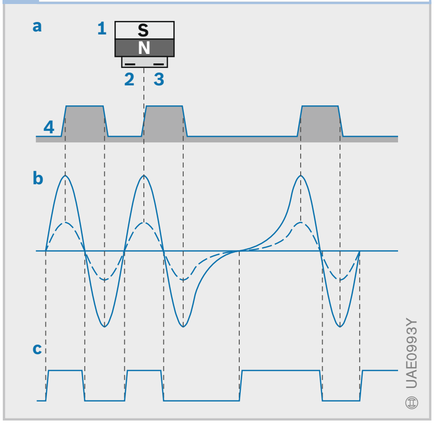


Fig. 4

a	Arrangement
b	Signal of Hall-effect sensor – high amplitude with small air gap – low amplitude with large air gap
c	Output signal
1	Magnet
2	Hall-effect sensor 1
3	Hall-effect sensor 2
4	Trigger wheel

5 Principle of speed sensing with an AMR sensor

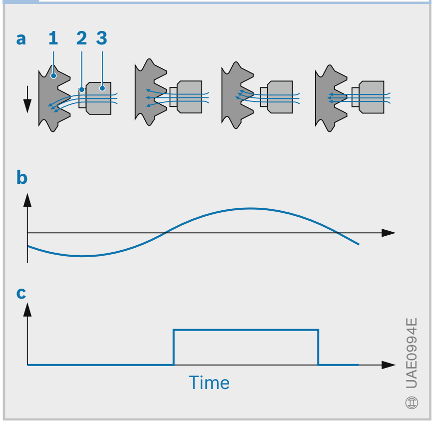


Fig. 5

a	Arrangement at different times
b	Signal from AMR sensor
c	Output signal
1	Trigger wheel
2	Sensor element
3	Magnet

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. This is required, for example, for ignition systems with single-spark ignition coils and for Sequential fuel injection (SEFI).

1 Hall-effect rod sensor (design)

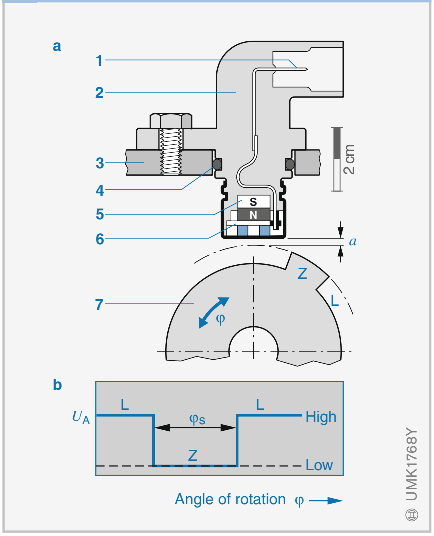


Fig. 1
a Positioning of sensor and single-track trigger wheel
b Output signal characteristic U_A

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

a Air gap
φ Angle of rotation

Design and method of operation

Hall-effect rod sensors

Hall-effect rod sensors (Fig. 1a) utilize the Hall effect: A rotor made ferromagnetic material (Pos. 7, trigger wheel with teeth, segments or aperture plate) rotates along with the camshaft. The Hall-effect IC (6) is located between the trigger wheel and a permanent magnet (5), which generates a magnetic field strength perpendicular to the Hall-effect element.

If one of the trigger-wheel teeth (Z) now passes the current-carrying sensor element (semiconductor plate), it changes the magnetic-field strength perpendicular to the Hall-effect element. This results in a voltage signal (Hall voltage) which is independent of the relative speed between sensor and trigger wheel. The evaluation electronics integrated in the sensor's Hall-effect IC conditions the signal and outputs it in the form of a square-wave signal (Fig. 1b).

2 Generations of camshaft sensors

	PG-1	PG-3-3	PG-3-5	PG-3-8
TIM	no	no	yes	yes
TPO	no	yes	no	yes
Accuracy	low	medium	medium	high

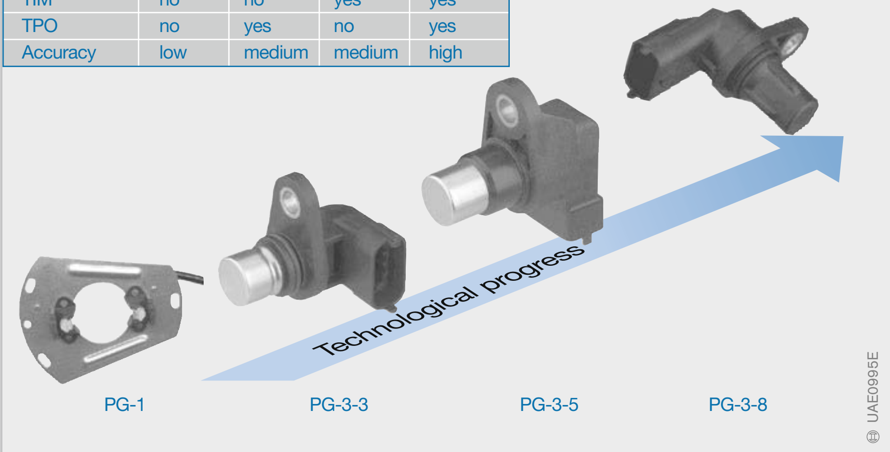


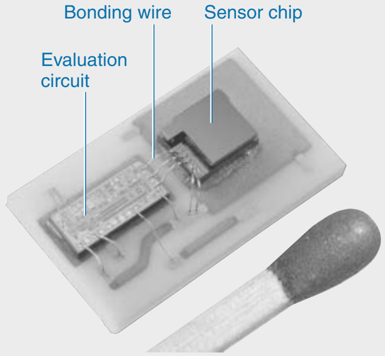
Fig. 2
TIM = Twist Intensive Mounting (i.e., the sensor can be rotated as desired about the sensor axis without any loss of accuracy. Important for minimizing type diversity).
TPO = True Power On (i.e., the sensor detects directly on switching on whether it is located above a tooth or a gap. Important for short synchronization times between crankshaft and camshaft signals).

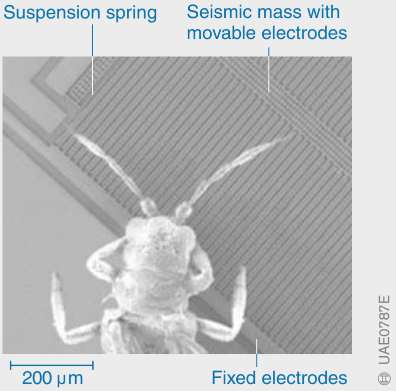
Miniaturization

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 special 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.

