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

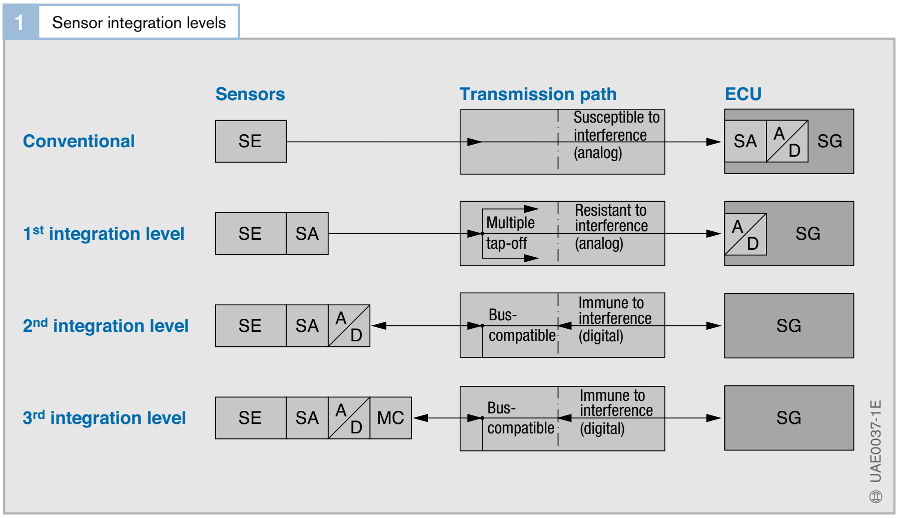


Fig. 1

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

K. Reif (Ed.), *Diesel Engine Management,* Bosch Professional Automotive Information,
DOI 10.1007/978-3-658-03981-3_22, © Springer Fachmedien Wiesbaden 2014

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…+1,000°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.

1 Coolant temperature sensor

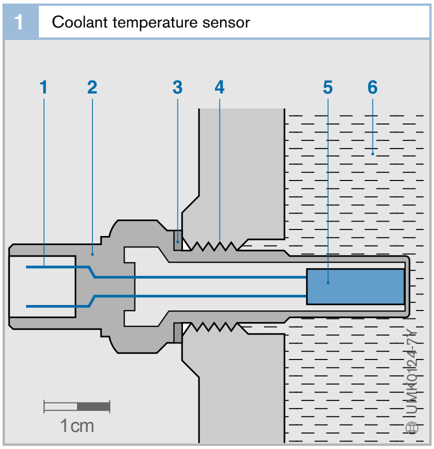
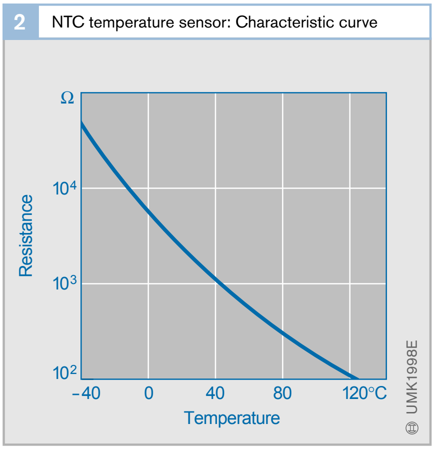


Fig. 1
1 Electrical connections
2 Housing
3 Gasket
4 Thread
5 Measuring resistor
6 Coolant

2 NTC temperature sensor: Characteristic curve



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...1,000 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

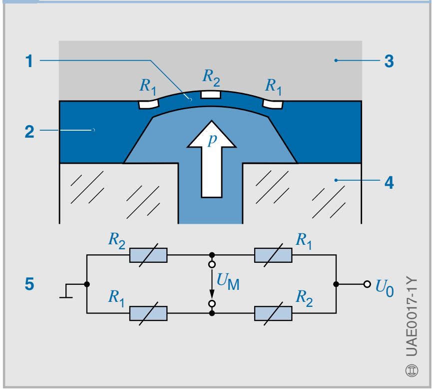


Fig. 1

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

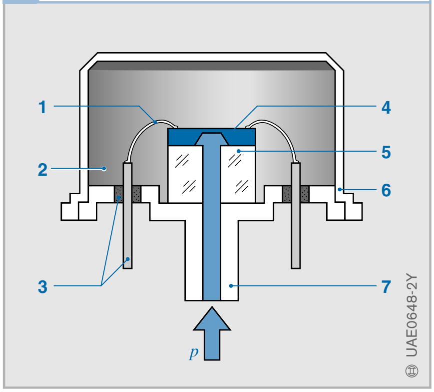
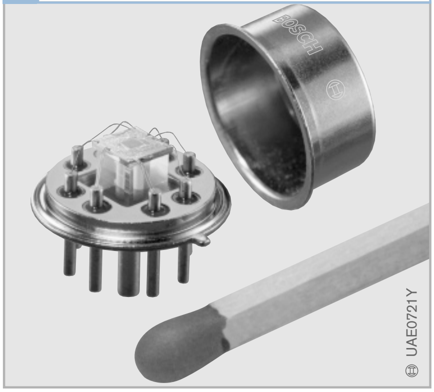


