BITS Pilani
Pilani Campus

Mechatronics
AE ZG511

Lecture

Sensor Characteristics

Static Characteristics

Dynamic Characteristics

Static characteristics

Range /span

It defines the maximum and minimum values of the inputs or the outputs for which the instrument is recommended to use. For example, for a temperature measuring instrument the input range may be 100-500 ^{o}C and the output range may be 4-20 mA. (Example – Range – 100°C to 500°C, Span – 400°C)

Sensitivity

It can be defined as the ratio of the *incremental output* and the *incremental input* . sensitivity of a thermocouple is denoted as 100µ*V*/°*C*.

Again sensitivity of an instrument may also vary with temperature or other external factors. This is known ***as sensitivity drift***.

Suppose the sensitivity of the spring balance mentioned above is 25 mm/kg at 20 ^{o}C and 27 mm/kg at 30^{o}C. Then the sensitivity drift/^{o}C is 0.2 (mm/kg)/^{o}C.

Static characteristics

$$Linearity = \frac{\Delta O}{O_{\max} - O_{\min}} \qquad (1)$$

where, $\Delta O = \max(\Delta O_1, \Delta O_2)$.

$$Hysteresis = \frac{H}{O_{\max} - O_{\min}} X100.$$

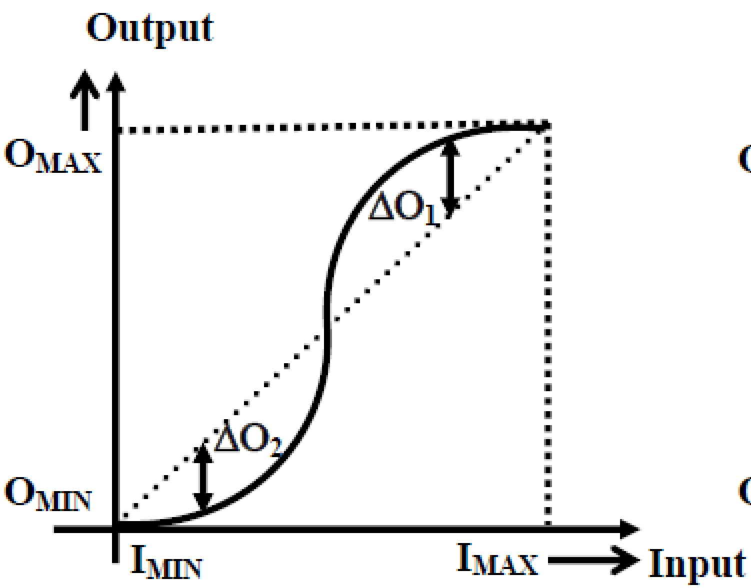


Fig. 1 Linearity

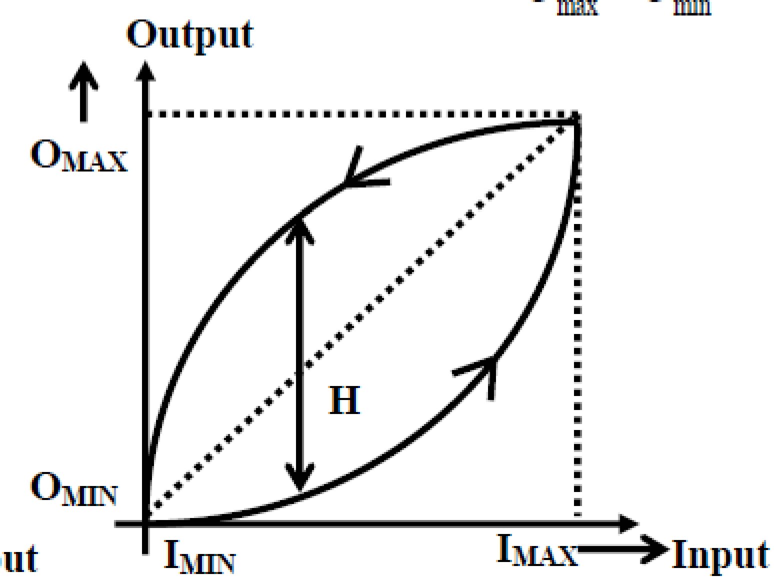


Fig. 2 Hysteresis

Static characteristics

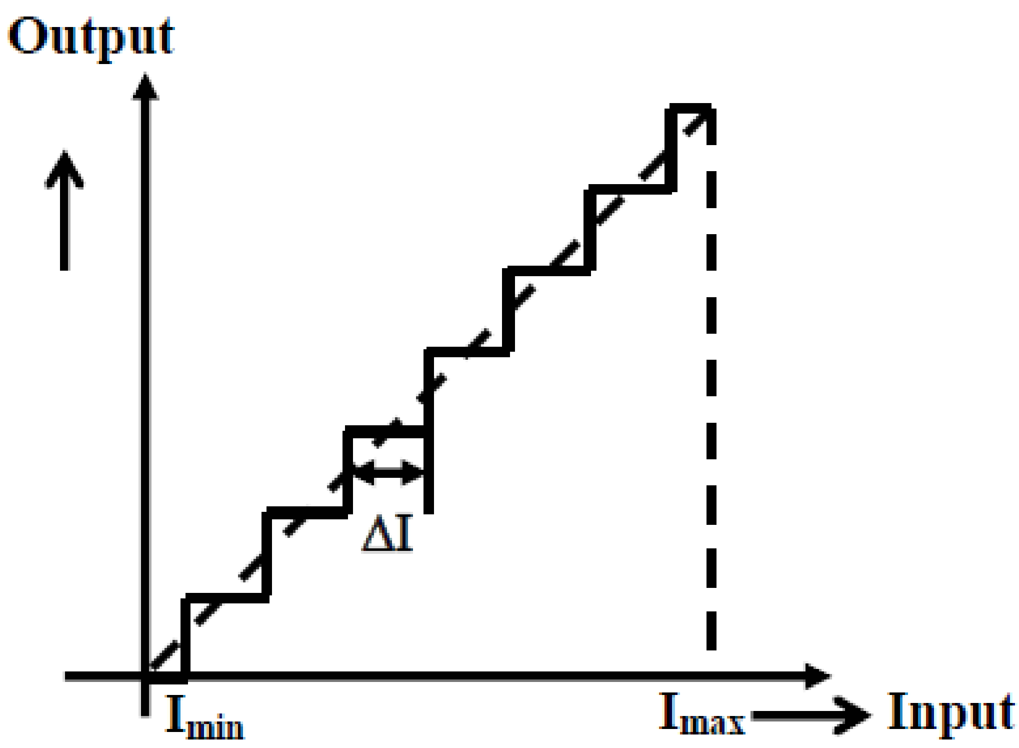


Fig. 3 Resolution

The smallest change in the input value that will produce an observable change in the output

Static characteristics

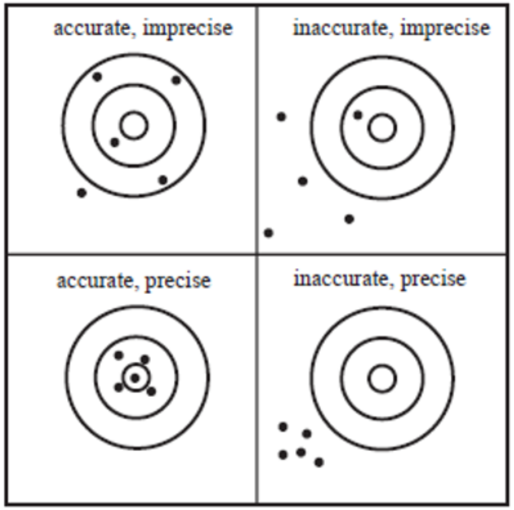
Accuracy

Accuracy indicates the closeness of the measured value with the actual or true value, and is expressed in the form of the *maximum error (= measured value – true value)* as a percentage of **full scale reading.**

Precision

Precision indicates the repeatability or reproducibility of an instrument (but does not indicate accuracy).

$$Precision = \frac{measured\ range}{\sigma_e}$$



Static characteristics

Stability

Ability to give the same output when used to measure a constant input *over a period of time*

Dead band /time

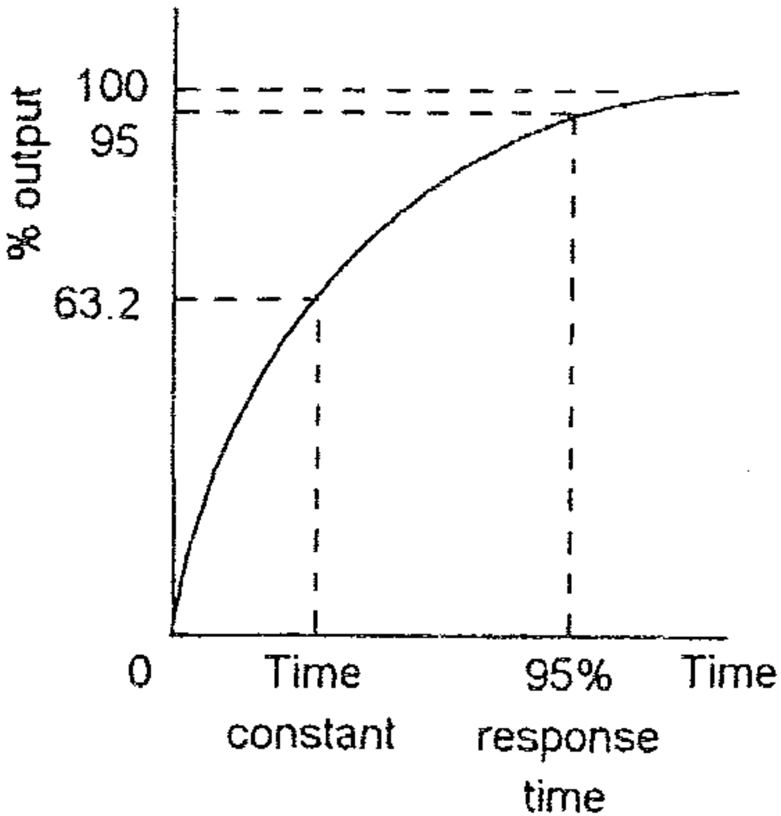
Range of input values for which there is no output

(Inductive speed sensors produce no output initially at low RPMs)

Output Impedance

The value should be specified for Sensors giving electrical output interfaced with electronic circuits. By their very nature, they **impede** the measurement.

Dynamic Characteristics



Response Time:

- Time for transducer to reach output (95%) of the input value

Time constant:

- 63.2 % of Response time

Rise time:

Output to reach 10% of input to 95% of input

Settling time:

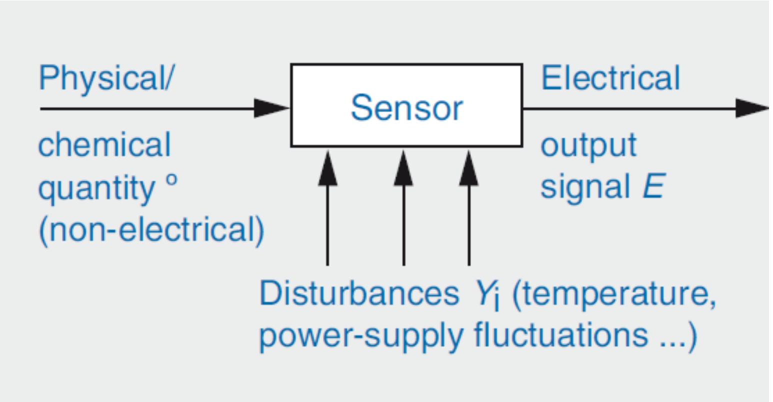
Time required for the output to settle down at 2% of the steady state value of the input.

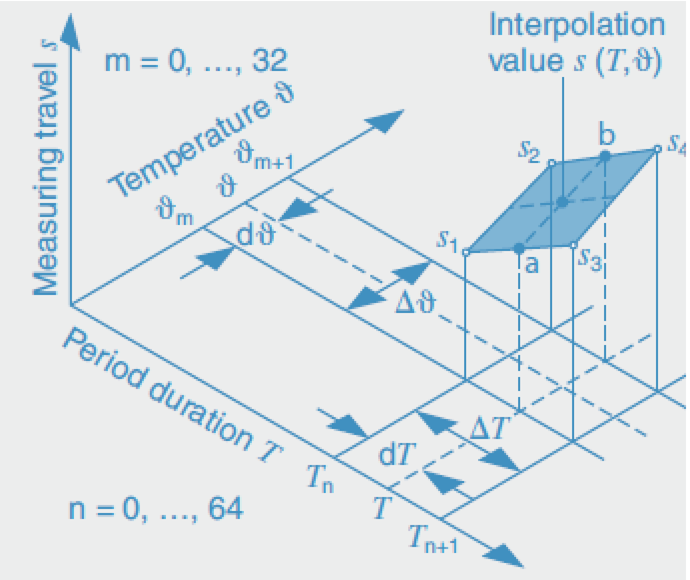
The above are due to inertia of sensors

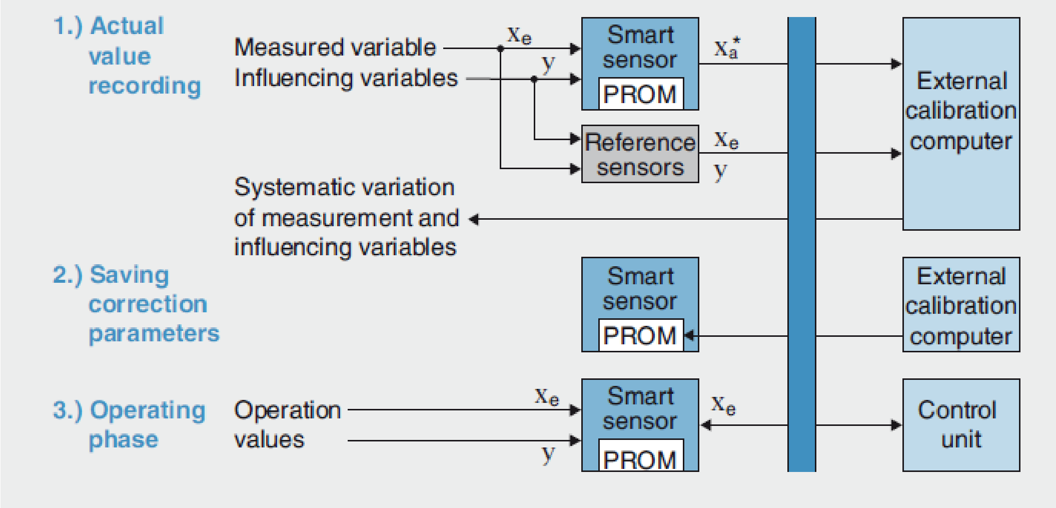
Typical Automotive Sensor specs

Sensor/type	Sensing method	Range	Accuracy (%)	Thermal range (°C)	Response time
Inlet manifold absolute or differential pressure sensor (petrol engines)	Piezoresistive silicon strain-gauged diaphragm *or* capacitive silicon diaphragm	0–105 kPa	±1 at 25 °C	−40 to +125	1 ms
Inlet and exhaust manifold pressure sensor (diesel engines)	As above	20–200 kPa	±3	As above	10 ms
Barometric absolute pressure sensor	As above	50–105 kPa	±3	As above	10 ms
Transmission oil pressure sensor	Differential transformer and diaphragm, *or* capacitive diaphragm (often stainless steel)	0–2000 kPa	±1	−40 to +160	10 ms
Inlet manifold air temperature sensor	Metal film or semiconductor film	−40 to +150 °C	±2 to ±5	−40 to +150	20 ms
Coolant temperature sensor	Thermistor	−40 to +200 °C	±2	As above	10 s
Diesel fuel temperature sensor	Thermistor	−40 to +200 °C	±2	+40 to +200	10 s
Diesel exhaust temperature sensor	Cr/Al thermocouple	−40 to +750 °C	±2	−40 to +750	10 s
Ambient air temperature sensor	Thermistor	−40 to +100 °C	±2	−40 to +100	10 s

Sensor Calibration







Sensor output signal Classification

Functional (MAP/MAF), **Safety** (Yaw rate), **Vehicle monitoring** (OBD)