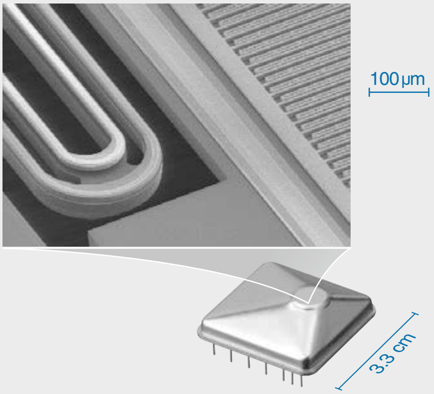
Bosch was the first to introduce a product with a micromechanical measuring element for automotive applications. This was an intake-pressure sensor for measuring load, and went into series production in 1994. Micromechanical acceleration and yaw-rate sensors are more recent developments in the field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

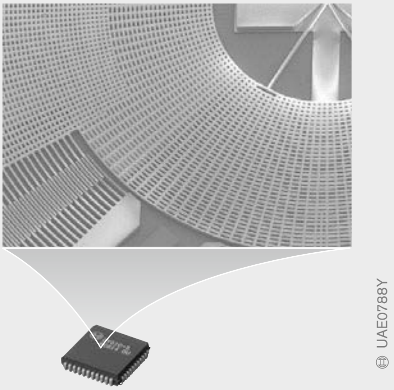
Micromechanical acceleration sensor


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

Hot-film air-mass meter

Application

To provide precise pilot control of the air/fuel ratio, it is essential for the supplied air mass to be exactly determined in the respective operating state. The hot-film air-mass meter measures some of the actually inducted air-mass flow for this purpose. It 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 or air-pressure changes have no effect upon measuring accuracy.

HFM5 design

The housing of the HFM5 hot-film air-mass meter (Fig. 1, Pos. 5) extends into a measuring tube (2), which can have different diameters depending on the air mass required for the engine (370 ... 970 kg/h).

1 HFM5 hot-film air-mass meter (schematic diagram)

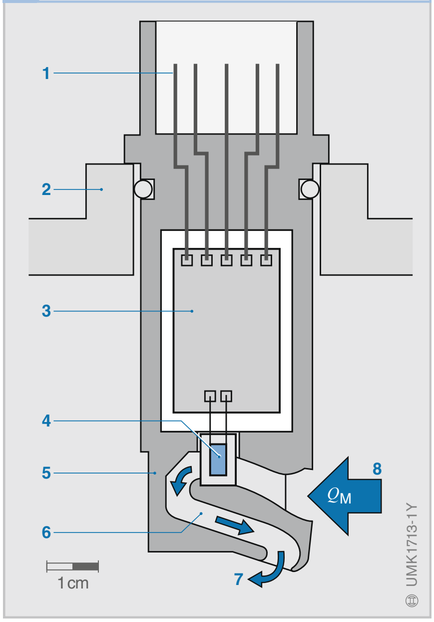


Fig. 1
1 Electrical connections (plug)
2 Measuring-tube or air-filter housing wall
3 Evaluation electronics (hybrid circuit)
4 Measuring cell
5 Sensor housing
6 Partial-flow measuring passage
7 Outlet, partial air flow Q_M
8 Inlet, partial air flow Q_M

The measuring tube normally contains a flow rectifier, which ensures that the flow in the measuring tube is uniform. The flow rectifier is either a combination of a plastic mesh with straightening action and a wire mesh, or is a wire mesh on its own (Fig. 3, Pos. 8). The measuring 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 measuring cell (Fig. 1, Pos. 4) in the air inlet (8) and the integrated evaluation electronics (3).

The sensor measuring cell consists of a semiconductor substrate. The sensitive surface is formed by a diaphragm which has been manufactured in micromechanical processes. This diaphragm incorporates temperature-sensitive resistors. The elements of the evaluation electronics (hybrid circuit) are installed on a ceramic substrate. This principle permits very compact design. The evaluation electronics is connected to the ECU by means of electrical connections (1).

The partial-flow measuring passage (6) is shaped so that the air flows past the measuring cell smoothly (without whirl effects) and back into the measuring tube via the air outlet (7). The length and location of the inlet and outlet of the partial-flow measuring passage have been chosen to provide good sensor performance even in the event of sharply pulsating flows.

Method of operation

The HFM5 hot-film air-mass meter is a thermal sensor which operates according tot he following principle: A centrally situated heating resistor on the measuring cell (Fig. 3, Pos. 3) heats a sensor diaphragm (5) and maintains it 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 heating resistor so as to be symmetrical to it (measuring points M1, M2). Without the flow of incoming air, the temperature profile (1) is the same on each side of the heating zone ($T_1 = T_2$).

As soon as air flows over the measuring cell, the uniform temperature profile at the diaphragm changes (2). On the inlet side, the temperature characteristic is steeper since the incoming air flowing past this area cools it off. On the opposite side, the temperature characteristic only changes slightly, because the incoming air flowing past has been heated by the heater element. The change in temperature distribution leads to a temperature differential (ΔT) between the measuring points M1 and M2.

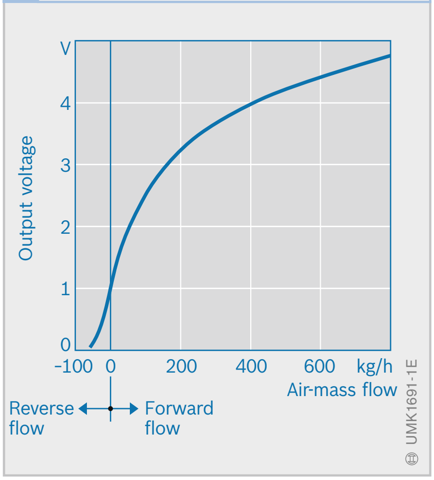
The heat dissipated to the air, and therefore the temperature characteristic at the measuring cell is dependent on the air mass flowing past. The temperature differential is (irrespective of the absolute temperature of the air flow past) a measure of the air-flow mass. It is also direction-dependent so that the air-mass sensor can record both the amount and the direction of an air-mass flow. 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 integrated in the sensor converts the resistance differential at the measuring points M1 and M2 into an analog voltage signal of between 0 and 5 V. Using the sensor characteristic (Fig. 2) stored in 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. An additional temperature sensor for evaluation functions can be integrated in the HFM5. It is not required for measuring the air mass.