Fig. 2

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



prised of a silicon chip (Fig. 1, 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, 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…1,000 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, 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, 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, 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

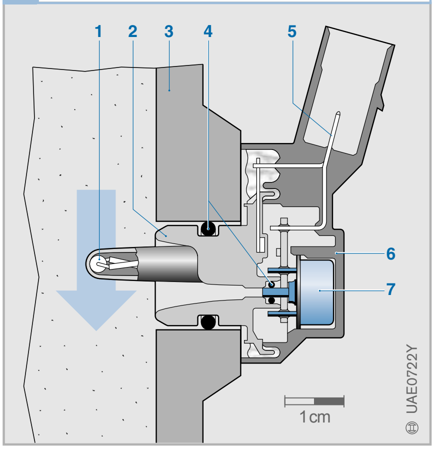
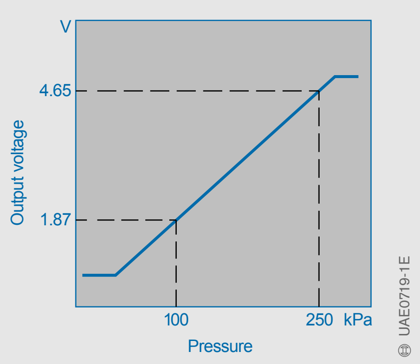


Fig. 4
1 Temperature sensor (NTC)
2 Lower section of case
3 Manifold wall
4 Seal rings
5 Electrical terminal (plug)
6 Case cover
7 Measuring element

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 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, 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, 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

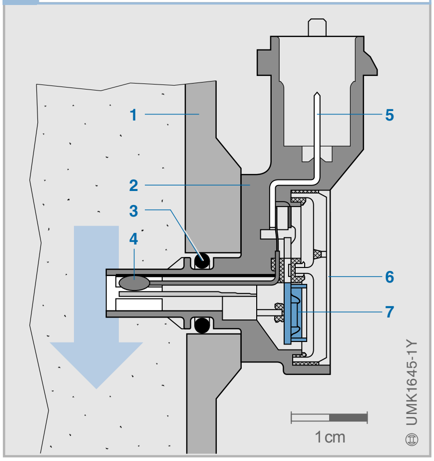


Fig. 6
1 Manifold wall
2 Case
3 Seal ring
4 Temperature sensor (NTC)
5 Electrical connection (socket)
6 Case cover
7 Measuring element

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

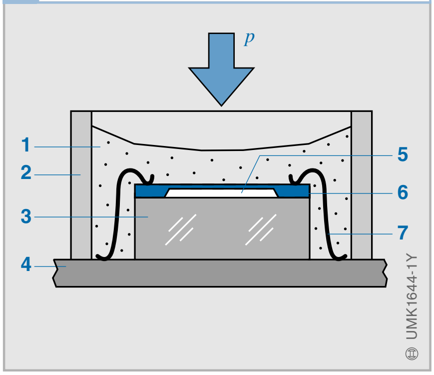


Fig. 8
1 Protective gel
2 Gel frame
3 Glass base
4 Ceramic hybrid
5 Chamber with reference volume
6 Measuring element (chip) with evaluation electronics
7 Bonded connection
p Measured pressure

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 (1,600 bar).
The fuel pressure is regulated in a control loop, and remains practically constant independent of load and engine speed.
Any deviations from the setpoint 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, 3). The sensor's measuring range is a function of diaphragm thickness (thicker diaphragms for higher pressures, thinner diaphragms 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 1,500 bar).

The 0...80 mV output voltage generated by the bridge is conducted to an evaluation circuit (2) 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

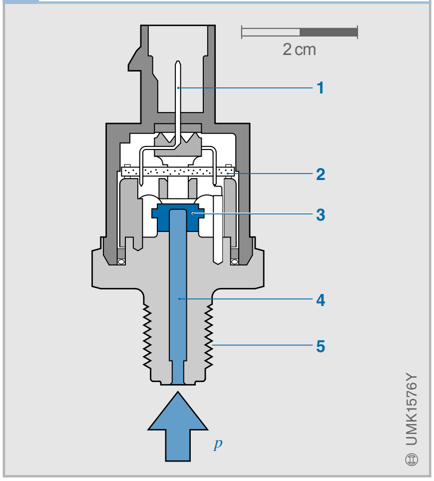
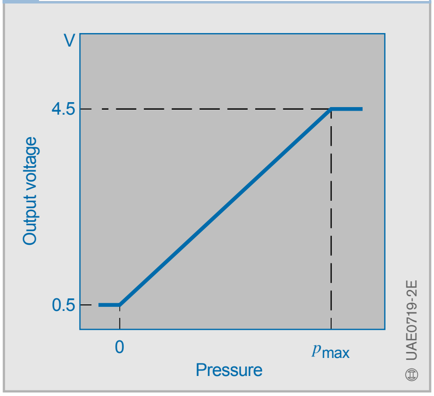