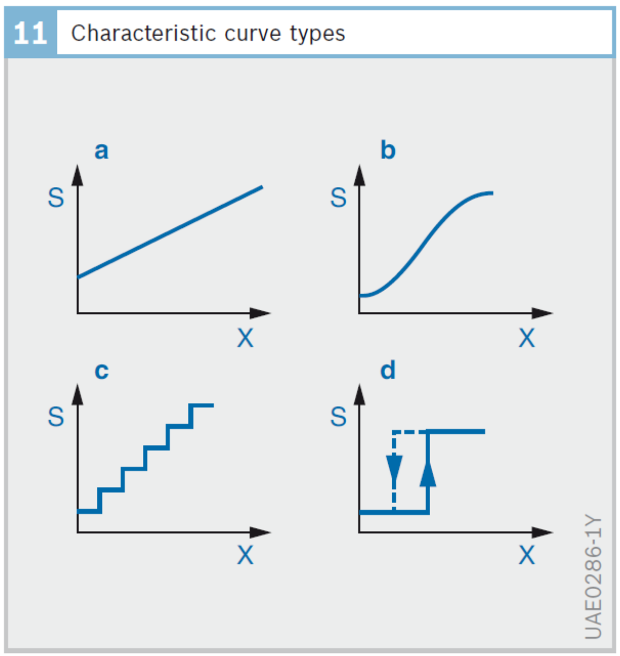


Fig. 11
S Output signal
X Measured variable

a Continuous, linear
b Continuous, nonlinear
c Discontinuous, multi-step
d Discontinuous, two-step (with hysteresis)

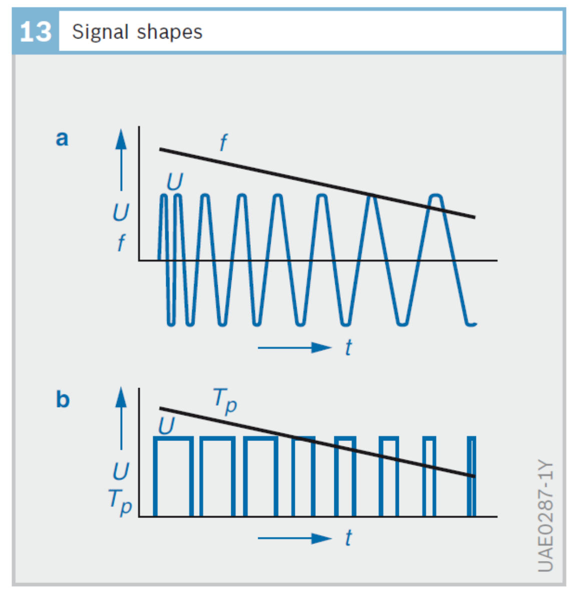


Fig. 13
a Output signal U, information parameter: frequency f
b Output signal U, information parameter: pulse duration T_P

Sensor Errors

$e = y_{\text{indicated}} - y_{\text{true}}$

$y_{\text{indicated}}$ = indicated value for the measured variable

y_{true} = ideal value, setpoint value for the measured variable (is determined with a measuring sensor that is more accurate than the sensor being examined by at least 1 class)

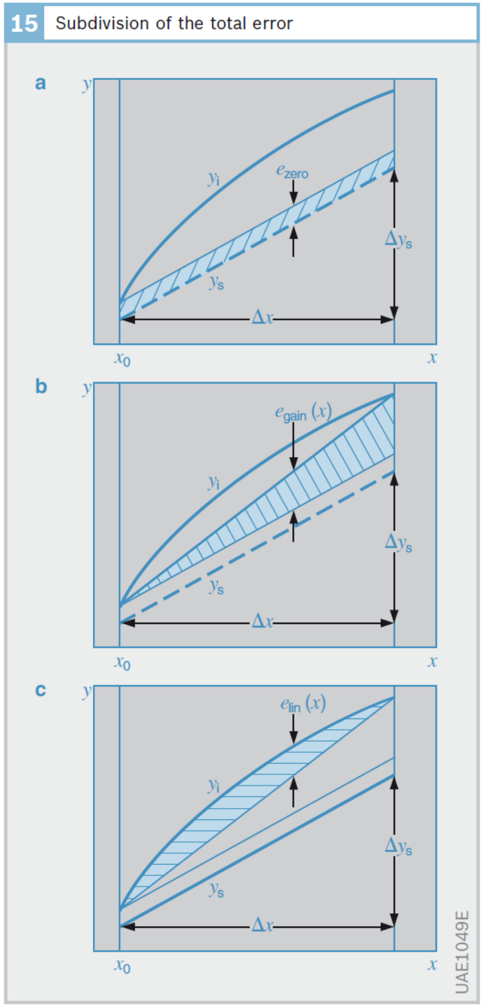
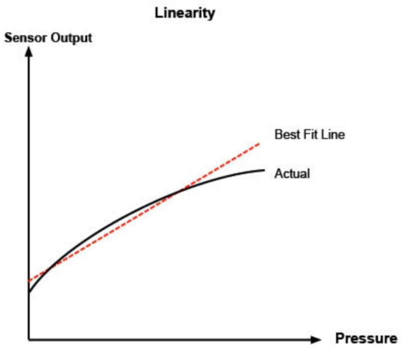


Fig. 15
a Zero error
b Gradient error
c Linearity error



Errors

- Systematic or deterministic
  - Zero,Gradient, Linearity
- Stochastic or Random
  - Drift due to noise, Aging errors

Sensor requirements

To withstand

Mechanical (Vibration/Shock

Environment (Temperature / humidity)

Chemical (Salt mist, fuel, engine oil)

EMI (Electromagnetic interference) - Incident radiation, excess voltage etc,

Trends

High reliability

Low costs

Low volume designs

Accuracy (+/- 1% general)

Sensor Reliability

MTBF

- If 10 components are tested for 100 hours, 2 components failed at 70 and 80 hours respectively, then MTBF is

$$((8*100) + 70 + 80) / 2 = 475$$

and failure rate (λ) = 1/ MTBF = 1/475 = 0.021 (failure / hour)

Sensor Reliability

Mean time between failure (MTBF) is a statistical quantity and inverse of Failure rate ($z = 1/\lambda$)

Failure rate is defined by λ – unit in 1/h; Stated in terms of ppm /h;

Reliability is defined a s $R(t) = \exp\left(-\int_0^t \lambda \, dt\right) = e^{-\lambda t}$

For example, if failure rate is 2×10^{-6} failures / hour, what is the MTBF. Find also Reliability and number of failures expected, for operating period of 50,000 hours if 2000 items are under testing.

MTBF $= \frac{1}{\lambda} = \frac{1}{2 \times 10^{-6}}$ which is 500,000 Hours

R(t) $= e^{-2 \times 10^{-6} \times 50000} = 0.905$

Sensor Integration

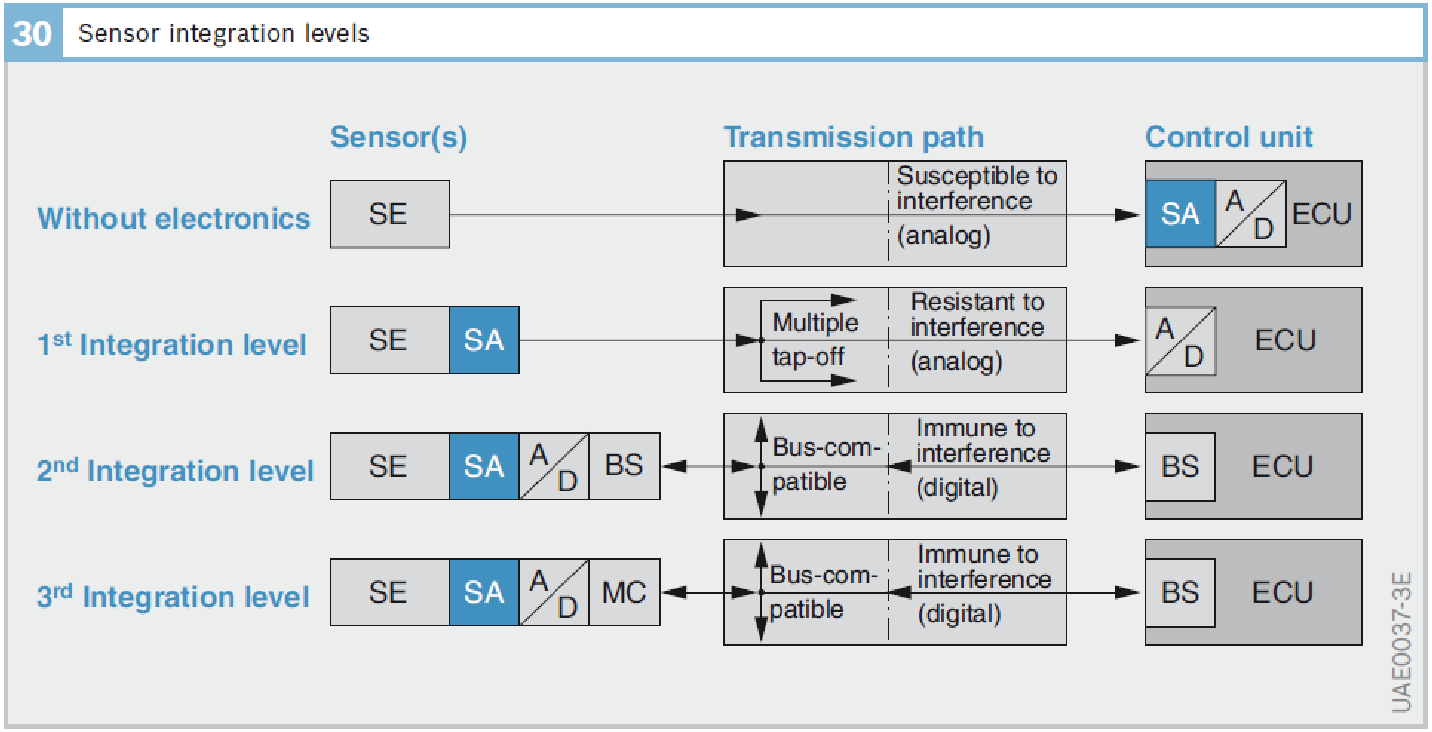


Fig. 30
SE Sensors
SA Signal conditioning
A/D Analog-Digital converter
ECU Control unit
MC Microcontroller
BS Bus interface

Variable reluctance sensors(Inductive)

$$v = N \frac{d\phi}{dt}$$

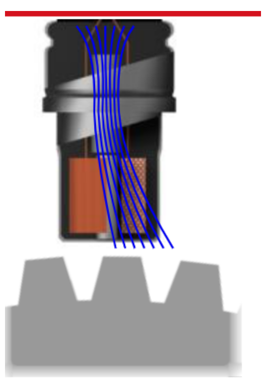
Where **N** is the number of turns

$$\phi = BA$$

Where ***B*** is the magnetic field density

A is the area of the coil

ϕ Magnetic flux



As the voltage increases, the potential for noise or interference (EMI) increases. There are three ways to combat this interference: shielding, filtering and air gap adjustment

- Self powered
- No external voltage is required
- Simple
- No moving parts
- Generate a signal proportional to the magnetic field's rate of change.
- Signal strength decreases with decreasing speed and, below a certain flux change rate, the signal disappears into the noise
- Conversely signal strength increases with speed of target, it can go as high as 100V and beyond, which is not something ECU is prepared to handle.

Inductive speed sensor

2 Figure illustrating the principle of the passive wheel-speed sensor

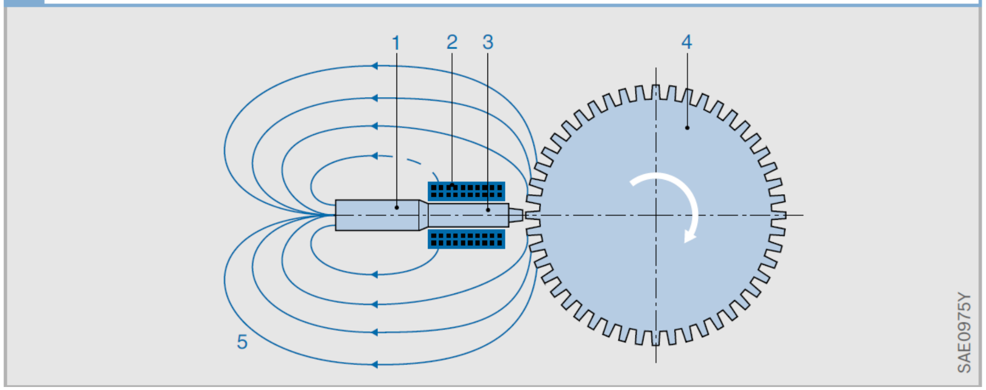
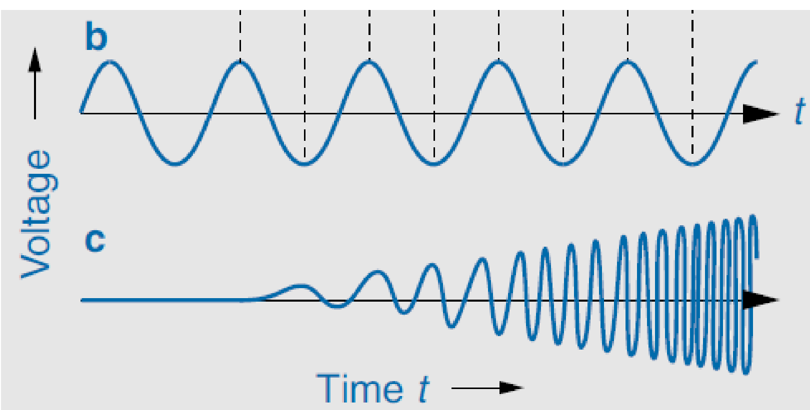


Fig. 2
1 Permanent magnet
2 Solenoid coil
3 Pole pin
4 Steel pulse wheel
5 Magnetic field lines

Coil properties	Inductance @ 1 kHz: 170 mH ± 10% Resistance: 850 Ohm ± 10% Magnet polarity: north pole towards front face Pole piece: diameter 2.7 mm
Polarity	Upon approach of ferrous metal, the signal pin is positive with respect to GND.