Incorrect air-mass readings will be registered if the sensor diaphragm is contaminated with dust, dirty water or oil. For the

2 Hot-film air-mass meter (characteristic curve)



3 Hot-film air-mass meter (measuring principle)

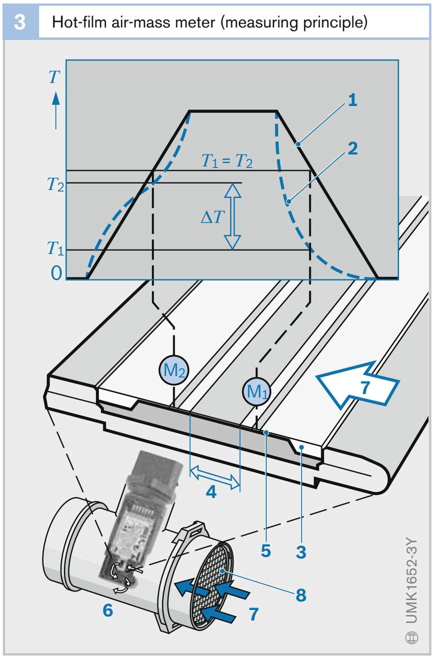


Fig. 3

1 Temperature profile without air flow
2 Temperature profile with air flow
3 Measuring cell
4 Heating zone
5 Sensor diaphragm
6 Measuring tube with air-mass sensor
7 Intake-air flow
8 Wire mesh

M_1, M_2 Measuring points
T_1, T_2 Temperature values at measuring points M_1 and M_2
ΔT Temperature differential

purpose of increasing the robustness of the HFM5, a protective device has been developed which, in conjunction with a deflector mesh, keeps dirty water and dust away from the sensor element (HFM5-CI; with C-shaped bypass and inner tube (I), which together with the deflector mesh protects the sensor).

HFM6 hot-film air-mass meter

The HFM6 uses the same sensor element as the HFM5 and has the same basic design. It differs in two crucial points:

- The integrated evaluation electronics operates digitally in order to obtain greater measuring accuracy
- The design of the partial-flow measuring passage is altered to provide protection against contamination directly upstream of the sensor element (similar to the deflector mesh in the HFM5-CI)

Digital electronics

A voltage signal is generated with a bridge circuit from the resistance values at the measuring points M1 and M2 (Fig. 3); this voltage signal serves as the measure of the air mass. The signal is converted into digital form for further processing.

4 HFM6 with improved contamination protection

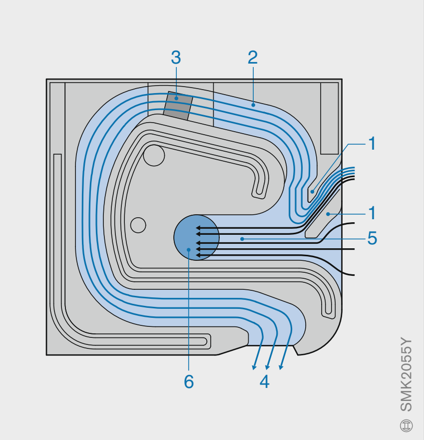


Fig. 4
1 Diverting edge
2 Partial-flow measuring passage (first passage)
3 Sensor element
4 Air outlet
5 Second passage
6 Particulate and water outlet

The HFM6 also takes into account the temperature of the intake air when determining the air mass. This increases significantly the accuracy of the air-mass measurement.

The intake-air temperature is measured by a temperature-dependent resistor, which is integrated in the closed control loop for monitoring the heating-zone temperature. The voltage drop at this resistor produces with the aid of an analog-digital converter a digital signal representing the intake-air temperature. The signals for air mass and intake-air temperature are used to address a program map in which the correction values for the air-mass signal are stored.

Improved protection against contamination

The partial-flow measuring passage is divided into two sections in order to provide better protection against contamination (Fig. 4). The passage which passes the sensor element has a sharp edge (1), around which air must flow. Heavy particulates and dirty-water droplets are unable to follow this diversion and are separated from the partial flow. These contaminants exit the sensor through a second passage (5). In this way, significantly fewer dirt particulates and droplets reach the sensor element (3) with the result that contamination is reduced and the service life of the air-mass sensor is significantly prolonged even when operated with contaminated air.

Piezoelectric knock sensors

Application

In terms of their principle of operation, knock sensors are basically vibration sensors and are suitable for detecting structure-borne acoustic oscillations. These occur as “knock”, for instance, in gasoline engines when uncontrolled combustion takes place. They are converted by the knock sensor into electrical signals (Fig. 1) and transmitted to the Motronic ECU, which counteracts the engine knock by adjusting the ignition angle.

Design and method of operation

Due to its inertia, a mass (Fig. 2, Pos. 2) excited by a given oscillation or vibration exerts a compressive force on a toroidal piezoceramic element (1) at the same frequency as the excitation oscillation. These forces effect a charge transfer within the ceramic element. An electrical voltage is generated between the top and bottom of the ceramic element which is picked off via contact washers (5) and processed in the Motronic ECU.

1 Knock-sensor signals (oscilloscope display)

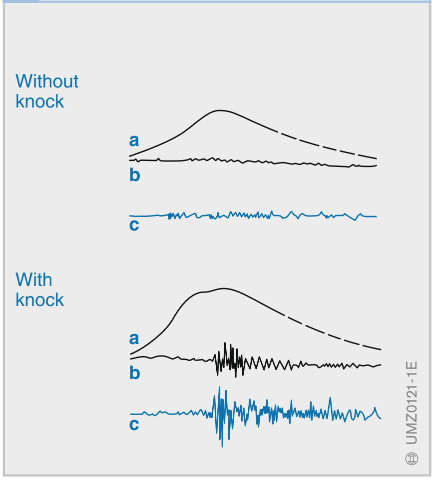


Fig. 1
a Cylinder-pressure curve
b Filtered pressure signal
c Knock-sensor signal

2 Knock sensor (design and mounting)

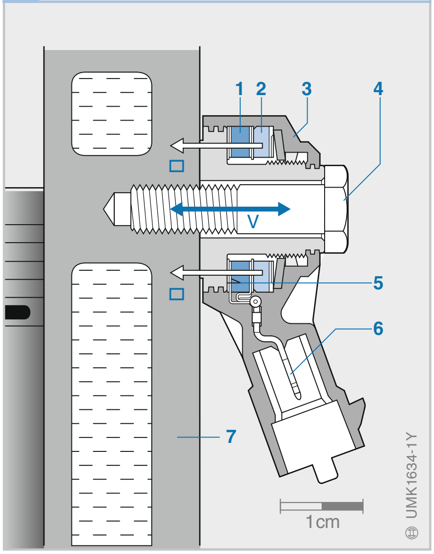


Fig. 2
1 Piezoceramic element
2 Seismic mass with compressive forces F
3 Housing
4 Bolt
5 Contact surface
6 Electrical connection
7 Engine block