Fig. 1

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)



Inductive engine-speed sensors

1 Inductive rpm sensor

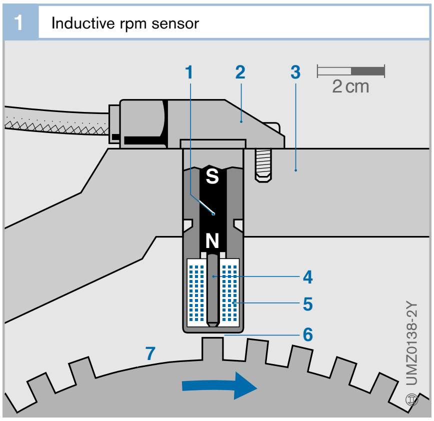


Fig. 1
1 Permanent magnet
2 Sensor housing
3 Engine block
4 Pole pin
5 Solenoid winding
6 Air gap
7 Trigger wheel with reference-mark gap

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, 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.

2 Signal from an inductive rpm sensor

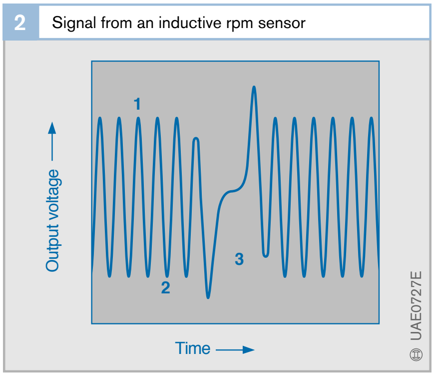


Fig. 2
1 Tooth
2 Tooth gap
3 Reference mark

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.

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)

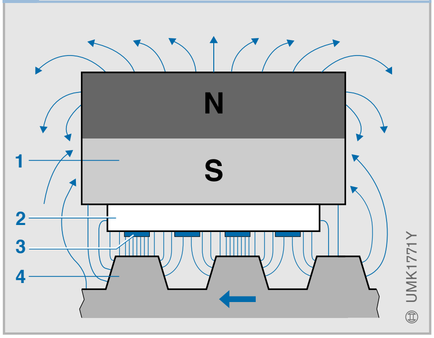


Fig. 1
1 Magnet
2 Homogenization wafer (Fe)
3 Magnetoresistor
4 Toothed pulse disc

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

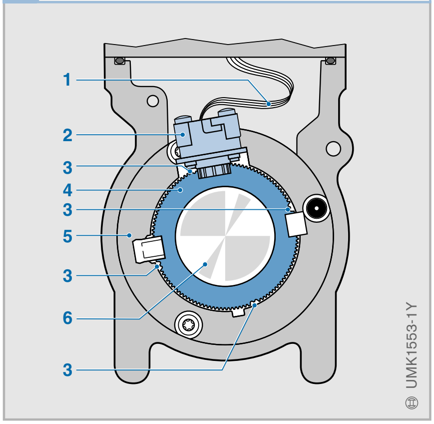


Fig. 2
1 Flexible conductive foil
2 Rotation-speed (rpm)/angle-of-rotation sensor
3 Tooth gap
4 Toothed pulse wheel (trigger wheel)
5 Rotatable mounting
6 Driveshaft

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, 7) rotates with the camshaft. The Hall-effect IC is located between the trigger wheel and a permanent magnet (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)