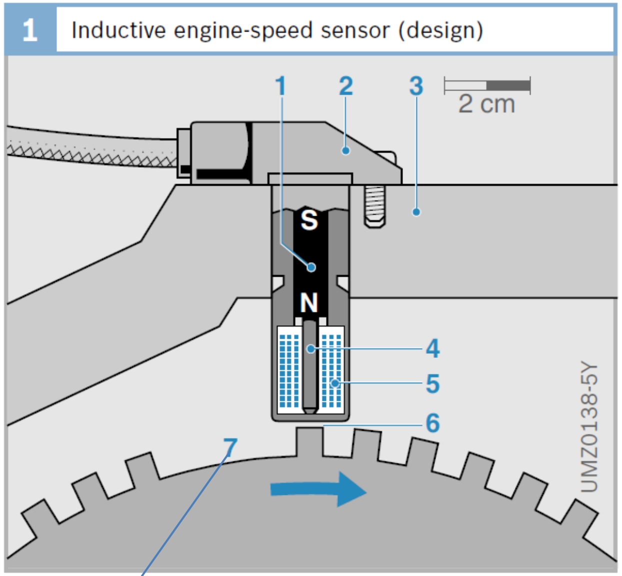
b Sensor signal at constant wheel speed

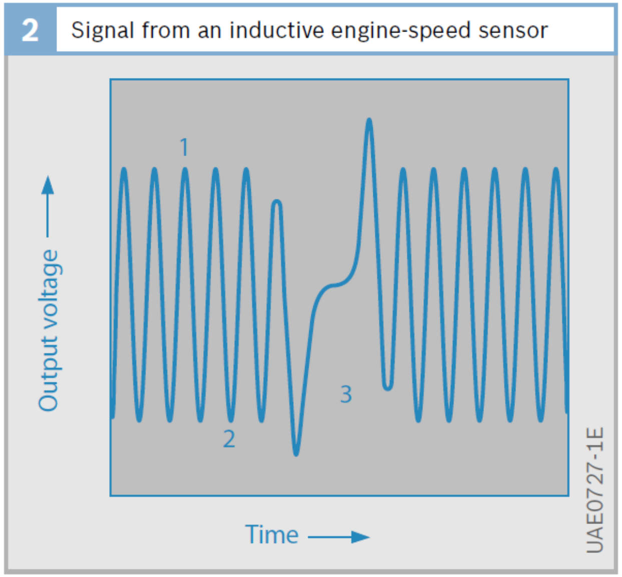
c Sensor signal at increasing wheel speed

Crankshaft position Sensors (Inductive)

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

Fig. 2
1 Tooth
2 Tooth space
3 Reference mark



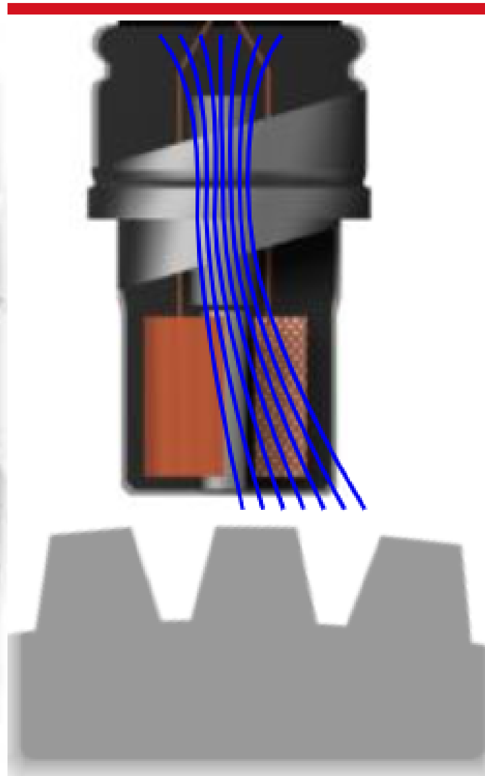


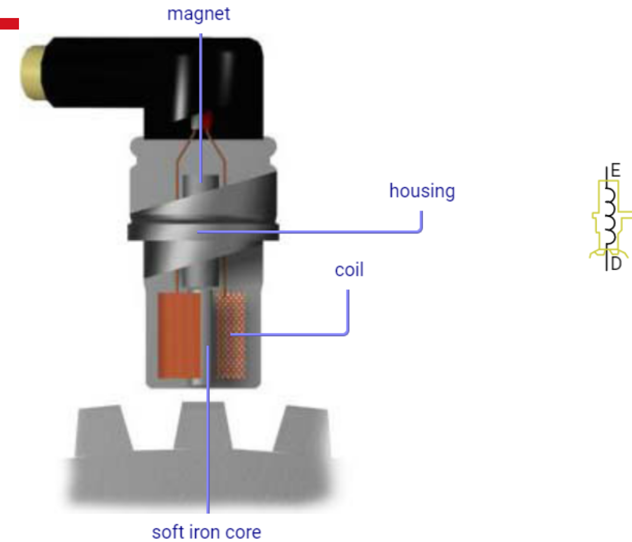
Pole wheel

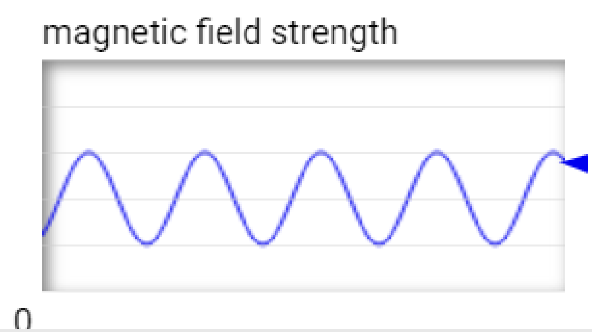
This missing teeth is allocated to a defined crankshaft position

Prerequisite: Toothed wheel of a ferrous material (e.g. Steel 1.0036).
Optimal performance with
- Involute gear
- Tooth width > 10 mm
- Side offset < 0.2 mm
- Eccentricity < 0.2 mm

Crankshaft position Sensors (Inductive)







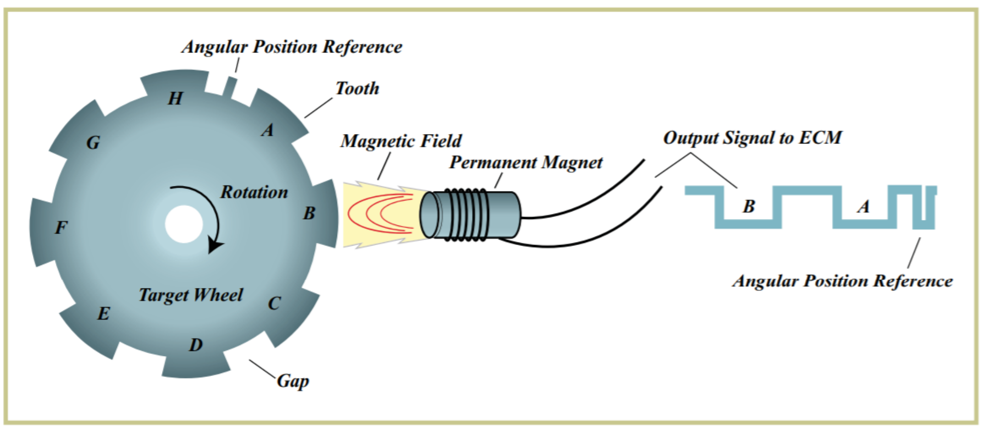
By measuring the frequency of the AC voltage, the control unit can determine the speed of the engine.

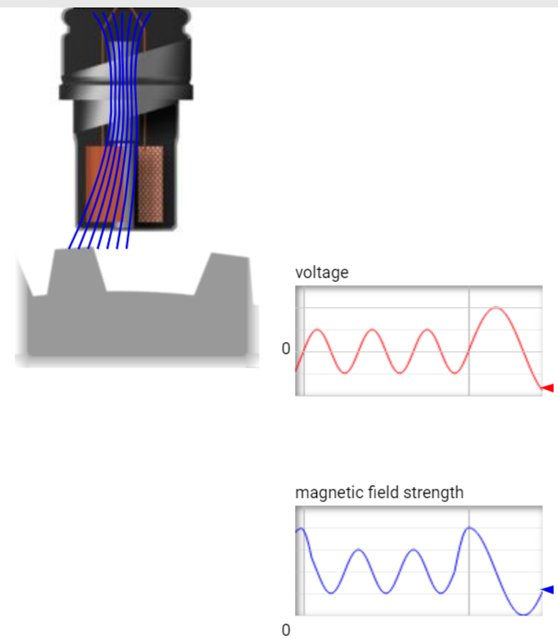
Crankshaft position Sensors (Inductive)

One tooth has been left off the gearwheel intentionally.

This tooth gap is right in front of the inductive pickup at the point when the crankshaft is 90° before TDC.
This means that with every crankshaft rotation there is a point when there is no tooth passing the inductive pickup.

The plotter shows the voltage produced at the point when the tooth gap passes the sensor.

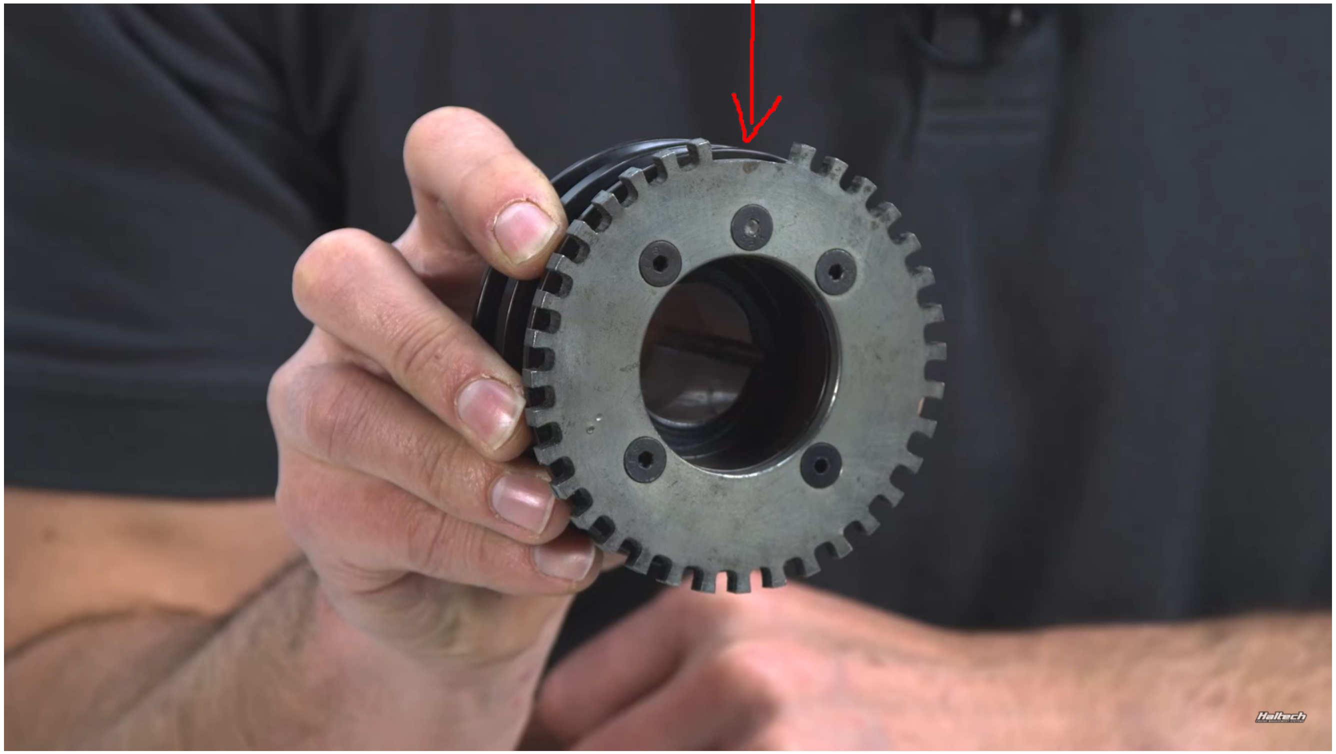




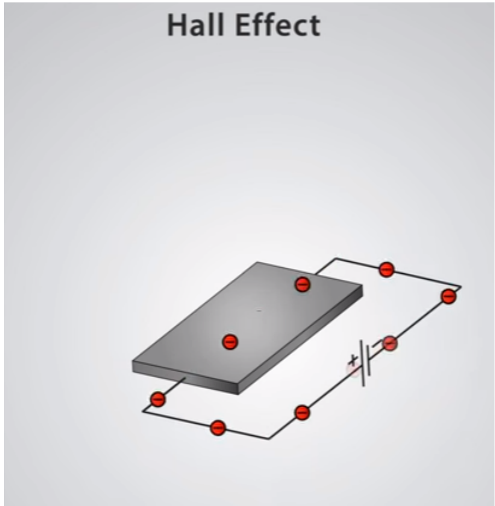
The control unit identifies the tooth gap from the different frequency of the signal and not from the magnitude of the voltage.

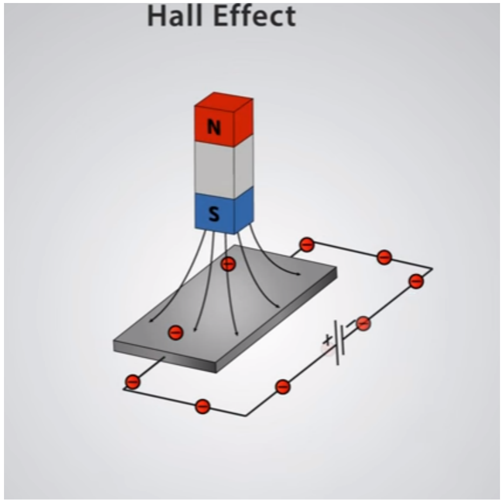
Crankshaft position Sensors (Inductive)

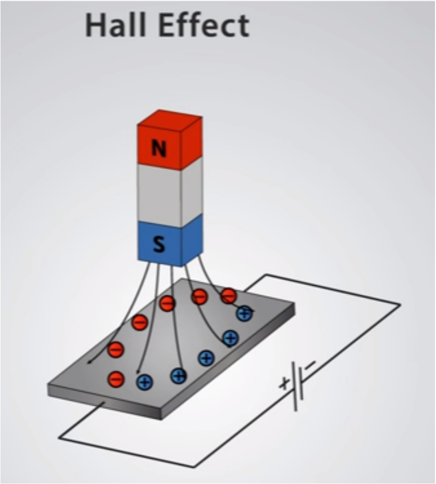
Missing tooth

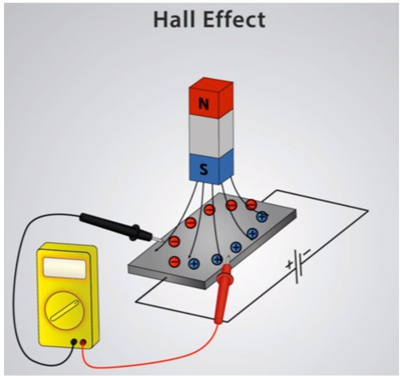


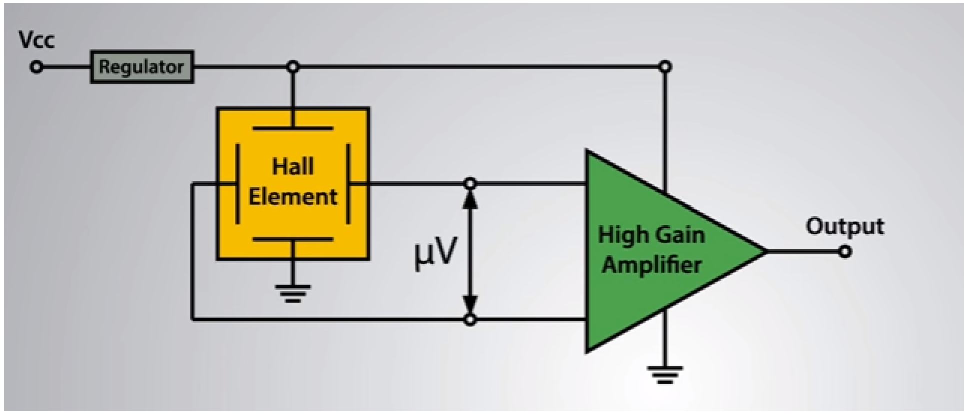
Hall effect sensors



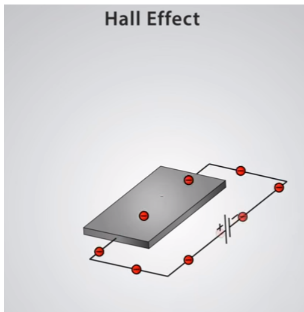


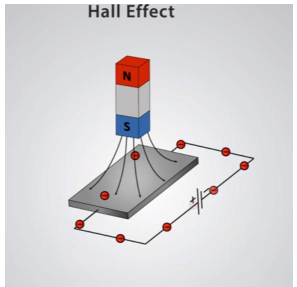






Hall effect





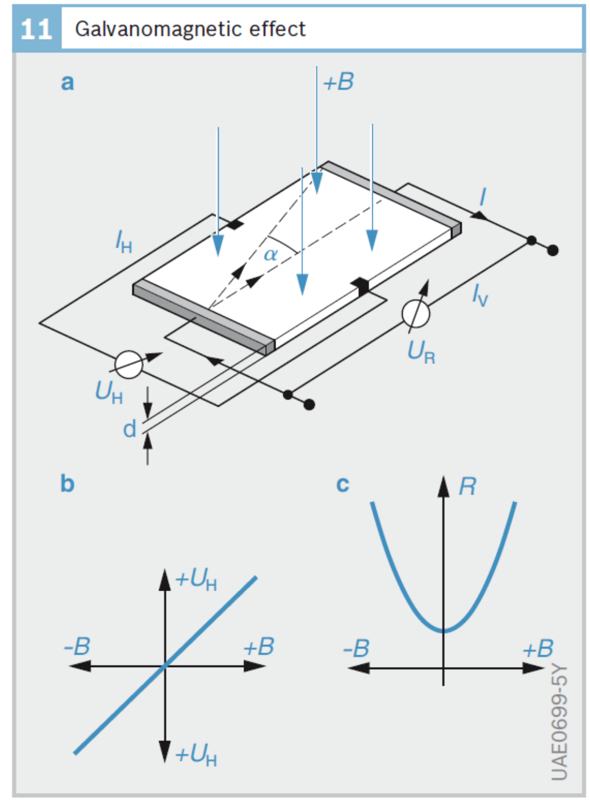
gallium arsenide (GaAs), indium antimonide (InSb)

The Hall effect is normally evaluated using thin semiconductor wafers. If a current carrying wafer of this type is exposed perpendicularly to magnetic induction *B*, the charge carriers are deflected by the Lorentz force normal to the field

The production of a potential difference across an electrical conductor when a magnetic field is applied in a direction perpendicular to that of the flow of current.