V Vibration

Mounting

In four-cylinder engines, one knock sensor is sufficient to record the knock signals for all the cylinders. Engines with more cylinders require two or more knock sensors. The knock-sensor installation point on the engine is selected so that knock can be reliably detected from each cylinder. The sensor is usually bolted to the side of the engine block. It must be possible for the generated signals (structure-borne-noise vibrations) to be introduced without resonance into the knock sensor from the measuring point on the engine block. A fixed bolted connection satisfying the following requirements is required for this purpose:

- The fastening bolts must be tightened to a defined torque
- The contact surface and the bore in the engine block must comply with prespecified quality requirements
- No washers of any type may be used for fastening purposes

Micromechanical pressure sensors

Application

Pressure is a non-directional force acting in all directions which occurs in gases and liquids. Micromechanical pressure sensors detect the pressure of various media in the motor vehicle, e.g.:

- Intake-manifold pressure, e.g., for load sensing in engine-management systems
- Charge-air pressure for boost-pressure control
- Ambient pressure for taking into account air density, e.g., in boost-pressure control
- Oil pressure for taking into account engine load in the service display
- Fuel pressure for monitoring the level of fuel-filter contamination

Micromechanical pressure sensors determine the absolute pressure of liquids and gases by measuring the pressure differential in relation to a reference vacuum.

Version with the reference vacuum on the component side

Design

The measuring cell of a micromechanical pressure sensor consists of a silicon chip (Fig. 1a, Pos. 2), in which a thin diaphragm is micromechanically etched (1). Four deformation resistors (R1, R2) are diffused into the diaphragm. The electrical resistance in these resistors changes in response to mechanical elongation. The measuring cell is surrounded and sealed on its component side by a cap (Fig. 2, Pos. 6), which encloses the reference vacuum underneath.

A temperature sensor (Fig. 3, Pos. 1), the signals of which can be evaluated independently, can also be integrated in the pressure-sensor housing.

Method of operation

The diaphragm of the sensor cell is deflected to varying degrees depending on the external pressure acting on it (the center of the diaphragm is deflected by 10...1000 µm). The four deformation resistors on the diaphragm change their electrical resistance 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 measuring resistors are arranged in a Wheatstone bridge circuit (Fig. 1b) and a change in their resistance

1 Pressure-sensor measuring cell with reference vacuum on the component side (schematic diagram)

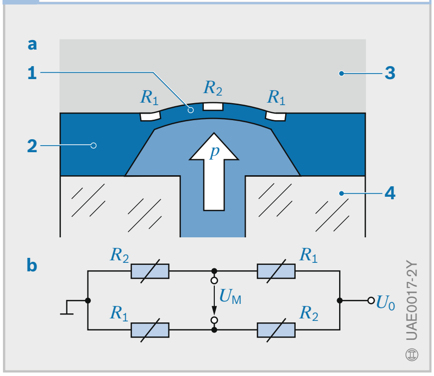


Fig. 1

a	Sectional drawing
b	Bridge circuit
1	Diaphragm
2	Silicon chip
3	Reference vacuum
4	Glass (Pyrex)
p	Measured pressure
U_0	Supply voltage
U_M	Measured voltage
R_1	Deformation resistor (compressed)
R_2	Deformation resistor (elongated)

2 Pressure-sensor measuring cell with cap and reference vacuum on the component side (design)

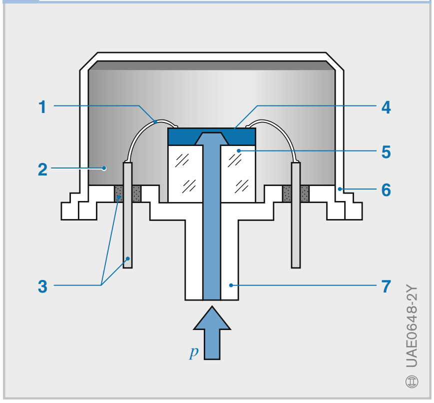


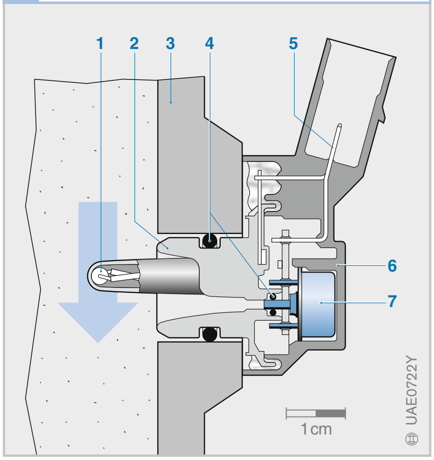
Fig. 2

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

values leads to a change in the ratio of the voltages across them. This leads to a change in the measurement voltage U_{M}. This as yet 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 if an individual resistor were used. The Wheatstone bridge circuit thus permits a higher sensor sensitivity.

3 Micromechanical pressure sensor with reference vacuum on the component side (design)



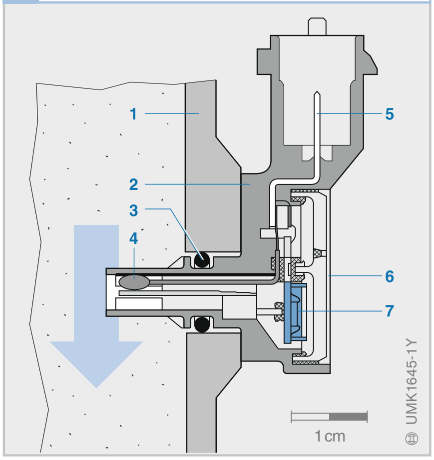
The signal-conditioning electronic circuitry is integrated on the chip. Its function is to amplify the bridge voltage, compensate for temperature influences, and linearize the pressure curve. The output voltage is in the range of 0...5 V and is supplied via electrical connections to the engine ECU (Fig. 3, Pos. 5). The ECU uses this output voltage to calculate the pressure.