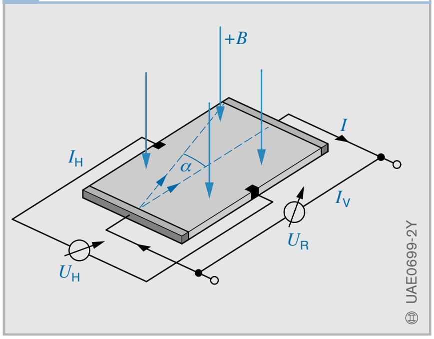


Fig. 1

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

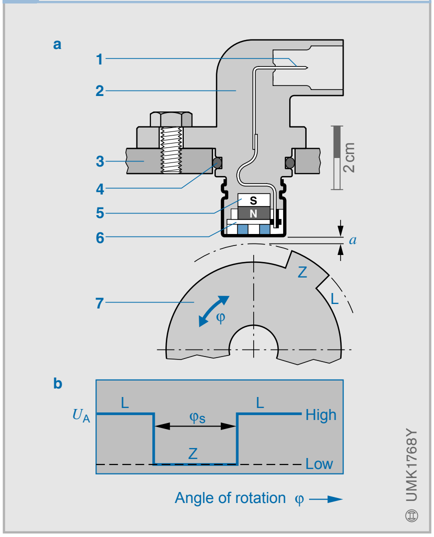


Fig. 2

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

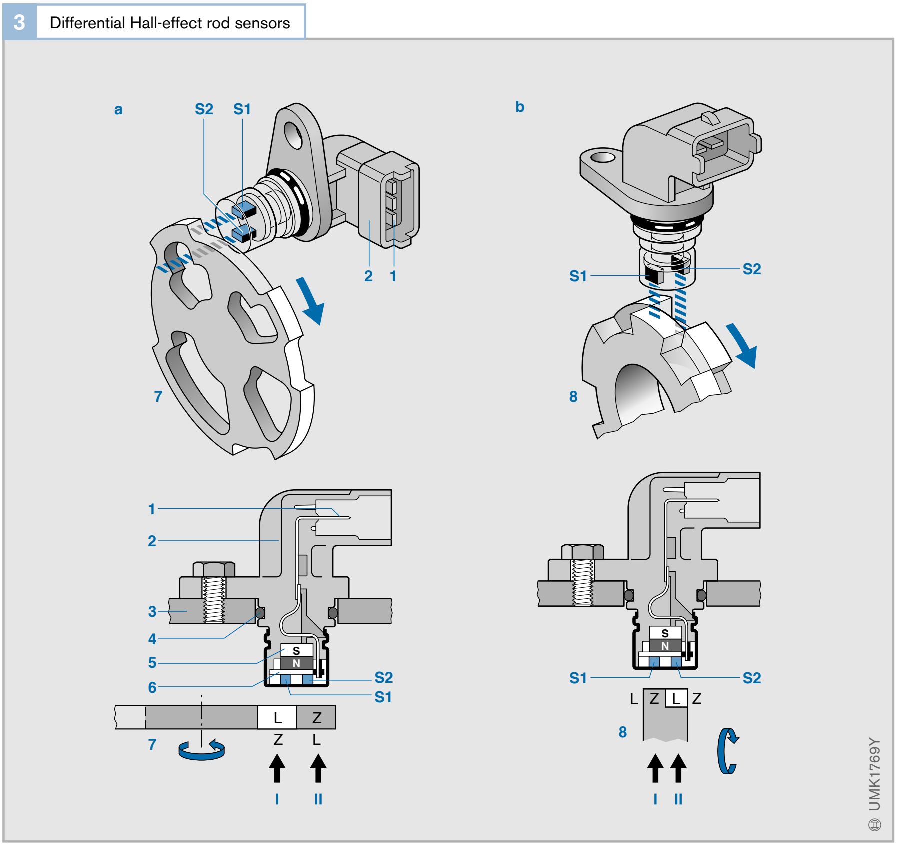


Fig. 3
a Axial tap-off (perforated plate)
b Radial tap-off (two-track trigger wheel)

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

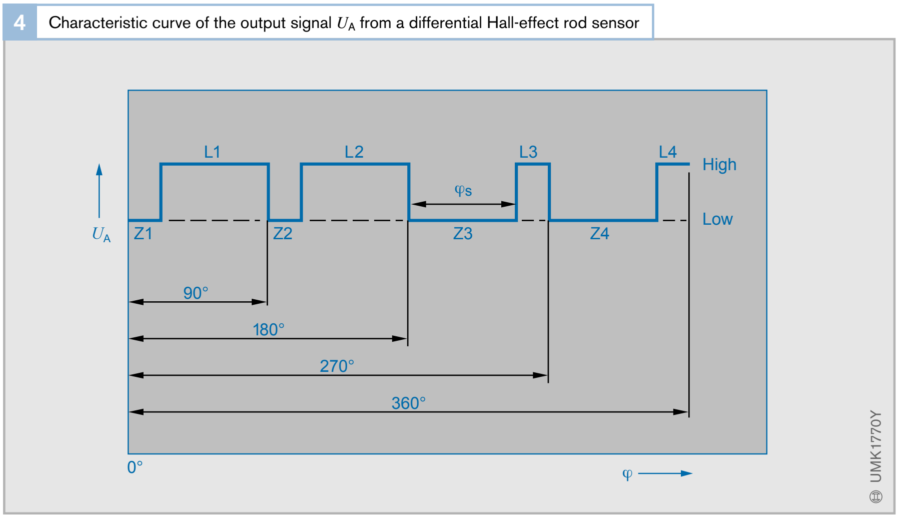


Fig. 4
Output signal “Low”: Material (Z) in front of S1, gap (L) in front of S2

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

φ_S Signal width

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 troubleshooting (Fig. 1). Instead of the second potentiometer, another version uses a low-idle switch which provides a signal for the ECU when the accelerator pedal is in the idle posi-