Fig. 11

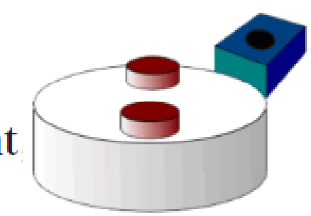
- a Circuit
- b Curve of Hall voltage U_H
- c Increase of wafer resistance R (Gaussian effect)
- B Magnetic induction
- I Wafer current
- I_H Hall current
- I_V Supply current
- U_R Longitudinal voltage
- α Deviation of the electrons due to the magnetic field



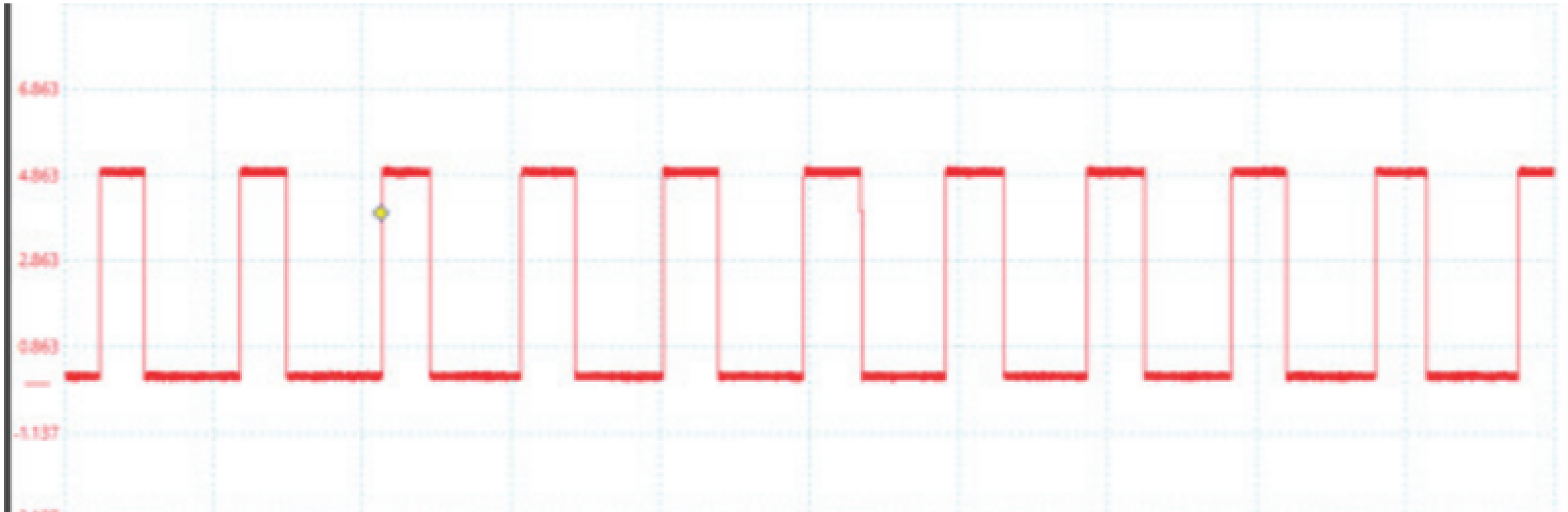
$$U_H = R_H \cdot I \cdot B/d$$

where R_H = Hall coefficient

d = wafer thickness

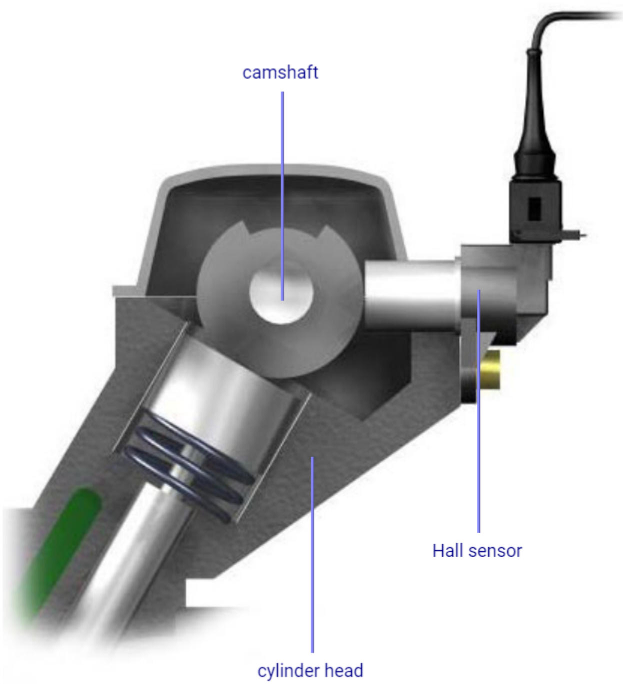


Hall effect



More the speed, more the frequency, amplititude of wave remains same.

Camshaft Position sensors

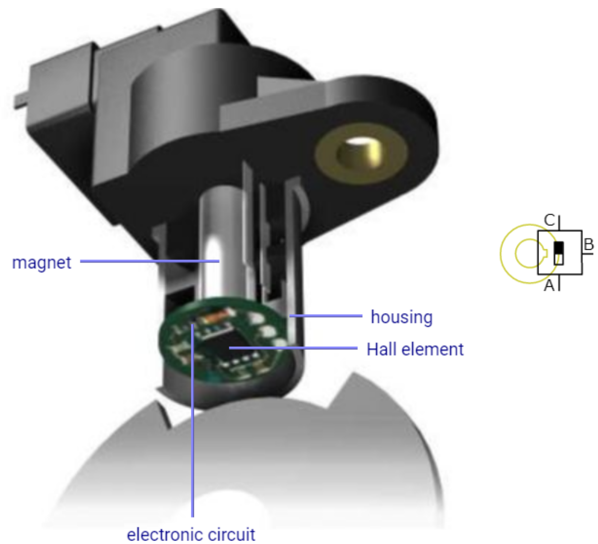


Introduction

The camshaft position sensor is used by the control unit to determine the position of the camshaft. The Hall principle is often used for this sensor.

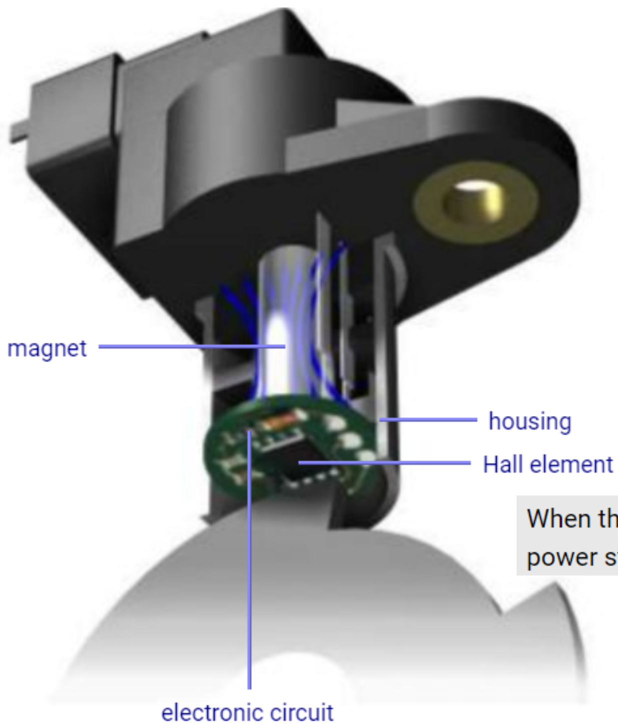
In engines with an overhead camshaft, the sensor is fitted in a recess in the cylinder head. The sensor 'sees' the camshaft through this recess.

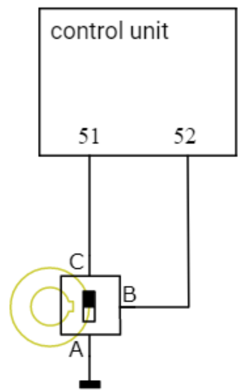
Because the camshaft has reference points which rotate along the sensor, the control unit is able to use these teeth to determine the position of the camshaft.



- The sensor is made up of
  - Housing
  - Electronic board
  - Permanent magnet
  - Hall element

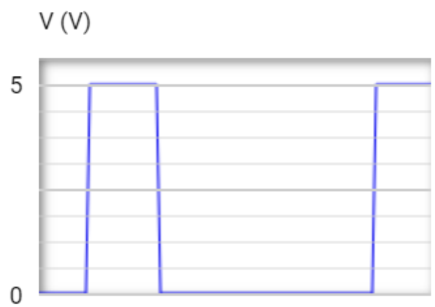
Camshaft Position sensors





Electric voltage is applied to C, A being grounded, B is the output wire

When the voltage is high, cylinder 1 is on a power stroke and when the voltage is low, cylinder 4 is about to start a power stroke.

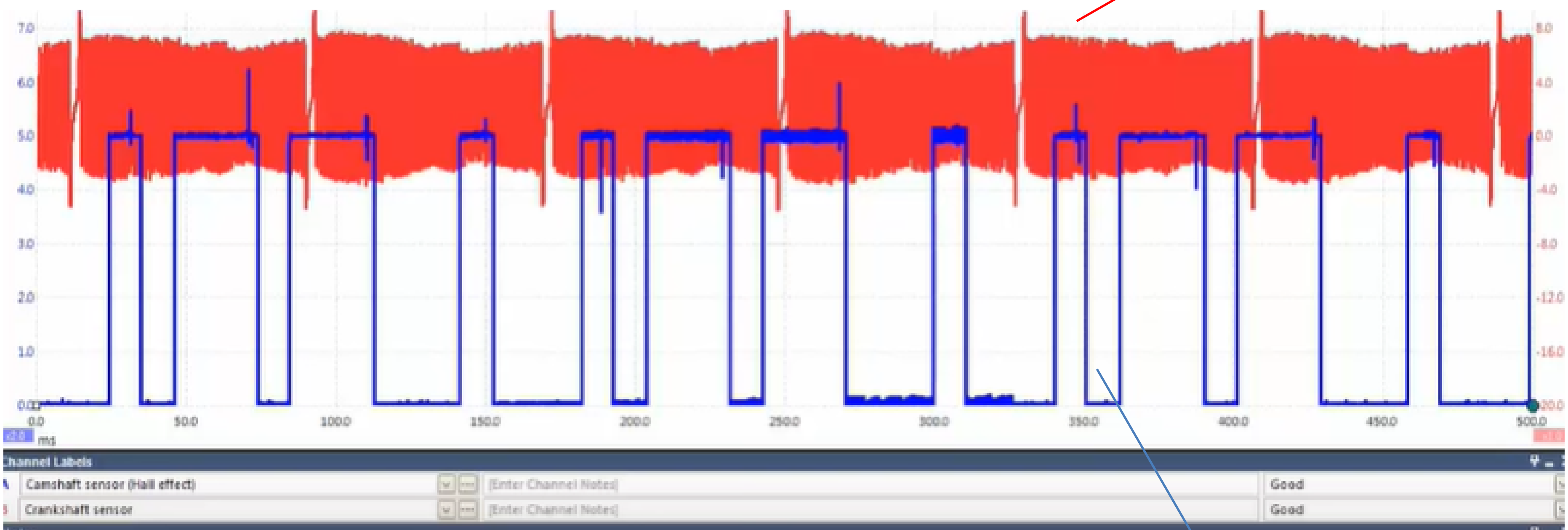


the recess produces 5 volts
no recess delivers 0 volts

The sensor can be encapsulated in a plastic housing which can protect sensor from external environment

Camshaft – Crankshaft Sync

Crankshaft Signal



Camshaft Signal

https://people.physics.anu.edu.au/~amh110/Hall_sensor/hall_sensor_trigger.htm

Differential Hall effect sensors

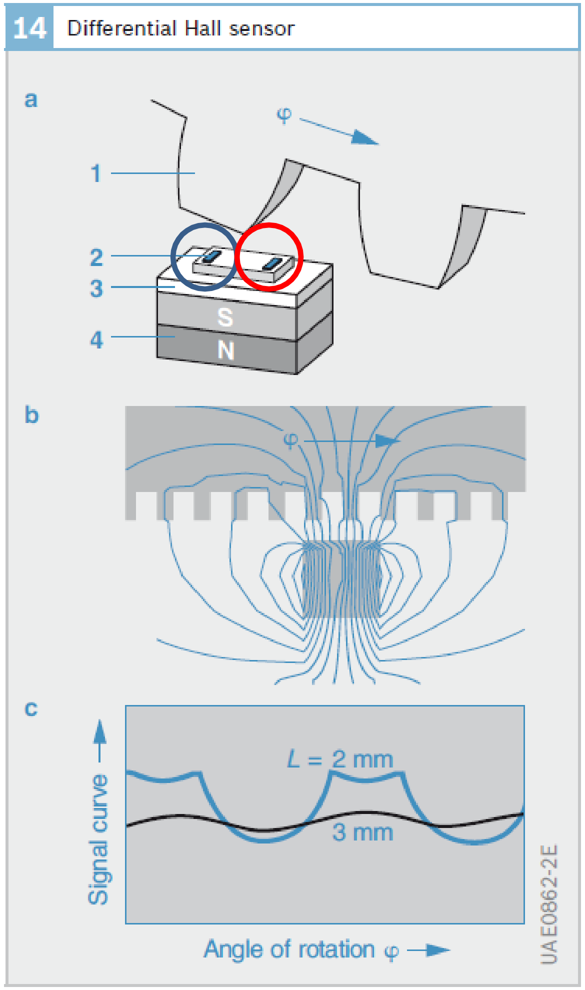


Fig. 14
a Design
b Field-strength distribution (1.5 times increment spacing)
c Signal curve for air-gap widths L
1 Ring gear
2 Differential Hall IC
3 Homogenizing wafer (soft iron)
4 Permanent magnet

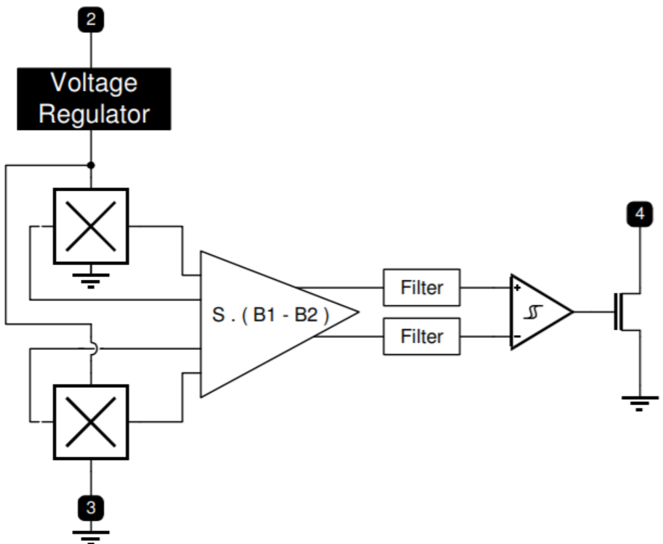
Electronics evaluates the difference between the two hall voltages. Output signal is independent of absolute value of the magnetic field strength.