Version with the reference vacuum in a special chamber

Design

A pressure sensor with the reference vacuum in a special chamber (Fig. 4) for use as an intake-manifold or boost-pressure sensor is easier to install than a sensor with the reference vacuum on the component side: A silicon chip (Fig. 5, Pos. 6) with etched diaphragm and four deformation resistors in a bridge circuit is located – like the pressure sensor with cap and reference vacuum on the component side – as a measuring cell on a glass base (3). In contrast to the sensor with the reference vacuum on the component 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

4 Micromechanical pressure sensor with reference vacuum in a special chamber (design)



5 Pressure-sensor measuring cell with reference vacuum in a special chamber (design)

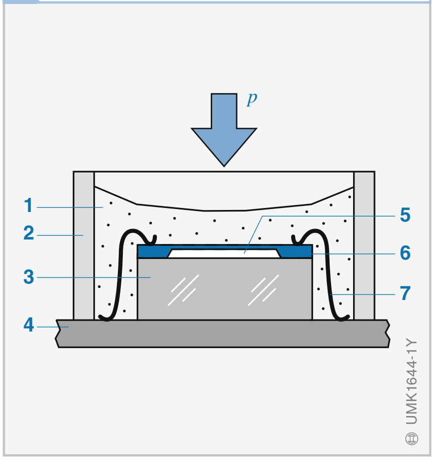


Fig. 3
1 Temperature sensor (NTC)
2 Housing base
3 Manifold wall
4 Sealing rings
5 Electrical connection (plug)
6 Housing cover
7 Measuring cell

Fig. 4
1 Manifold wall
2 Housing
3 Sealing ring
4 Temperature sensor (NTC)
5 Electrical connection (plug)
6 Housing cover
7 Measuring cell

Fig. 5
1 Protective gel
2 Gel frame
3 Glass base
4 Ceramic hybrid
5 Chamber with reference vacuum
6 Measuring cell (chip) with evaluation electronics
7 Bonded connection

p Measured pressure

is situated. This means that a special gel must be used on this side of the sensor to protect it against environmental influences. The reference vacuum (5) is enclosed in the cavity (special chamber) between the silicon chip and the glass base. 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 housing. It protrudes into the air flow, and can therefore respond to temperature changes with a minimum of delay (Fig. 4, Pos. 4).

Method of operation

The method of operation, and with it the signal conditioning and signal amplification together with the characteristic curve, correspond to that used in the pressure sensor with cap and reference vacuum on the component side. The only difference is that the measuring cell's diaphragm is deformed in the opposite direction and therefore the deformation resistors are "bent" in the other direction.

6 High-pressure sensor

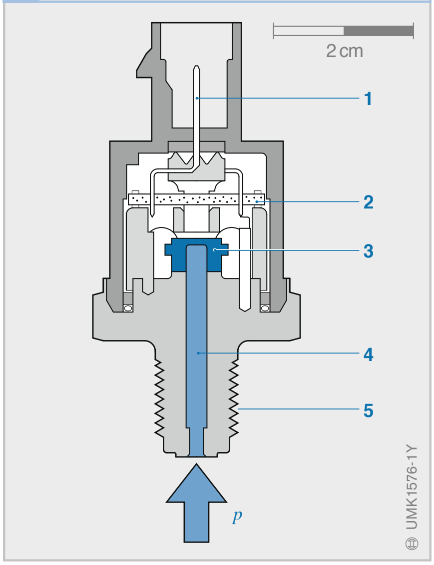


Fig. 6
1 Electrical connection (socket)
2 Evaluation circuit
3 Steel diaphragm with deformation resistors
4 Pressure port
5 Mounting thread

High-pressure sensors

Application

High-pressure sensors are used in a motor vehicle to measure fuel pressure and brake-fluid pressure, e.g:

- Rail-pressure sensor for gasoline direct injection (pressure up to 200 bar)
- Rail-pressure sensor for common-rail diesel-injection system (pressure up to 2000 bar)
- Brake-fluid pressure sensor in the hydraulic modulator of the Electronic Stability Program (pressure up to 350 bar)

Design and method of operation

High-pressure sensors operate according to the same principle as micromechanical pressure sensors. The core of the sensor is a steel diaphragm, onto which deformation resistors have been vapor-deposited in the form of a bridge circuit (Fig. 6, Pos. 3). The sensor's measuring range is dependent on the thickness of the diaphragm (thicker diaphragms for higher pressures, thinner diaphragms for lower pressures). As soon as the pressure to be measured is applied to one side of the diaphragm via the pressure port (4), the deformation resistors change their resistance values as a result of the deflection of the diaphragm. The output voltage generated by the bridge circuit is proportional to the applied pressure. This voltage is transmitted via connecting leads (bonding wires) to an evaluation circuit (2) in the sensor. The evaluation circuit amplifies the bridge signal to 0...5 V and transmits it to the ECU, which calculates the pressure with the aid of a characteristic curve.

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 (B) and structured vertically using a mask and etching (C). In the final processing step, the "sacrificial" oxide layer underneath the polysilicon layer is removed by means of gaseous hydrogen fluoride (D). 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

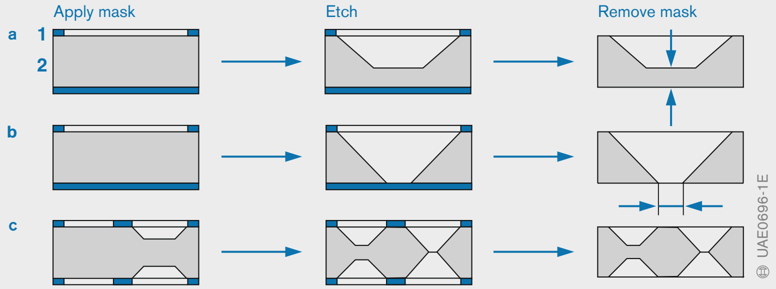


Fig. 1
a Diaphragms
b Openings
c Beams and webs

1 Etching mask
2 Silicon

2 Surface micromechanics (processing steps)

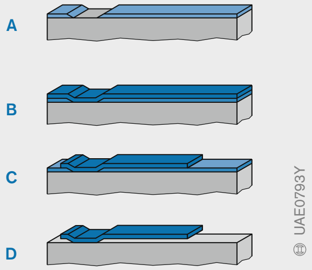


Fig. 2
A Cutting and structuring the sacrificial layer
B Cutting the polysilicon
C Structuring the polysilicon
D Removing the sacrificial layer

3 Surface micromechanics (structure details)

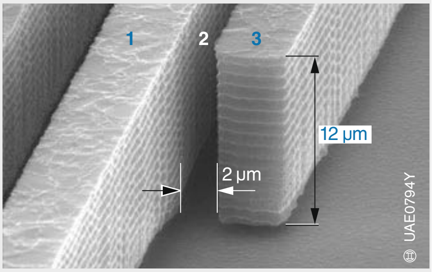


Fig. 3
1 Fixed electrode
2 Gap
3 Spring electrodes

Two-step lambda oxygen sensors

Application

These sensors are used in gasoline engines equipped with two-step lambda control. They project between the engine exhaust and the catalytic converter into the exhaust pipe and simultaneously detect the exhaust-gas flow from all the cylinders. Because the lambda sensor is heated, it can be installed further away from the engine so that even extended periods of driving at full load present no problems. The LSF4 sensor is also suitable for use in exhaust systems with several sensors (e.g., OBD II).