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

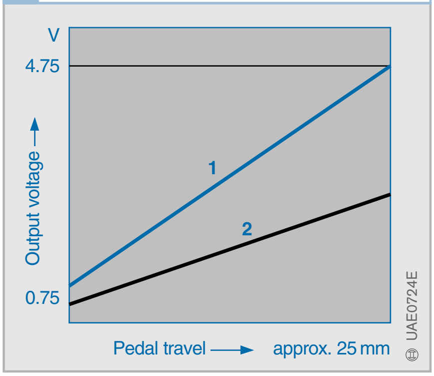


Fig. 1
1 Potentiometer 1 (master potentiometer)
2 Potentiometer 2 (50% of voltage)

2 Accelerator-pedal-sensor versions

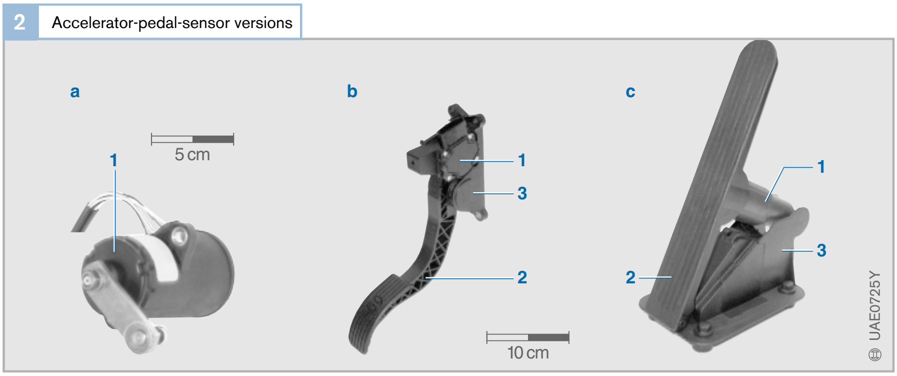


Fig. 2
a Individual accelerator-pedal sensor
b Top-mounted accelerator-pedal module
c Bottom-mounted accelerator-pedal module FMP1
1 Sensor
2 Vehicle-specific pedal
3 Pedal bracket

tion. 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, 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

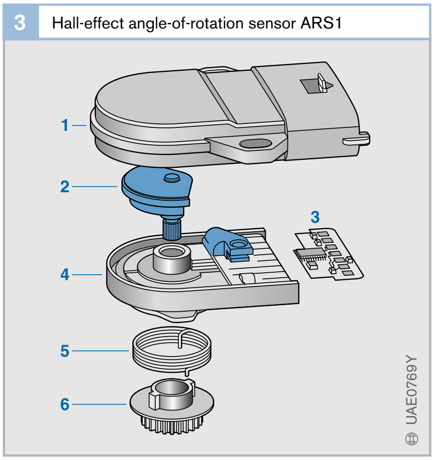


Fig. 3
1 Housing cover
2 Rotor (permanent magnet)
3 Evaluation electronics with Hall-effect sensor
4 Housing base
5 Return spring
6 Coupling element (e.g. gear)

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

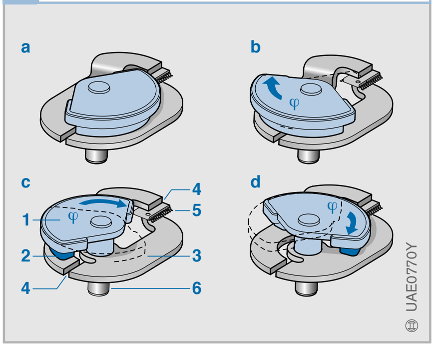


Fig. 4
1 Rotor (permanent magnet)
2 Pole shoe
3 Conductive element
4 Air gap
5 Hall-effect sensor
6 Shaft (magnetically soft)