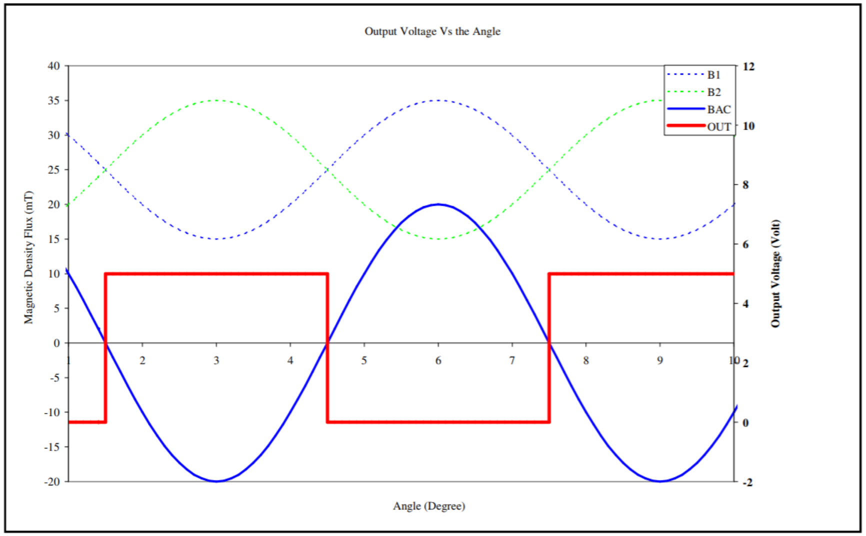
<u>This results in voltage signal (Hall voltage) which is independent of relative speed between sensor and pulse wheel.</u>

If a simple Hall sensor only is used to sense a gear wheel, this will not be able to distinguish whether the magnetic flux has modified as a result of the gear wheel turning further or by a change in distance (e.g. vibrations, mounting tolerances).

Differential Hall effect sensors

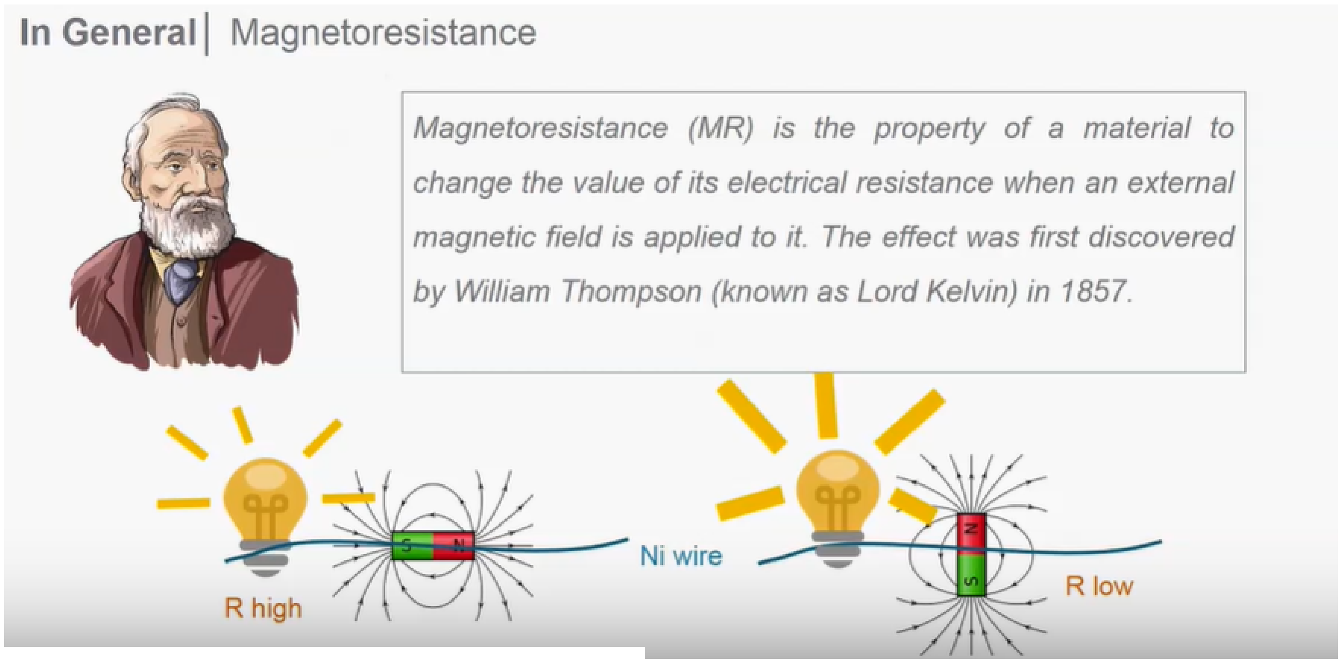
1. Functional Diagram

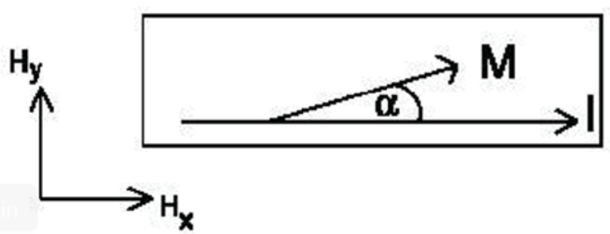




Pin 1 – Not used
Pin 2 – Vdd (Supply)
Pin 3 – Vss (Ground)
Pin 4 - Output

Magneto resistive sensors





The change in resistivity is found experimentally to be

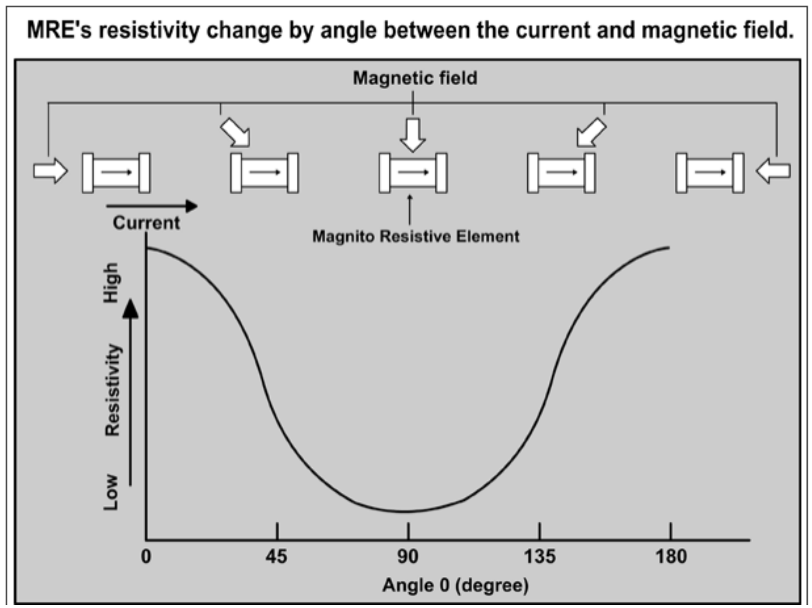
$$R = R_0 \cdot \left(1 + \frac{\Delta R}{R} \cdot \cos^2 \alpha\right) \qquad (1)$$

where R_0 is the resistivity with magnetization perpendicular to the sense current (α=90°).

Magneto resistive sensors

The magnetoresistive method is considered to be similar to the Hall Effect method. However, unlike Hall Effect devices that identify a field strength, magnetoresistive devices detect a field direction.

Minimum resistance



Maximum resistance

Magneto resistive sensors

23 Magnetoresistive differential sensor

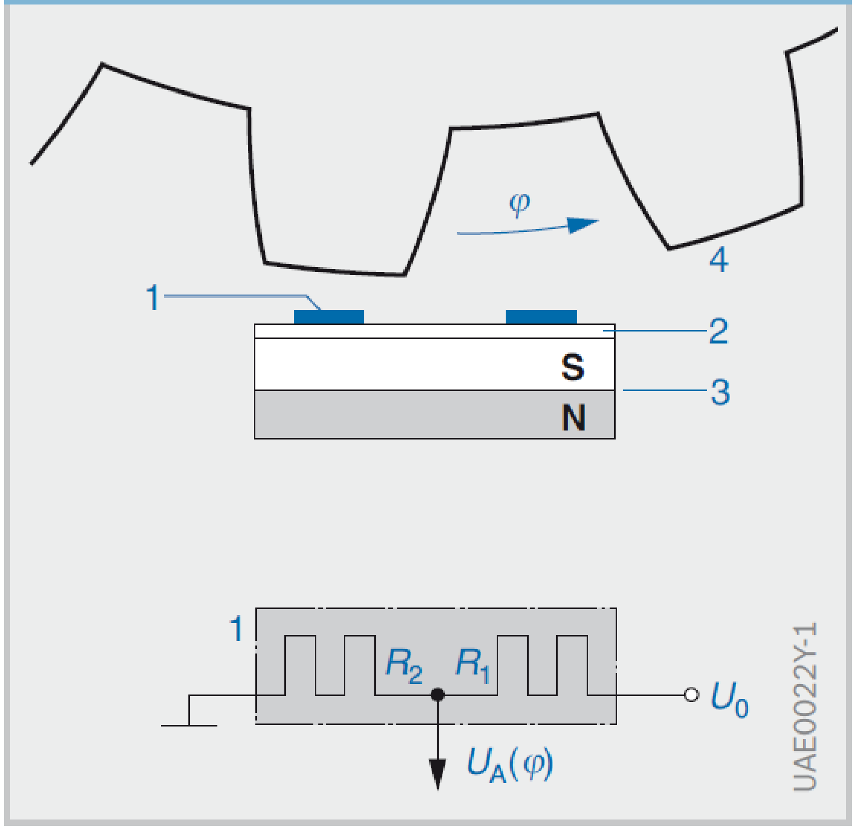


Fig. 23
Magnetic activation of a magnetoresistive differential sensor for gear wheel scanning (incremental angular position measurement, speed of rotation sensing)

1 Magnetoresistors R_1, R_2
2 Soft-magnetic substrate
3 Permanent magnet
4 Gear wheel
U_0 Supply voltage
U_A Output voltage at angle of rotation φ

Wheel speed sensor

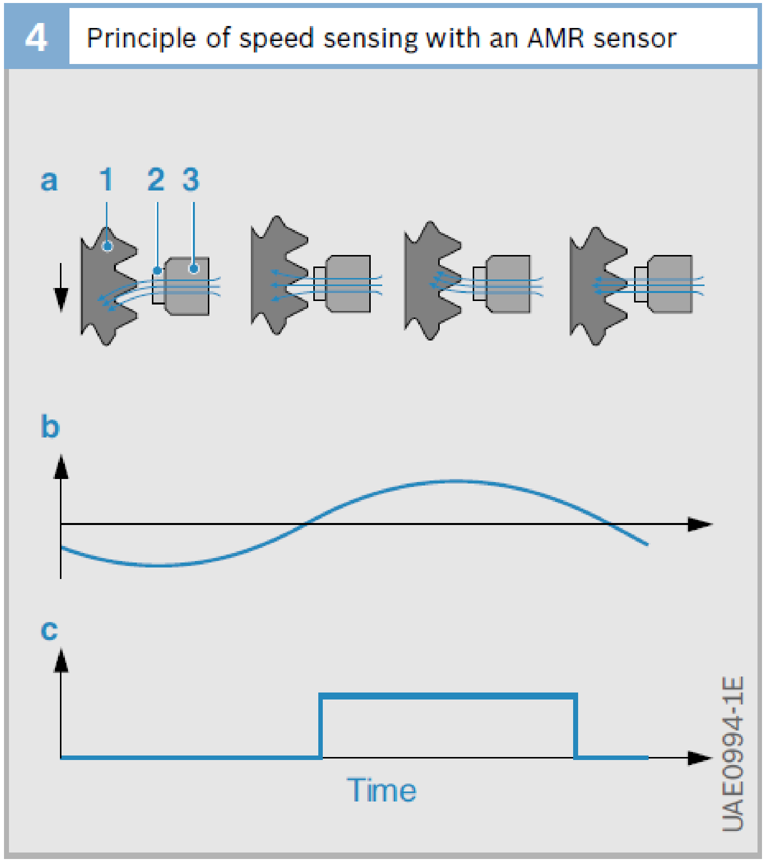


Fig. 4

a Configuration at various times

b Signal from AMR sensor

c Output signal

1 Pulse wheel

2 Sensor element

3 Magnet

Wheel speed sensor

From an electronic point of view, the wheel sensor is made up of two components.

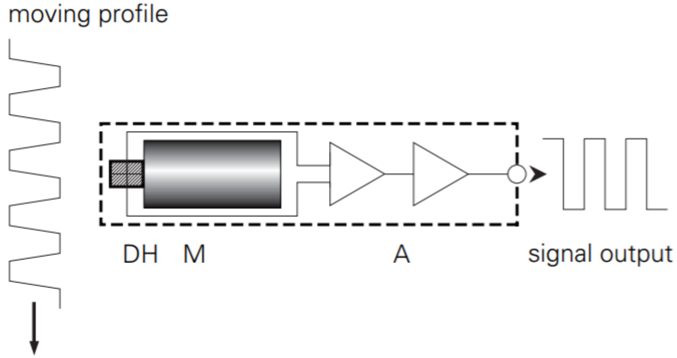
- sensor component
- electronic component

The sensor component is made up of the MRE elements.
The angle between the magnetic field and the direction of current through the resistors changes in proportion to the speed of the wheel.
This changes the resistance value of the MRE resistor.

The electronic component ensures that the resistance value is converted to a usable signal for the ESP control unit.

Transmission speed sensors

Principle of Operation



Transmission speed sensors are exposed to very severe operating stresses because of

- Extreme ambient temperatures between -40 and +150 °C
- An aggressive operating environment caused by the transmission oil, also known as ATF (contains special additives for transmissions and has a low condensate content)
- High mechanical stress with vibrational accelerations up to 30 *g*
- Abraded metallic materials and a build-up of particles in the transmission

The Differential-Hall-Effect Principle

The Hall effect (named for its discoverer) utilizes the fact that a magnetic field generates a voltage within a hall element. Its level is independent of its rate of change (i.e. speed of motion) – unlike the induction effect of magnetic pick-ups, which rely on the rate and therefore are weak at low speed. The sensors A5S0… include the necessary magnet (M) and the dual hall element (DH). With the profile passing by, the magnetic field varies, thereby creating the signal voltage within the hall element. Here it is important to keep in mind, that the signal does not fade at low speed.

The principle engages a twin chip hall element and the signal amplifier (A) uses only the difference between both. It is then amplified to provide the power square wave output.

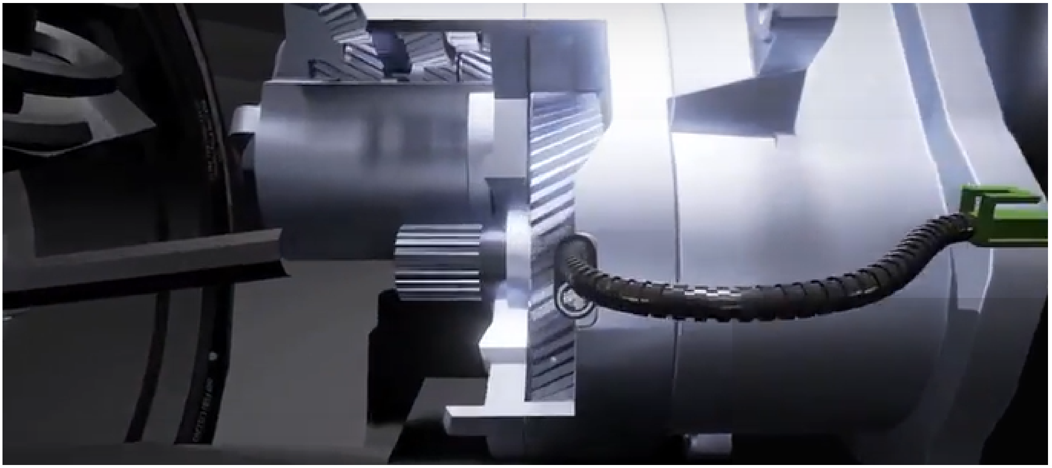
Its Advantages

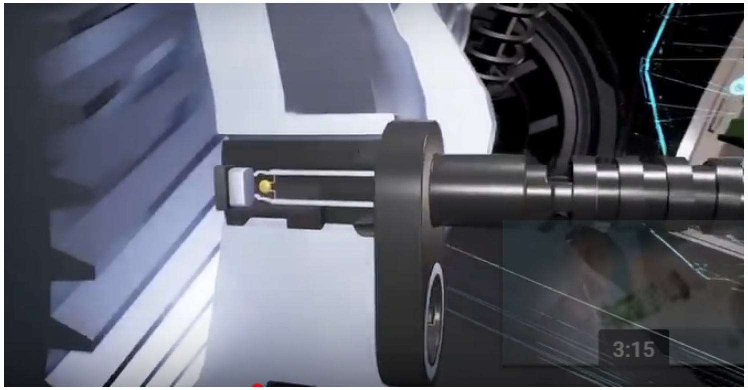
By its nature, this differential principle compensates target vibrations. And it diminishes the influence of external magnetic stray field. Both important aspects for a reliable signal. And it operates down to zero speed.