Two-step lambda sensors compare the residual-oxygen content in the exhaust gas with the oxygen content in the reference atmosphere (surrounding air inside the sensor) and indicate whether a rich ($\lambda < 1$) or lean mixture ($\lambda > 1$) is present in the exhaust gas. The sudden jump in the characteristic curve of these sensors permits mixture control to $\lambda = 1$ (Fig. 1).

Method of operation

Two-step lambda oxygen sensors operated on the principle of a galvanic oxygen concentration cell with a solid electrolyte (Nernst principle). The ceramic element is conductive for oxygen ions from a temperature of approximately 350 °C (safe, reliable operation at > 350 °C). Due to the abrupt change in the residual-oxygen content on the exhaust-gas side in the range of $\lambda = 1$ (e.g., $9 \cdot 10^{-15}$ % vol. for $\lambda = 0.99$ and 0.2 % vol. for $\lambda = 1.01$), the different oxygen content on both sides of the sensor generates an electrical voltage between the two boundary layers. This means that the oxygen content in the exhaust gas can be used as a measure of the air/fuel ratio. The integrated heater ensures that the sensor functions even at extremely low exhaust-gas temperatures.

The voltage output by the sensor U_S is dependent on the oxygen content in the exhaust gas. In the case of a rich mixture ($\lambda < 1$), it reaches 800...1000 mV, and, in the case of a lean mixture ($\lambda > 1$), it reaches only about 100 mV. The transition from rich to lean occurs at U_{reg} = 450...500 mV.

The temperature of the ceramic element influences its ability to conduct the oxygen ions, and thus the shape of the output-voltage curve as a function of the excess-air factor λ (the values in Fig. 1 are therefore temperature-dependent). In addition, the response time for a voltage change when the mixture composition changes is also strongly dependent on temperature.

Whereas these response times at ceramic-element temperatures of below 350 °C are in the seconds range, the sensor responds at optimum operating temperatures of around 600 °C in less than 50 ms. When an engine is started, therefore, lambda closed-loop control is deactivated until the minimum operating temperature of about 350 °C is reached. During this period, the engine is open-loop-controlled.

1 Voltage curve of a two-step lambda sensor for different operating temperatures

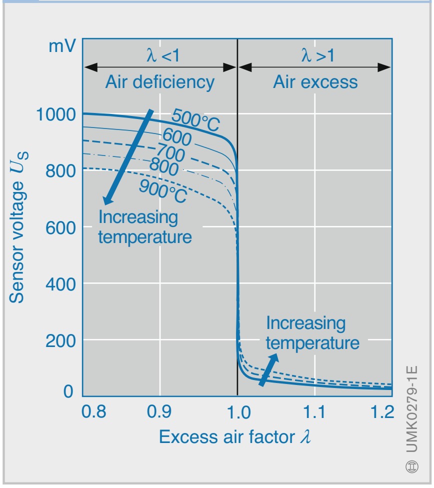


Fig. 1
- a Rich mixture (air deficiency)
- b Lean mixture (excess air)

Design

LSH25 finger-type sensor

Sensor ceramic element with protective tube
The solid electrolyte is a ceramic element which is impermeable to gas. It is composed of a mixed oxide of the elements zirconium and yttrium in the shape of a tube closed off at one end (finger). The surfaces have been provided on both sides with electrodes made from a microporous, thin noble-metal coating.

The platinum electrode on the exhaust side, which protrudes into the exhaust pipe, acts like a small catalytic converter: Exhaust gas which reaches this electrode is treated catalytically and brought to a stoichiometric balance ($\lambda = 1$). In addition, the side that is exposed to the exhaust gas has a porous, ceramic multiple layer (spinel layer) to protect it against contamination and erosive damage. The ceramic element is also

3 Configuration of a finger-type lambda sensor in the exhaust pipe

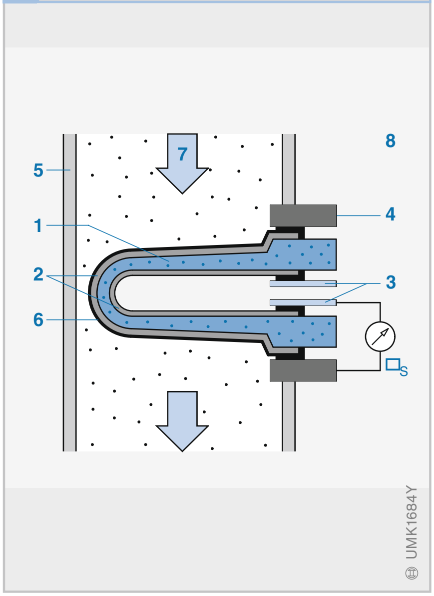


Fig. 3
1 Sensor ceramic element
2 Electrodes
3 Contacts
4 Housing contact
5 Exhaust pipe
6 Ceramic protective layer (porous)
7 Exhaust gas
8 Outside air

U_S Sensor voltage

2 LSH25 heated finger-type lambda sensor (view and section)

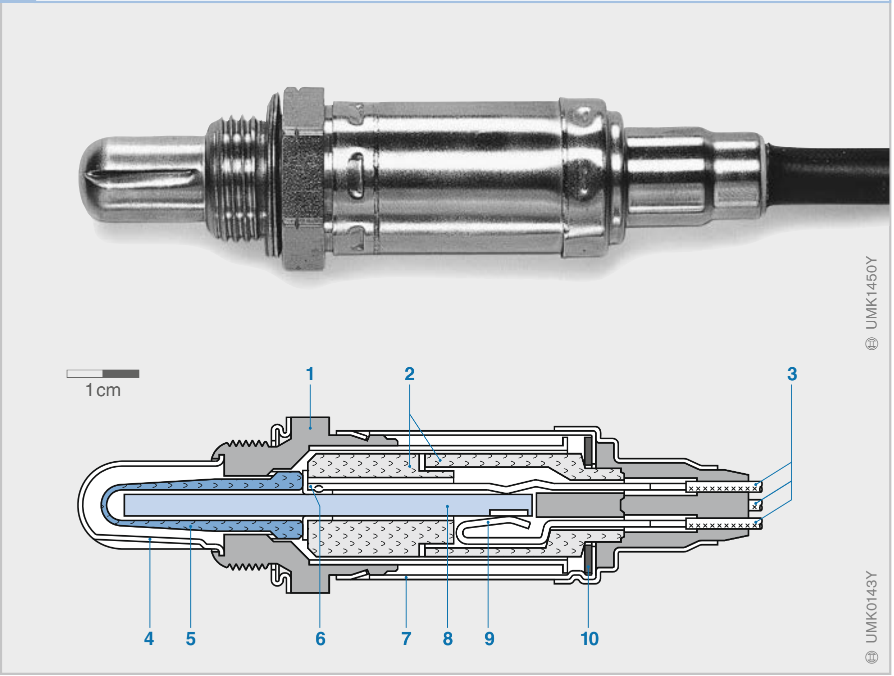


Fig. 2
1 Sensor housing
2 Ceramic support tube
3 Connecting cable
4 Protective tube with slots
5 Active sensor ceramic element
6 Contact element
7 Protective sleeve
8 Heater element
9 Clamp-type connections for the heater element
10 Disc spring

protected against mechanical impact and thermal shocks by a metal tube. Various slots in the protective tube are designed in such a way that they, on the one hand, provide particularly effective protection and thermal and chemical loads, and, on the other hand, prevent the ceramic element from cooling excessively when the exhaust gas is “cool”.