φ Angle of rotation

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

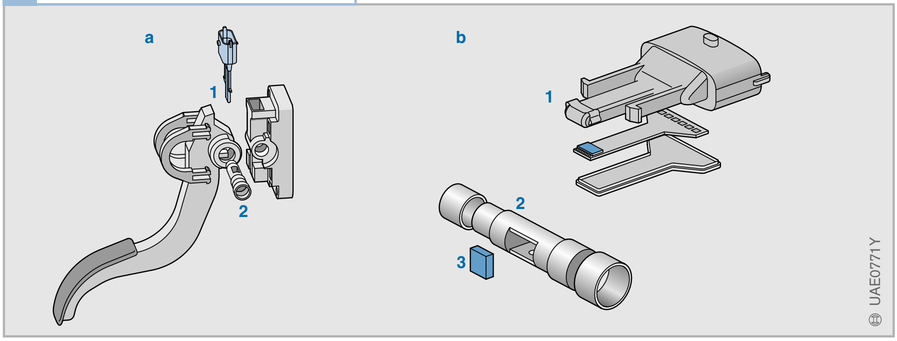


Fig. 5
a Installation in the accelerator-pedal module
b Components

1 Hall-effect sensor
2 Pedal shaft
3 Magnet

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, 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.

1 Hot-film air-mass meter HFM5 (circuit)

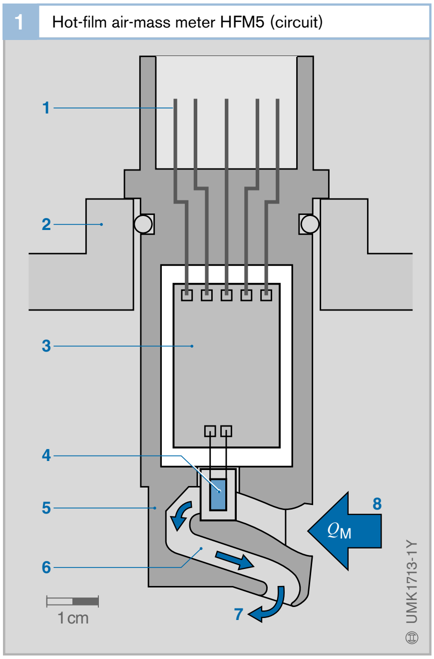


Fig. 1
1 Electrical plug-in connection
2 Measuring tube or air-filter housing wall
3 Evaluation electronics (hybrid circuit)
4 Sensor element
5 Sensor housing
6 Partial-flow measuring tube
7 Air outlet for the partial air flow Q_M
8 Intake for partial air flow Q_M

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).

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, 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 ($T_1 = T_2$).

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.

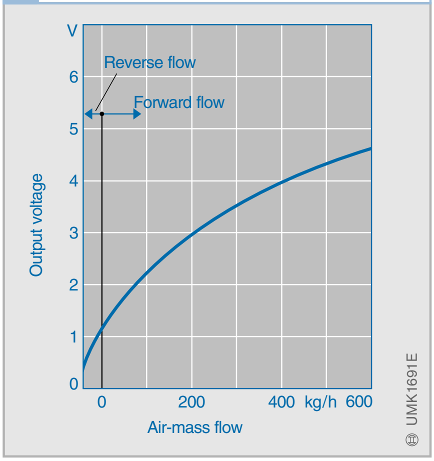
The heat dissipated to the air, and therefore the temperature characteristic at the sensor element is a function of the air mass flow. Independent of the absolute temperature of the air flowing past, the temperature differential is a measure of the air mass flow. Apart from this, the temperature differential 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

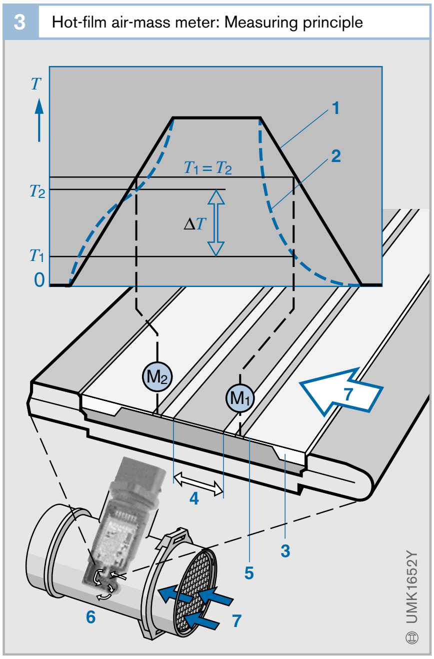


Fig. 3
1 Temperature profile without air flow across sensor element
2 Temperature profile with air flow across sensor element
3 Sensor element
4 Heated zone
5 Sensor diaphragm
6 Measuring tube with air-mass meter
7 Intake-air flow

M_1, M_2 Measuring points

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

LSU4 planar broad-band Lambda oxygen sensor

Application

As its name implies, the broad-band Lambda oxygen 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 make precise measurements not only at the stoichiometic point $\lambda = 1$, but also in the lean range (λ>1) and in the rich range (λ<1). In combination with electronic closed-loop control circuitry, these sensors generate an unmistakable, continuous electrical signal (Fig. 2) in the range from $0.7 < \lambda < \infty$ (= air with 21% O_2).