Transmission speed sensors

Transmission speed sensors are used to calculate the actual gear ratio of the transmission while in use. There are generally two speed sensors that work in conjunction to provide accurate transmission data to the vehicle's powertrain control module. The first is known as the input shaft speed (ISS) sensor and measures the speed of the transmission' input shaft. The other sensor is the output shaft speed (OSS) sensor

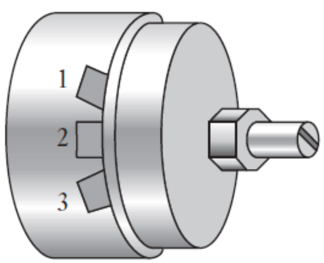
https://www.allegromicro.com/en/Insights-and-Innovations/Videos/Differential-Speed-Sensor-System-Solutions-Video



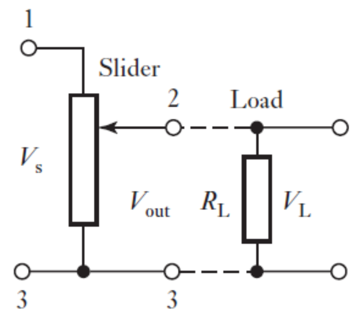


Displacement Sensors

Angular position measurement using Potentiometers

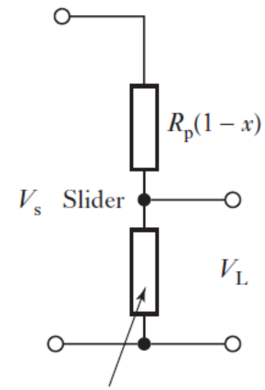


A rotary potentiometer



The circuit when connected to a load

The circuit as a potential divider



R_L in parallel with xR_p

If the potentiometer has N turns then the resolution, as a percentage, is 100/N

Used to sense accelerator position in cars

Potentiometer

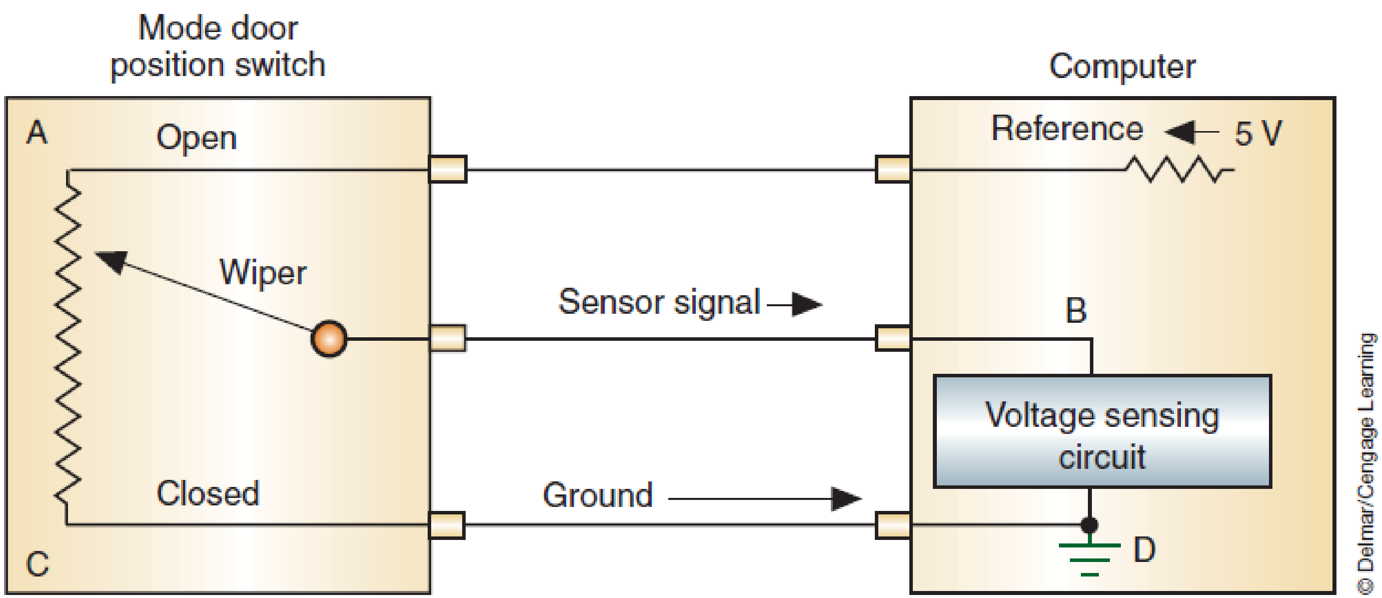
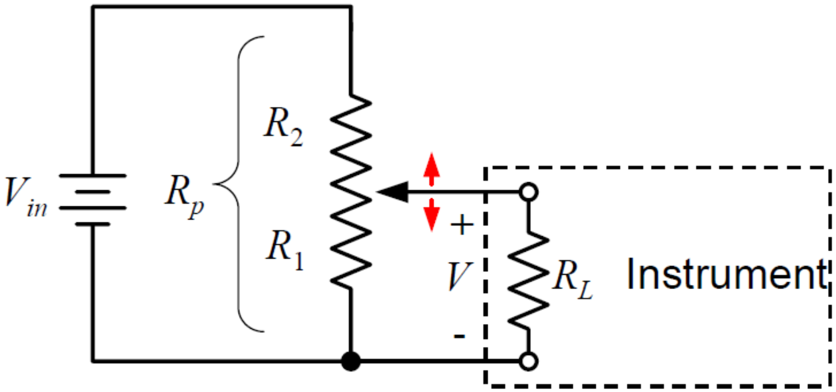


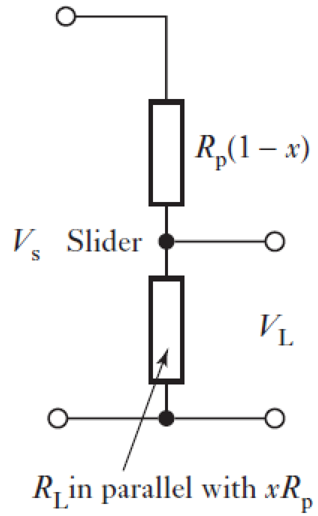
FIGURE 10-14 **A potentiometer sensor circuit measures the amount of voltage drop to determine position.**

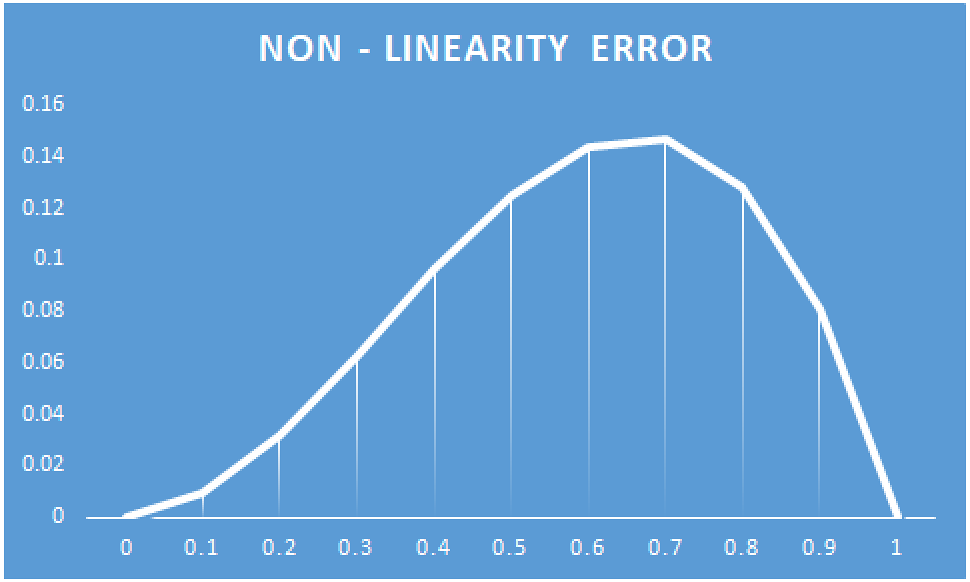
Displacement Sensors



Non – Linearity Error

$$= V_s \frac{R_p}{R_L}(x^2 - x^3)$$





Potentiometer travel

Displacement Sensors

Non – Linearity Error

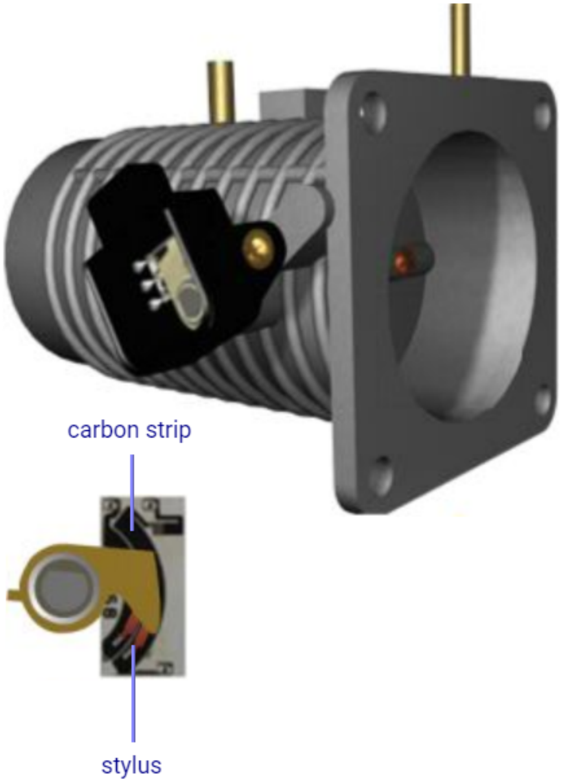
$$= V_s \frac{R_p}{R_L}(x^2 - x^3)$$

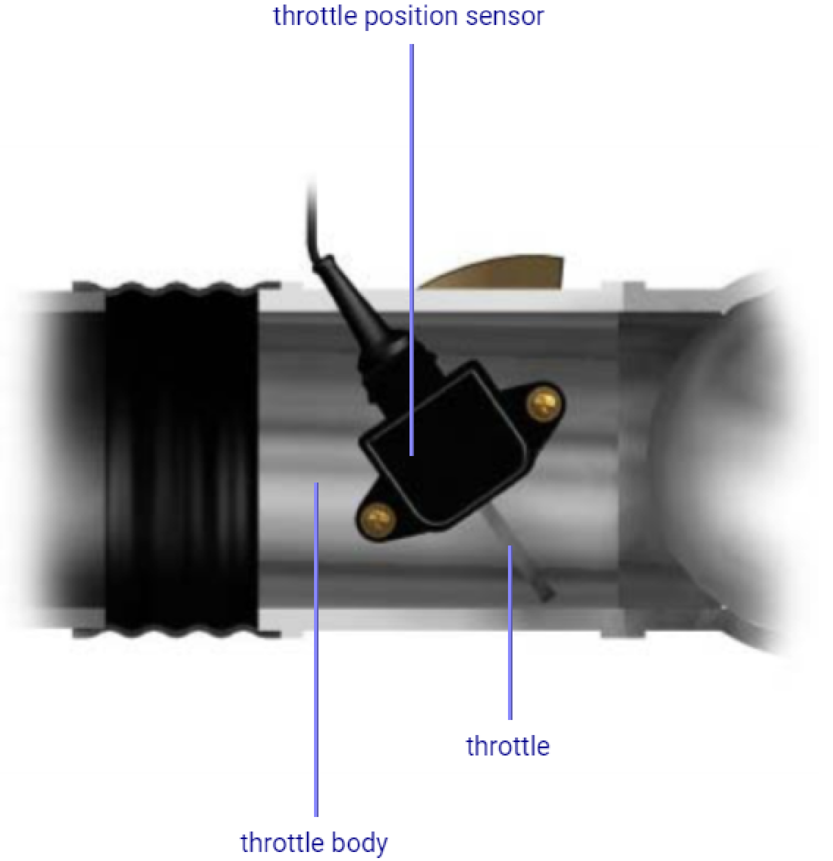
To illustrate the above, consider the non-linearity error with a potentiometer of resistance 500 Ω, when at a displacement of half its maximum slider travel, which results from there being a load of resistance 10 kΩ. The supply voltage is 4 V. Using the equation derived above

$$\text{error} = 4 \times \frac{500}{10\,000}(0.5^2 - 0.5^3) = 0.025\text{ V}$$

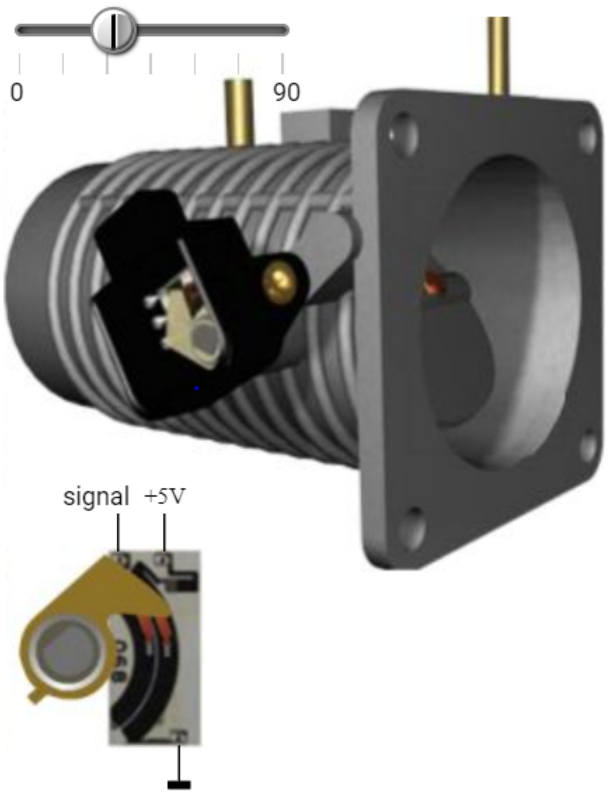
As a percentage of the full range reading, this is 0.625%.

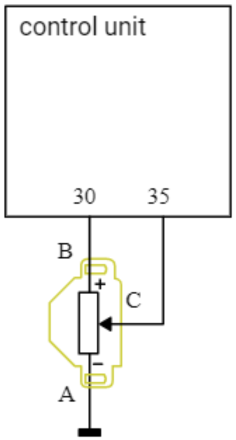
Throttle position sensor



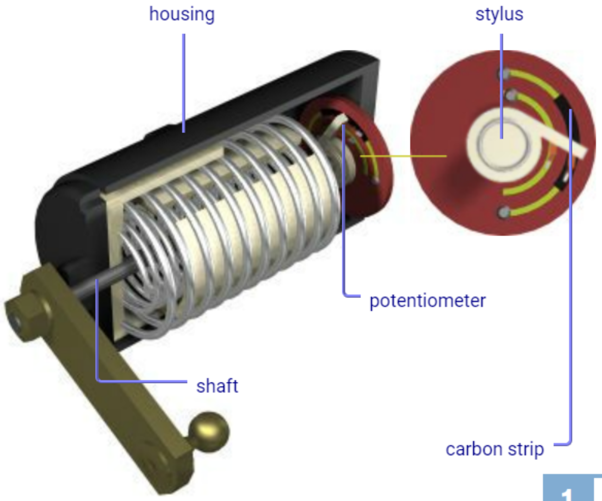


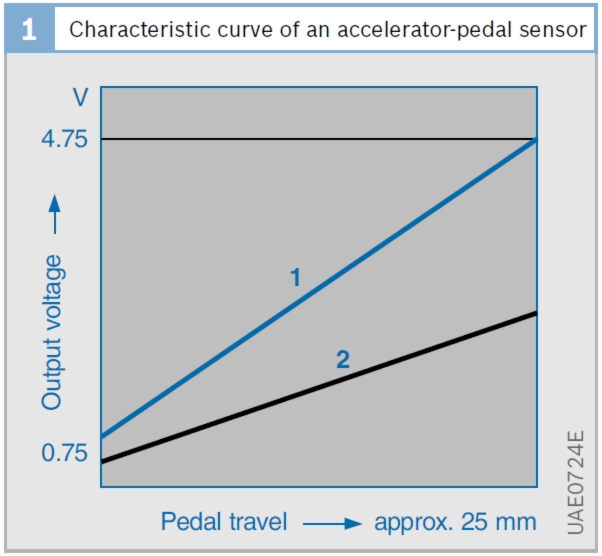
Throttle position sensor





Accelerator position sensor

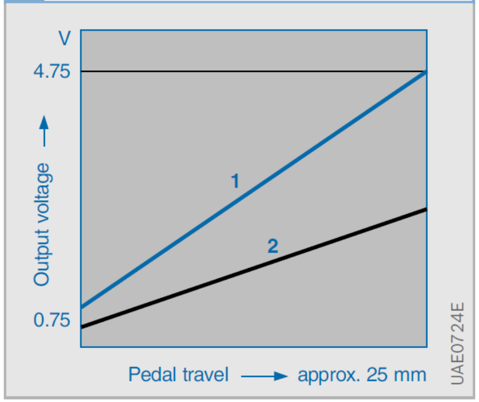




Accelerator position sensor

The engine control unit receives the measured value picked off at the potentiometer wiper as a voltage. The control unit uses a stored sensor curve to convert this voltage into the relative pedal travel or the angular position of the accelerator pedal (Fig. 1).
A second (redundant) sensor is incorporated for diagnosis purposes and for use in cas malfunctions. It is a component part of the monitoring system. One sensor version operates with a second potentiometer, which always delivers half the voltage of the first potentiometer at all operating points. Thus, two independent signals are available for fault-detection purposes.