The sensor’s “open” inner chamber facing away from the exhaust gas is connected to the outside air, which acts as a reference gas (Fig. 3).

Sensor element with heater element and electrical connection

A ceramic support tube and a disc spring hold and seal the active, finger-shaped sensor ceramic element in the sensor housing. A contact element between the support tube and the active sensor ceramic element provides the contact between the inner electrode and the connecting cable.

The outer electrode is connected to the sensor housing by the metal sealing ring. A protective 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 connecting cable is crimped to the contact element which protrudes from the sensor, and is protected against moisture and mechanical damage by a temperature-resistant cap.

The finger-type sensor (Fig. 2) is also equipped with an electrical heater element. This ensures that the ceramic-element temperature remains sufficiently high, even at low engine load and thus low exhaust-gas temperature.

This external heating is so quick that the sensor reaches operating temperature 20...30 s after the engine has started and therefore lambda closed-loop control can come into operation. Finally, sensor heating provides for an optimal ceramic-element operating temperature above the operating limit of 350 °C and thus ensures low and stable exhaust-gas emissions.

4 Planar lambda sensor (functional layers)

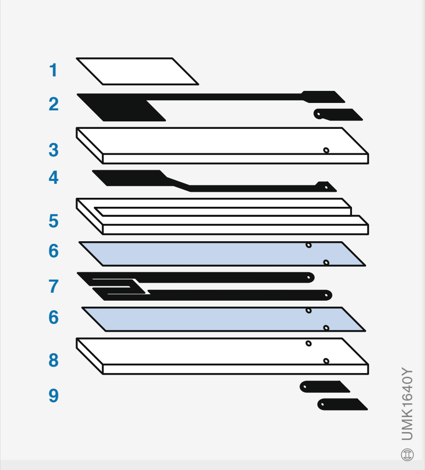


Fig. 4
1 Porous protective layer
2 Outer electrode
3 Sensor foil
4 Inner electrode
5 Reference-air-passage foil
6 Insulation layer
7 Heater
8 Heater foil
9 Connection contacts

5 LSF4 planar lambda sensor (schematic diagram)

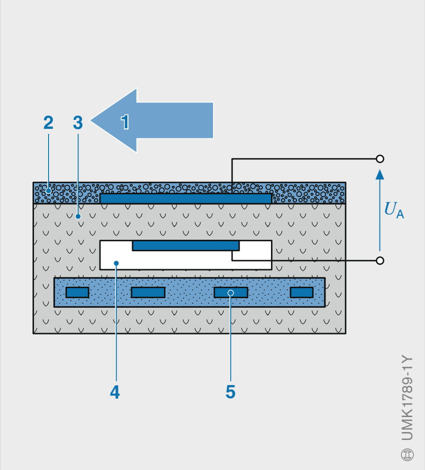


Fig. 5
1 Exhaust gas
2 Porous ceramic protective layer
3 Measuring cell with microporous noble-metal coating
4 Reference-air passage
5 Heater

U_A Output voltage

LSF4 planar lambda sensor

In terms of its function, the planar lambda sensor corresponds to the heated finger-type sensors with a voltage-jump curve at $\lambda = 1$. However, on the planar sensor, the solid electrolyte is comprised of a number of individual laminated foils stacked one on top of the other (Fig. 4). The sensor is protected against thermal and mechanical influences by a double-walled protective tube.

The planar ceramic element (measuring cell and heater are integrated) is shaped like a long stretched-out wafer with rectangular cross-section.

The surfaces of the measuring cell are provided with a microporous noble-metal coating, which also has a porous ceramic coating on the exhaust-gas side to protect it against the erosive effects of the exhaust-residues. 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 even in the event of low power input.

The reference-air passage inside the LSF4 lambda sensor – operating as a reference-gas sensor (Figs. 5 and 6) – has access to the ambient air. It can therefore compare the residual oxygen in the exhaust gas with the oxygen in the reference atmosphere, i.e., the ambient air inside the sensor. Thus, the planar-sensor voltage also demonstrates an abrupt change (Fig. 1) in the area of the stoichiometric composition of the air/fuel mixture ($\lambda = 1$).

6 LSF4 planar lambda sensor (view and section)

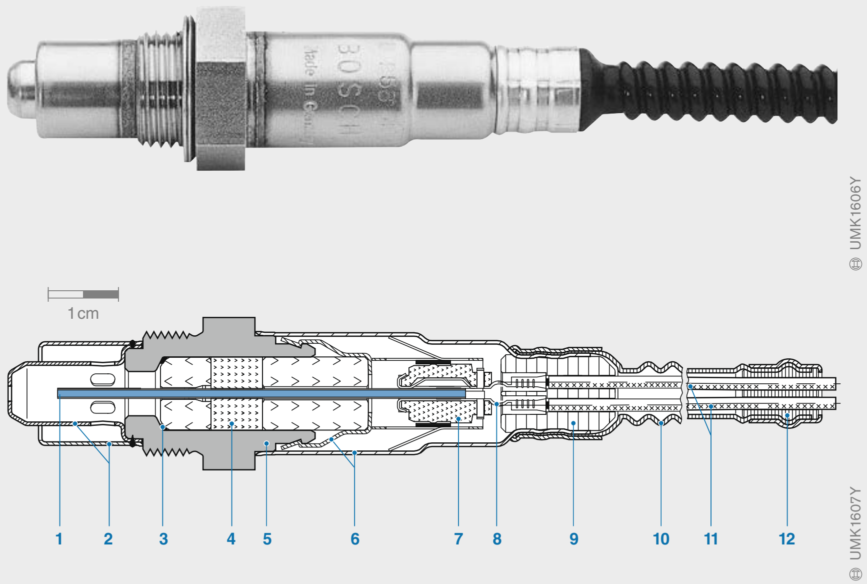


Fig. 6

1 Planar measuring cell
2 Double protective tube
3 Sealing ring
4 Seal pack
5 Sensor housing
6 Protective sleeve
7 Contact holder
8 Contact clip
9 PTFE grommet
10 PTFE shaped sleeve
11 Five connecting leads
12 Seal

LSU4 planar broad-band lambda oxygen sensor

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 ratio in the combustion chamber. The excess-air factor λ describes this air/fuel ratio.