These characteristics enable the broad-band Lambda sensor to be used not only in gasoline-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 therefore 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: **L**ambda **S**ensor **U**niversal (taken from the German), in other words Universal Lambda Sensor).

The sensor protrudes into the exhaust pipe and detects the flow of exhaust-gas flow from all cylinders.

In a number of systems, several Lambda sensors are installed for even greater accuracy. Here, for instance, they are fitted in the individual exhaust tracts of V-engines.

Design and construction

The LSU4 broad-band Lambda sensor (Fig. 3) is a planar dual-cell limit-current sensor. It features a zirconium-dioxide/ceramic (ZrO_2) measuring cell (Fig. 1), which is the 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, 8) is so arranged with respect to the Nernst concentration cell (7) that there is a 10...50 µm diffusion gap (6) The gap is connected to the exhaust gas through a gas-access passage (10). The porous diffusion barrier (11) serves to limit the inflow of oxygen molecules from the exhaust gas.

1 Planar broad-band Lambda oxygen sensor (installation in the exhaust pipe and schematic diagram of the measuring cell)

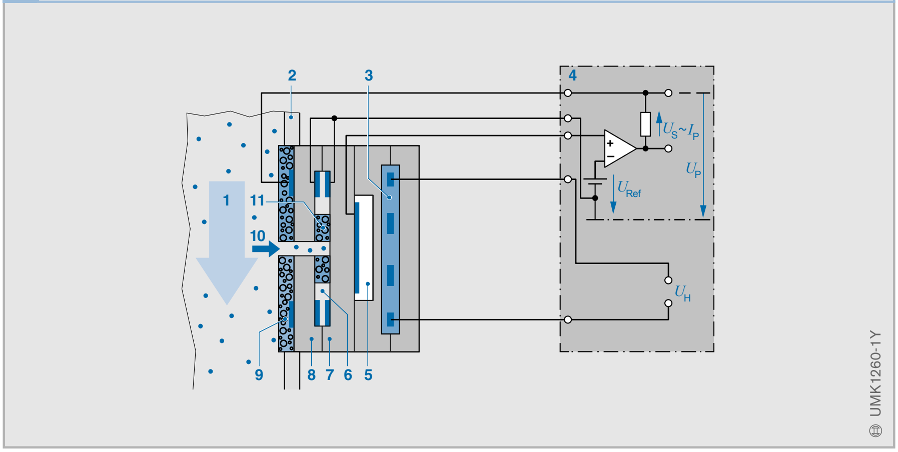


Fig. 1
1 Exhaust gas
2 Exhaust pipe
3 Heater
4 Control electronics
5 Reference cell with reference-air passage
6 Diffusion gap
7 Nernst concentration cell
8 Oxygen-pump cell with pump electrode
9 Porous protective layer
10 Gas-access passage
11 Porous diffusion barrier

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

On the one side, the Nernst concentration cell is connected to the atmosphere by a reference-air passage (5), 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.

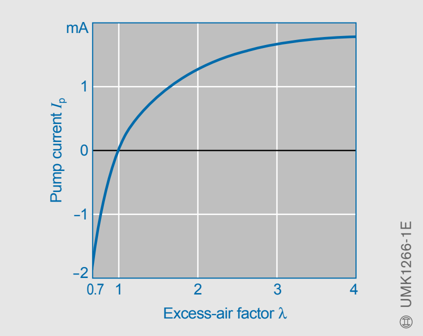
Method of operation

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 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 this a nonlinear 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 Lambda oxygen sensor (view and section)

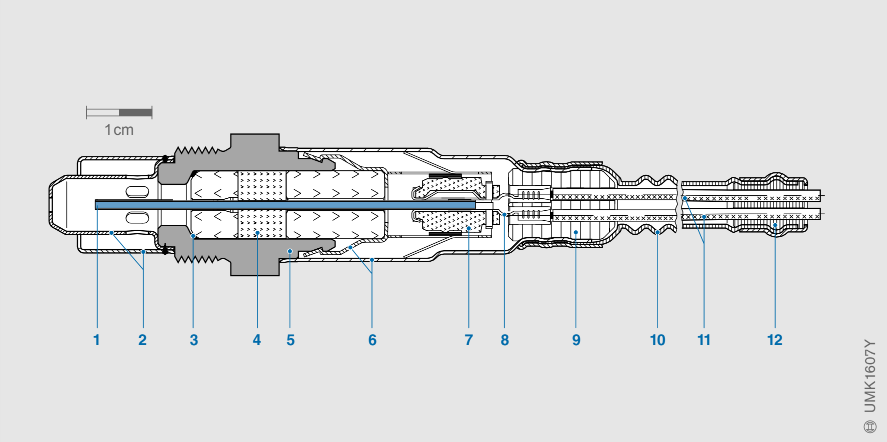


Fig. 3
1 Measuring cell (combination of Nernst concentration cell and oxygen-pump cell)
2 Double protective tube
3 Seal ring
4 Seal packing
5 Sensor housing
6 Protective sleeve
7 Contact holder
8 Contact clip
9 PTFE sleeve (Teflon)
10 PTFE shaped sleeve
11 Five connecting leads
12 Seal ring