1 Characteristic curve of an accelerator-pedal sensor



Accelerator position sensor

Accelerator position (Hall type)

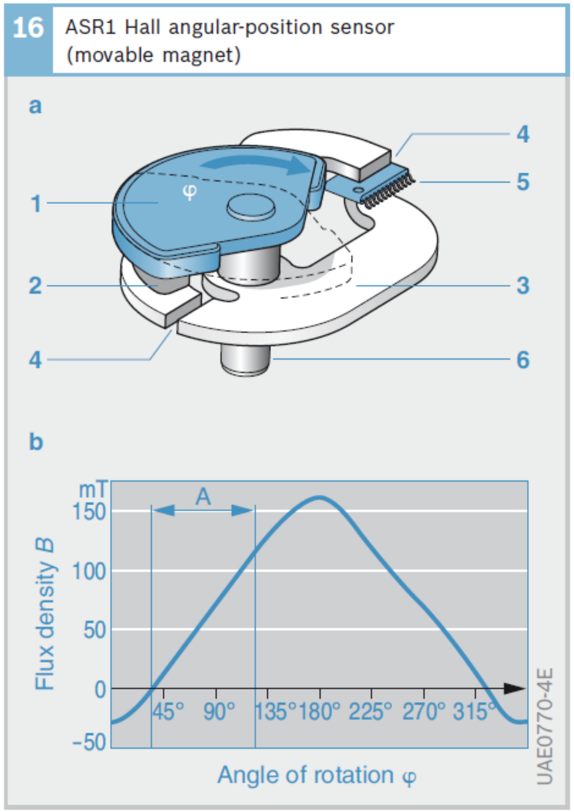
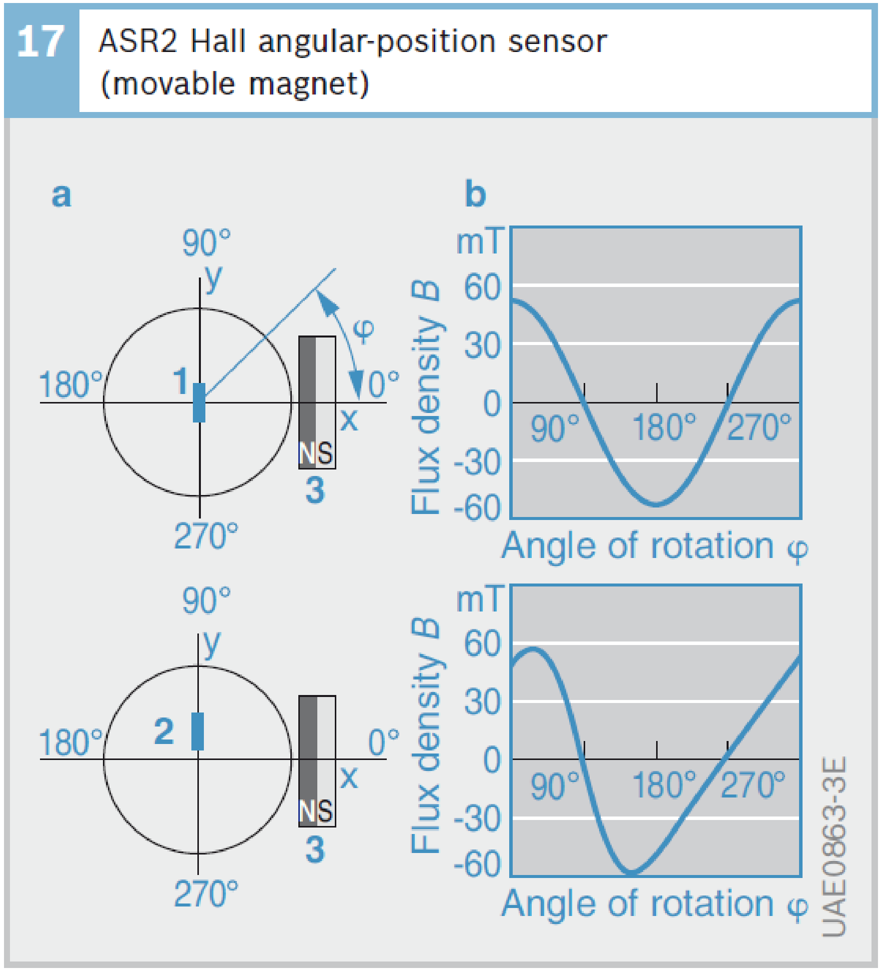


Fig. 16

Linear characteristic curve for angles up to approximately 90º

- a Design
- b Characteristic curve with working range A
- 1 Rotor disk (permanent-magnetic)
- 2 Pole shoe
- 3 Conductive element
- 4 Air gap
- 5 Hall sensor
- 6 Shaft (soft magnetic)

Differential Hall effect sensors



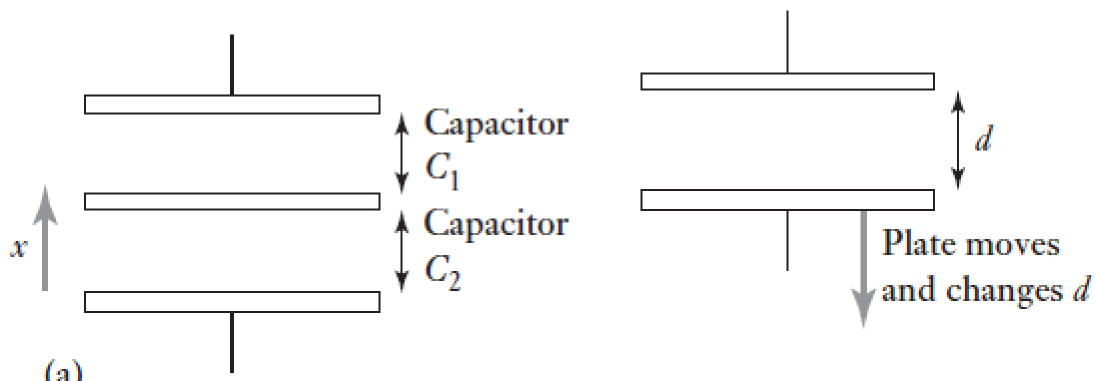
a	Principle of operation
b	Characteristic curve
1	Hall IC positioned in the mid-point of the circular path
2	Hall IC located outside the mid-point (linearization)
3	Magnet

Capacitive measuring principle

The capacitance C of a parallel plate capacitor is given by

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d}$$

where ε_r is the relative permittivity of the dielectric between the plates, ε_0 a constant called the permittivity of free space, A the area of overlap between the two plates and d the plate separation.



(a)

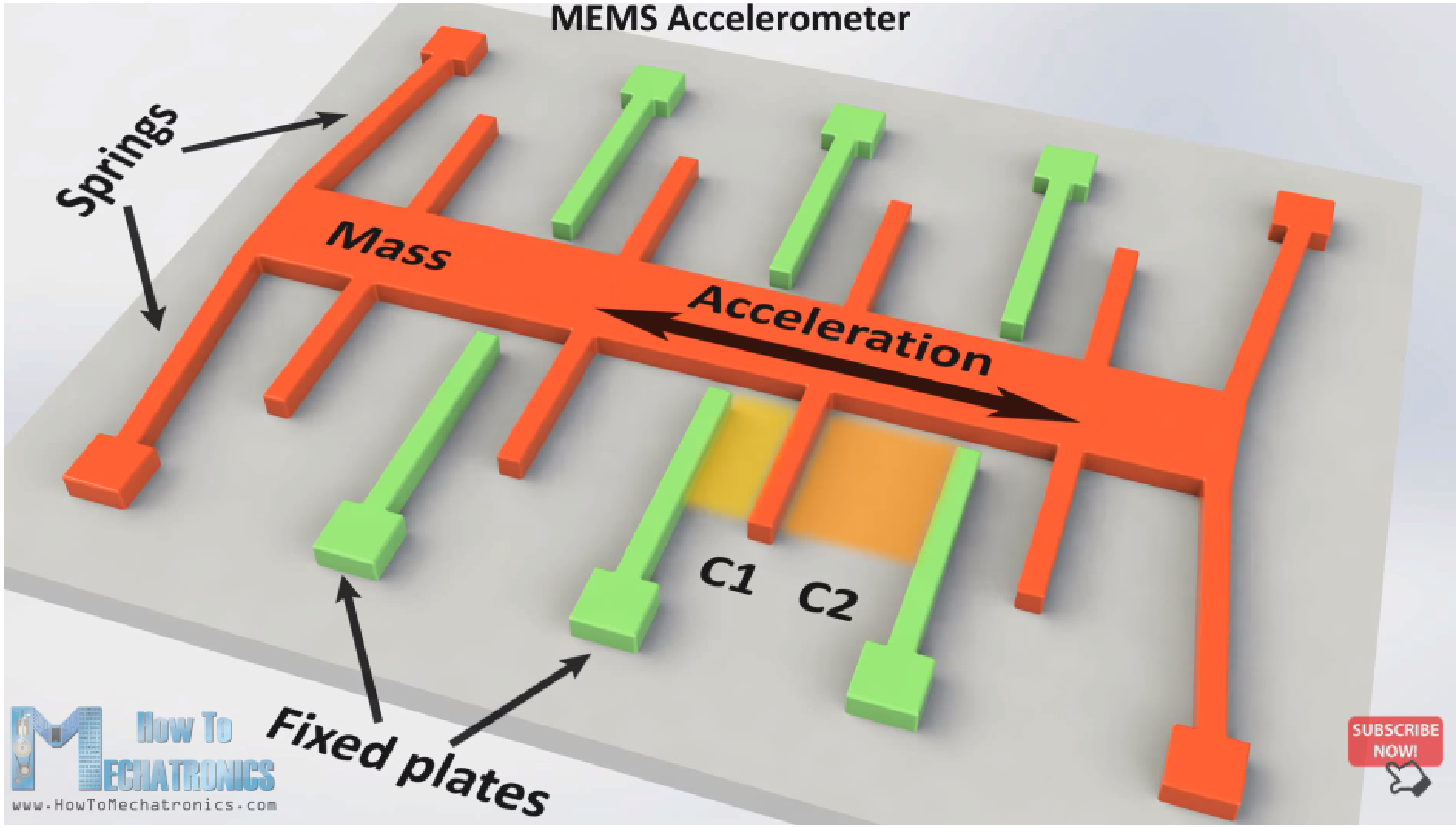
$$C_1 = \frac{\varepsilon_0 \varepsilon_r A}{d + x}$$

$$C_2 = \frac{\varepsilon_0 \varepsilon_r A}{d - x}$$

When C_1 is in one arm of an a.c. bridge and C_2 in the other, then the resulting out-of-balance voltage is proportional to x.

Accelerometers

F = ma



Accelerometers

Acceleration sensors

Measured variables

Acceleration sensors are suitable

- For knock control in gasoline engines
- For triggering restraint systems (e.g. air-bag and seat-belt pretensioners)
- For detecting the accelerations of the vehicle for the antilock brake system (ABS) or the electronic stability program (ESP) or
- For the evaluation of body acceleration for use by the chassis and suspension control systems

1 Measuring range of acceleration sensors

Applications	Measuring range
Knock control	40 g
Passenger protection	
– Airbag, seat-belt pretensioner	35 to 100 g
– Side impact, front sensing	100 to 400 g
– Roll-over detection	3 to 7 g
ESP, HHC, ABS	0.8 to 1.8 g
Chassis and suspension control	
– Design	1 g
– Axle/damper	10 to 20 g
Car alarm	1 g

Acceleration sensors measure the force F executed on an inert mass m by an acceleration a:

(1) $F = m \cdot a$

$$F = m \cdot a = c \cdot x$$

The system's measurement sensitivity S is therefore:

$$S = x/a = m/c$$

c- spring constant

m- mass of sensor element

This indicates that a large mass together with low spring stiffness result in high measurement sensitivity.

$$F = m \cdot a = c \cdot x + p \cdot \dot{x} + m \cdot \ddot{x}$$

$$\omega_0 = \sqrt{\frac{c}{m}}$$

$$\omega_0^2 \cdot S = 1$$

Sensitivity can be expected to be reduced by factor 1/4 when the resonant frequency is doubled. It is only clearly below their resonant frequency that such spring-mass systems display adequate proportionality between measured variable and deflection.

Accelerometers

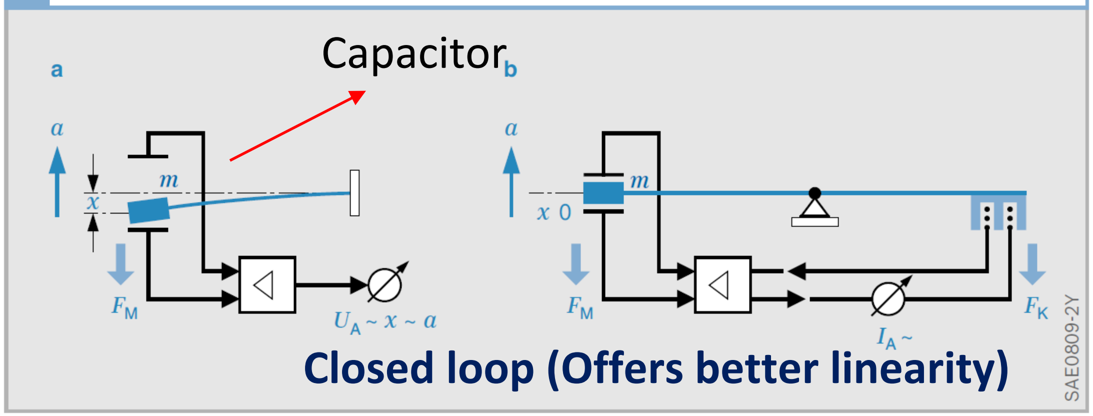
Fig. 1
Schematic:
a Excursion-measuring
b Closed-loop position controlled
a Measured acceleration
x System excursion
F_M Measuring force (inertial force on the mass m)
F_K Compensating force
I_A Output current
U_A Output voltage

Damping
To prevent an excessive resonance, which would cause interference, pure deflection systems demand defined damping that is independent of the temperature. If the damping coefficient p is related to the other parameters in equation (4), this results in Lehr's damping factor D:

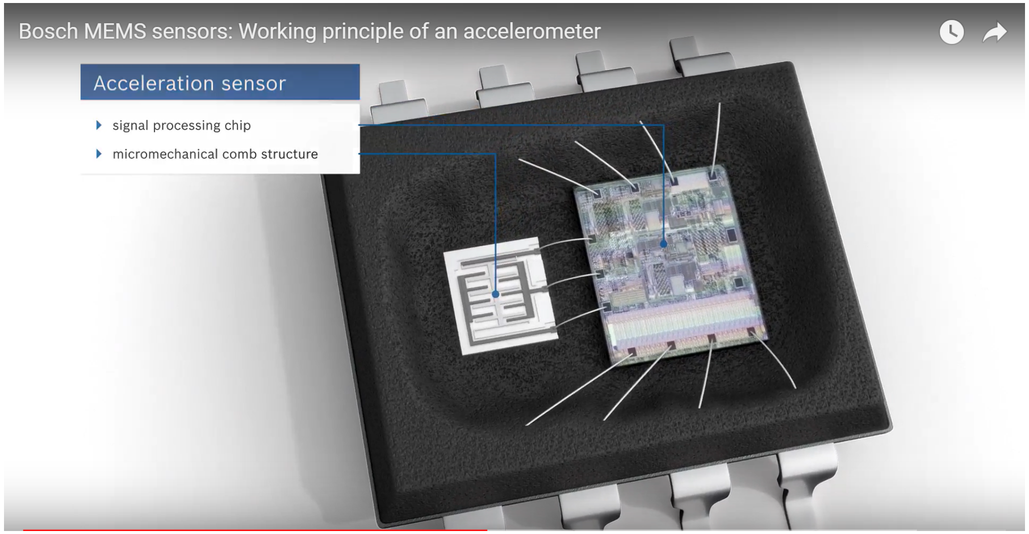
$$D = \frac{p}{2 \cdot c} \cdot \omega_0 = \frac{p}{2 \cdot \sqrt{c \cdot m}} \quad (7)$$

The closed loop minimizes the mass displacement because any force on the mass induced by acceleration is counteracted immediately by an opposite electrostatic force.