The sensor projects into the exhaust pipe and registers the exhaust-gas mass flow from all cylinders. It is capable of making precise measurements not only at the stoichiometric point at $\lambda = 1$, but also in the lean ($\lambda > 1$) and rich ($\lambda < 1$) ranges. In conjunction with control electronics, it delivers an unmistakable, continuous electrical signal in the range of $0.7 < \lambda < \infty$ (air with 21 % O_2) (Fig. 3). 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 lean and rich air/fuel mixtures. This type of lambda sensor is therefore also suitable for lambda closed-loop control with lean-burn concepts on gasoline engines, as well as for diesel engines, gas-powered engines and gas-powered central heaters and water heaters (hence the German designation LSU: Lambda-Sonde-Universal = universal lambda sensor).

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

The LSU4 broad-band lambda sensor (Fig. 2) is a planar dual-cell limit-current sensor. It features a measuring cell (Fig. 1) made of zirconium-dioxide ceramic (ZrO_2), and is a combination of a Nernst concentration cell (sensor cell which functions in the same way 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 arranged in relation to the Nernst concentration cell (7) in such a way that there is a 10...50 µm diffusion gap (6). Here, there are two porous platinum electrodes: one pump electrode and one Nernst measuring electrode. The diffusion gap is connected to the exhaust gas by way of a gas-access passage (10). A porous diffusion barrier (11) serves to limit the flow of oxygen molecules from the exhaust gas.

On the one side, the Nernst concentration cell is connected to the surrounding atmo-

1 Planar broad-band lambda sensor (schematic design of the measuring cell and installation in the exhaust pipe)

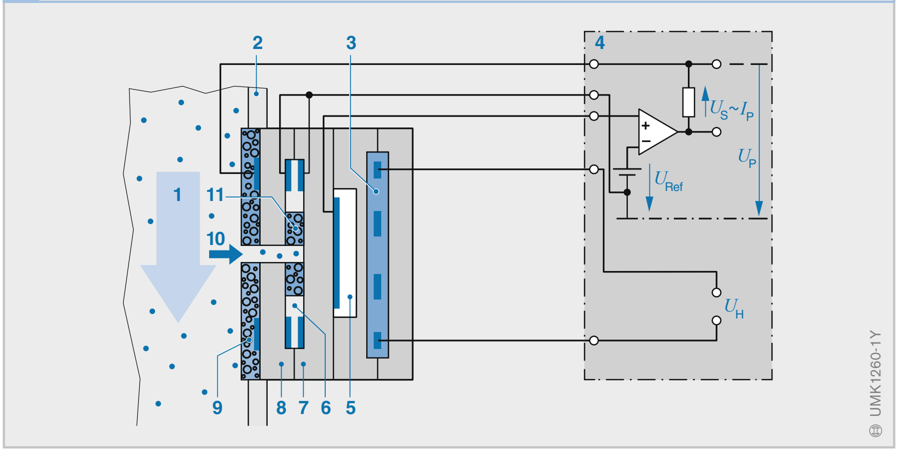


Fig. 1

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 with Nernst measuring electrode (on diffusion-gap side) and reference electrode (on reference-cell side)
8	Oxygen pump cell with 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

sphere by a reference-air passage (5), and on the other, it is connected to the exhaust gas in the diffusion gap.

The sensor requires control-electronics circuitry to generate the sensor signal and to regulator the sensor temperature.

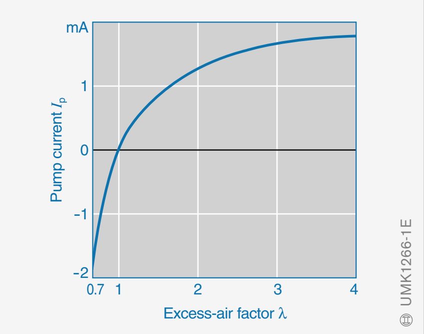
An integrated heater (3) heats the sensor so that it quickly reaches the operating temperature of 650...900 °C which is required for a signal that can be evaluated. This function drastically reduces the influence of the exhaust-gas temperature on the sensor signal.

Method of operation

The exhaust gas enters the actual measuring chamber (diffusion gap) of the Nernst concentration cell through the pump cell's small 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 the ambient air 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 aid 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 the exhaust gas is rich, the oxygen (due to the decomposition of CO_2 and H_2O at the exhaust-gas electrode) is pumped from the surrounding exhaust gas and into the diffusion gap (negative pump current). At $\lambda = 1$, no oxygen needs to be transported, and the pump current is zero. The pump current is proportional to the oxygen concentration in the exhaust gas and is thus a (non-linear) measure of the excess-air factor λ (Fig. 3).

3 Pump current I_P of a broad-band lambda sensor as a function of the exhaust-gas excess-air factor λ



2 LSU4 planar broad-band lambda sensor (view and section)

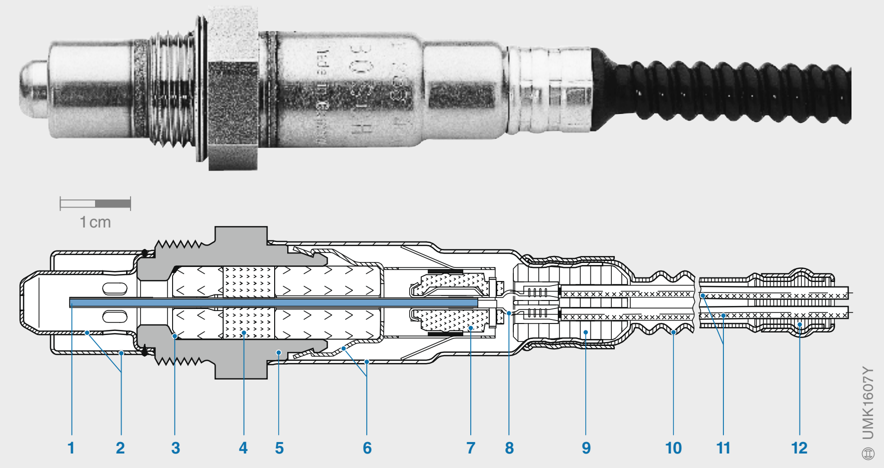


Fig. 2

1 Measuring cell (combination of Nernst concentration cell and oxygen pump cell)
2 Double protective tube
3 Sealing ring
4 Seal pack
5 Sensor housing
6 Protective sleeve
7 Contact holder
8 Contact clip
9 PTFE grommet
10 PTFE shaped sleeve
11 Five connecting leads
12 Seal