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

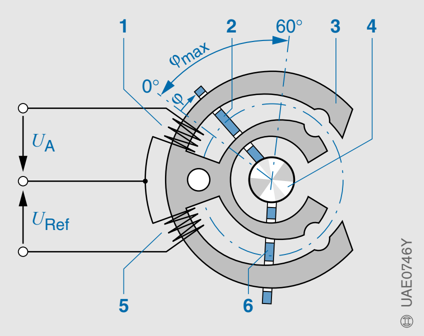


Fig. 1
1 Measuring coil
2 Measuring short-circuiting ring
3 Soft-iron core
4 Control-collar shaft
5 Reference coil
6 Reference short-circuiting ring

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

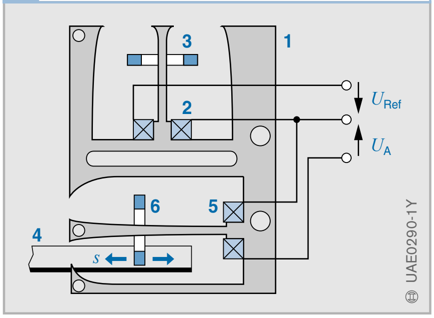


Fig. 2
1 Soft-iron core
2 Reference coil
3 Reference short-circuiting ring
4 Control rack
5 Measuring coil
6 Measuring short-circuiting ring

s Control-rack travel

3 Voltage ratio as a function of control-rack travel

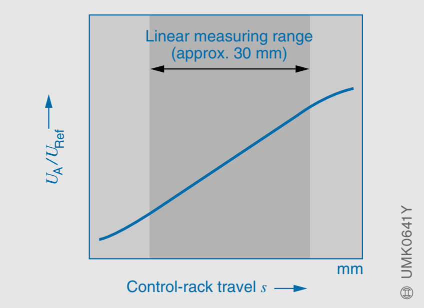


Fig. 3
U_A Output voltage
U_{Ref} Reference voltage

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 and construction

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

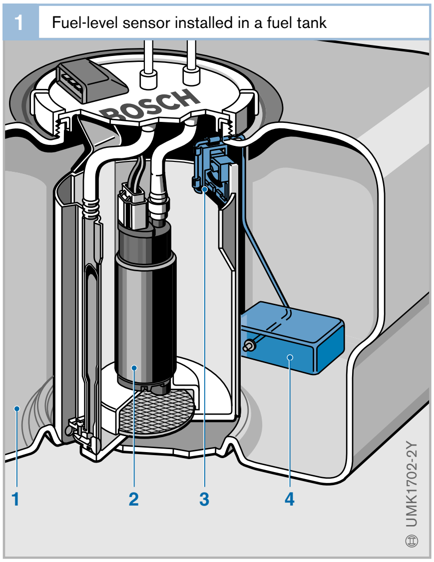


Fig. 1
1 Fuel tank
2 Electric fuel pump
3 Fuel-level sensor
4 Float

2 Fuel-level sensor

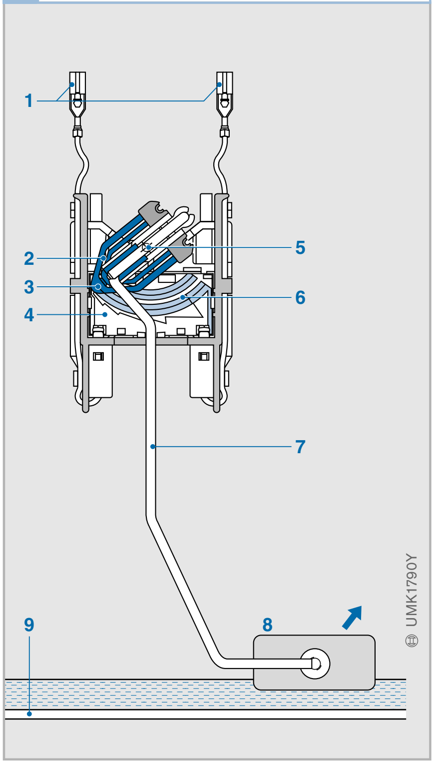


Fig. 2
1 Electrical connections
2 Wiper spring
3 Contact rivet
4 Resistor board
5 Bearing pin
6 Twin contact
7 Float lever
8 Float
9 Fuel-tank floor