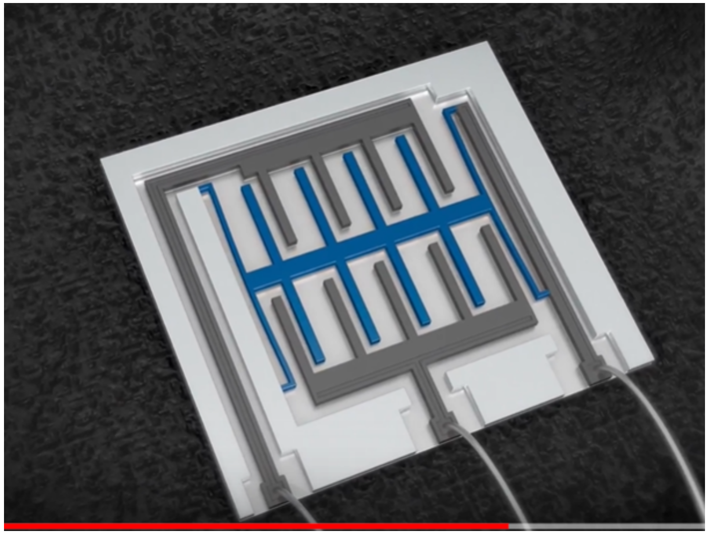
1 Displacement or travel-measuring acceleration sensors



Accelerometers

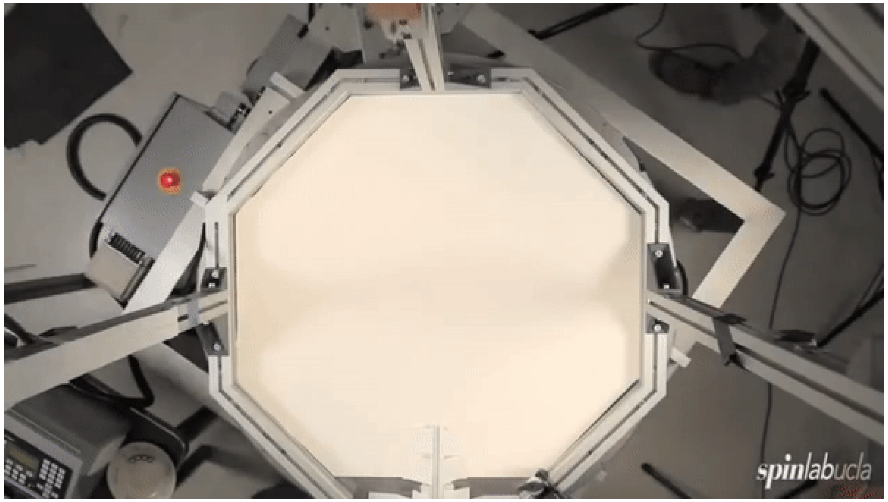


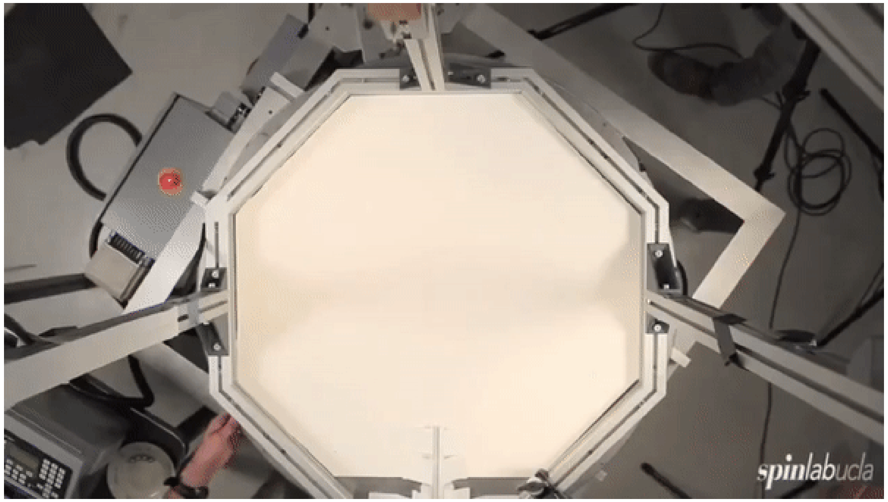
https://www.youtube.com/watch?v=RLQGZl0lpjQ



https://www.youtube.com/watch?v=i2U49usFo10

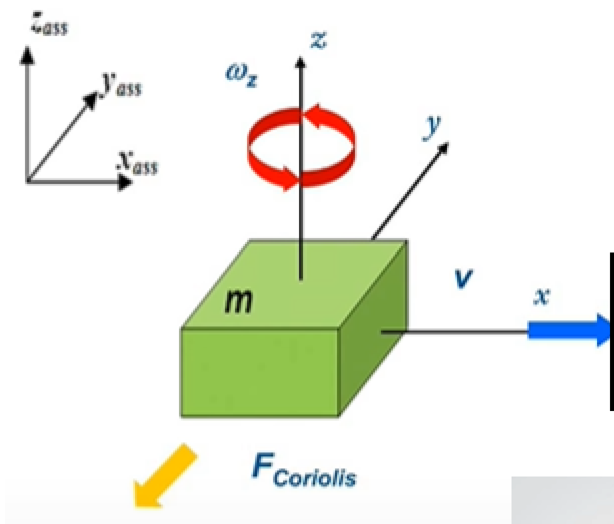
Coriolis force

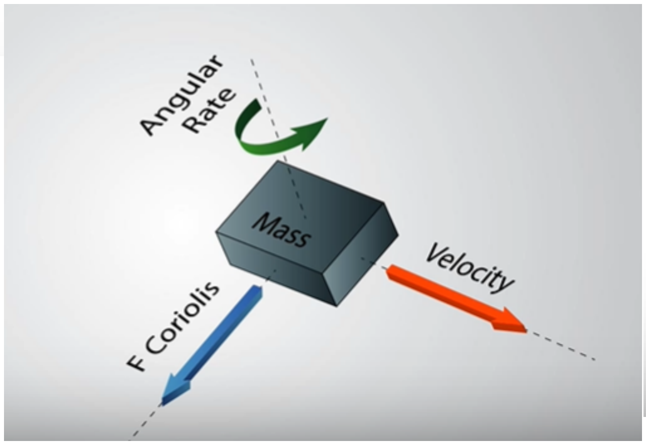


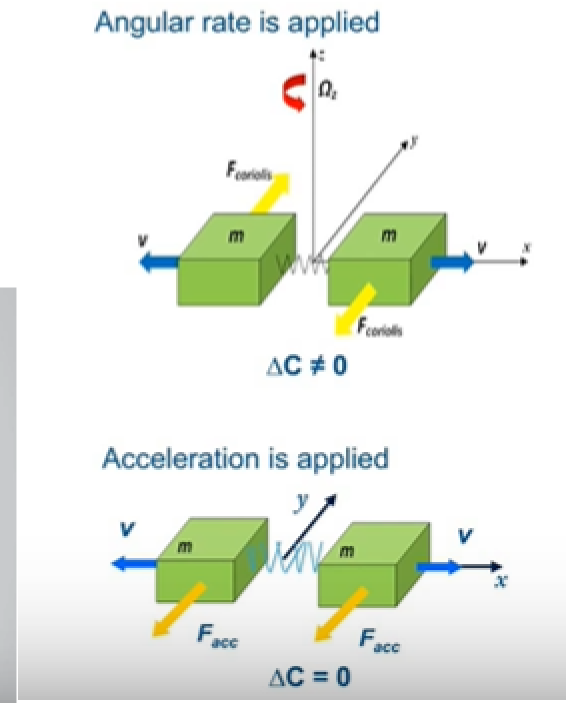


an effect whereby a mass moving in a rotating system experiences a force (the *Coriolis force*) acting perpendicular to the direction of motion and to the axis of rotation.

Yaw- rate sensor



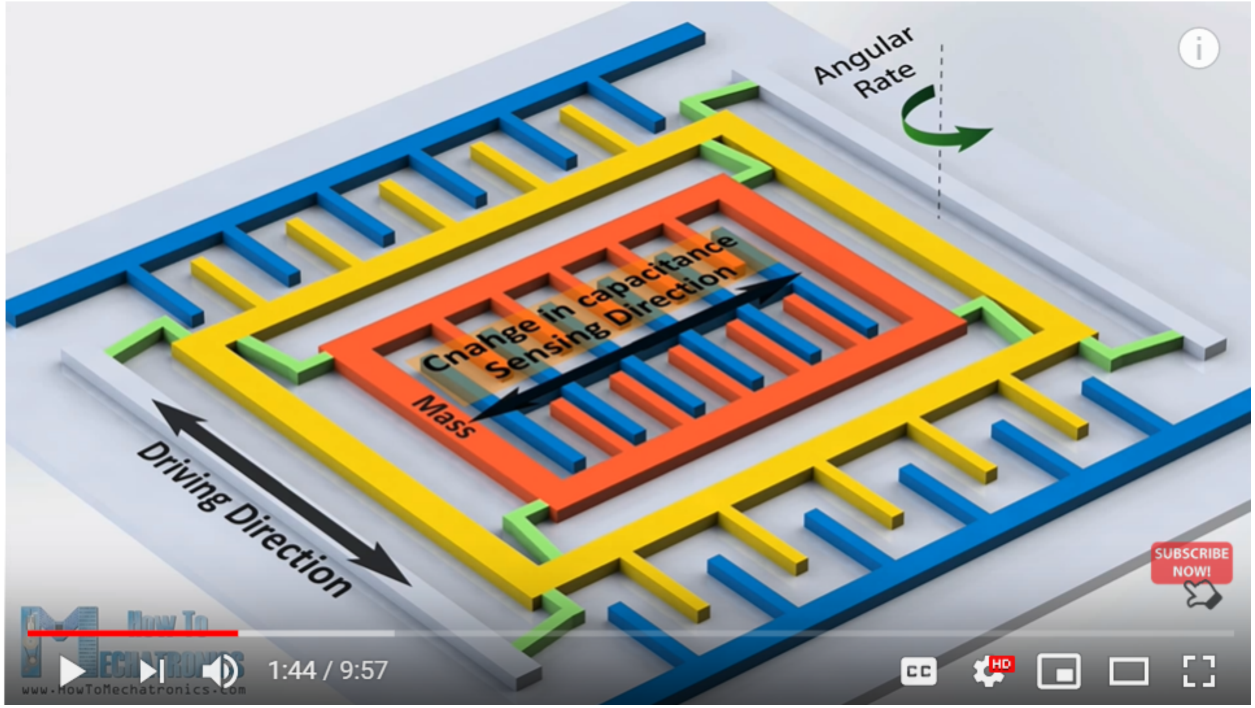




an effect whereby a mass moving in a rotating system experiences a force (the *Coriolis force*) acting perpendicular to the direction of motion and to the axis of rotation.

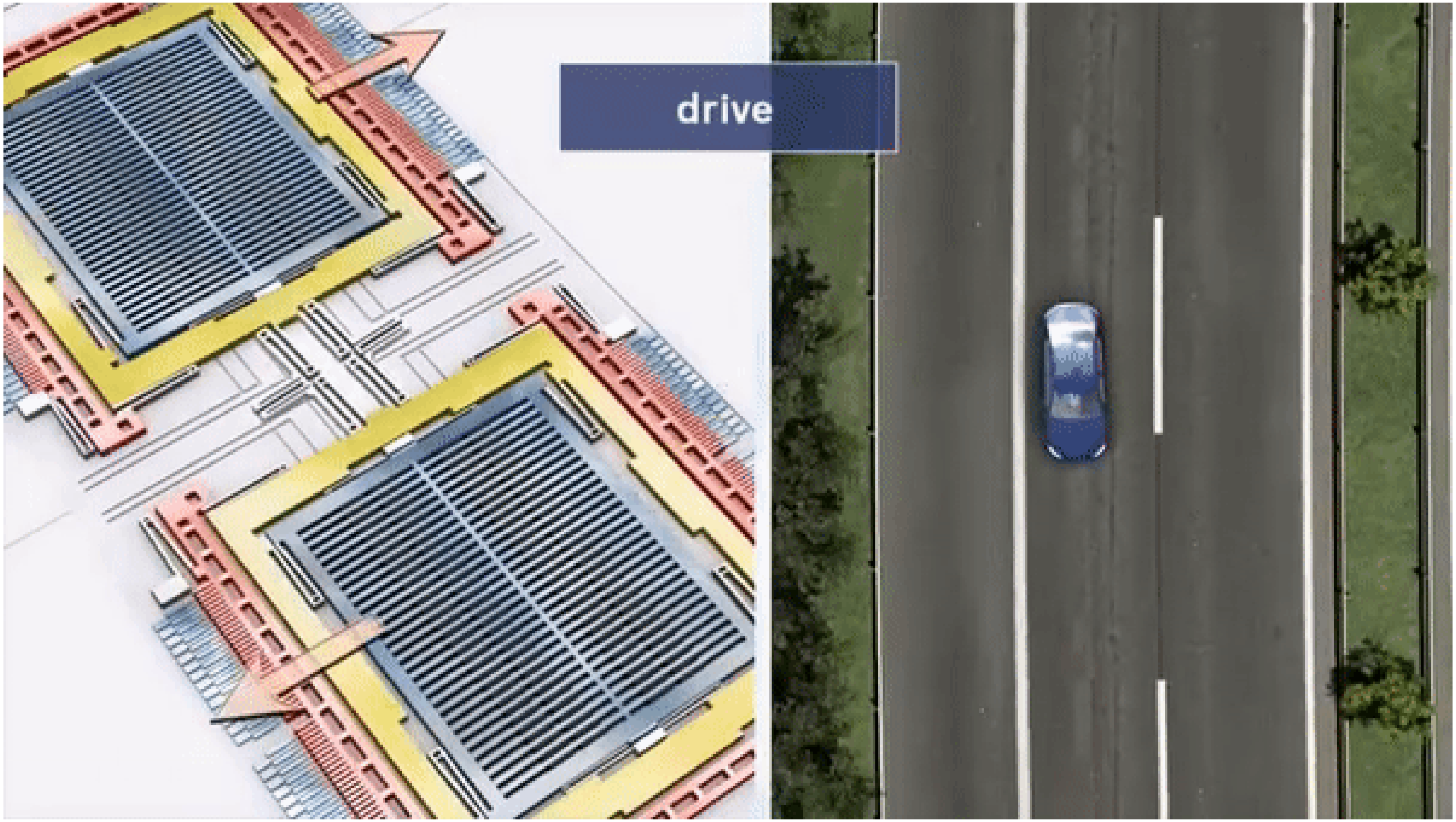
- Coriolis force $-2m\boldsymbol{\Omega} \times \boldsymbol{v}'$
- centrifugal force $-m\boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \boldsymbol{r}')$

Yaw- rate sensor (Micromechanical)



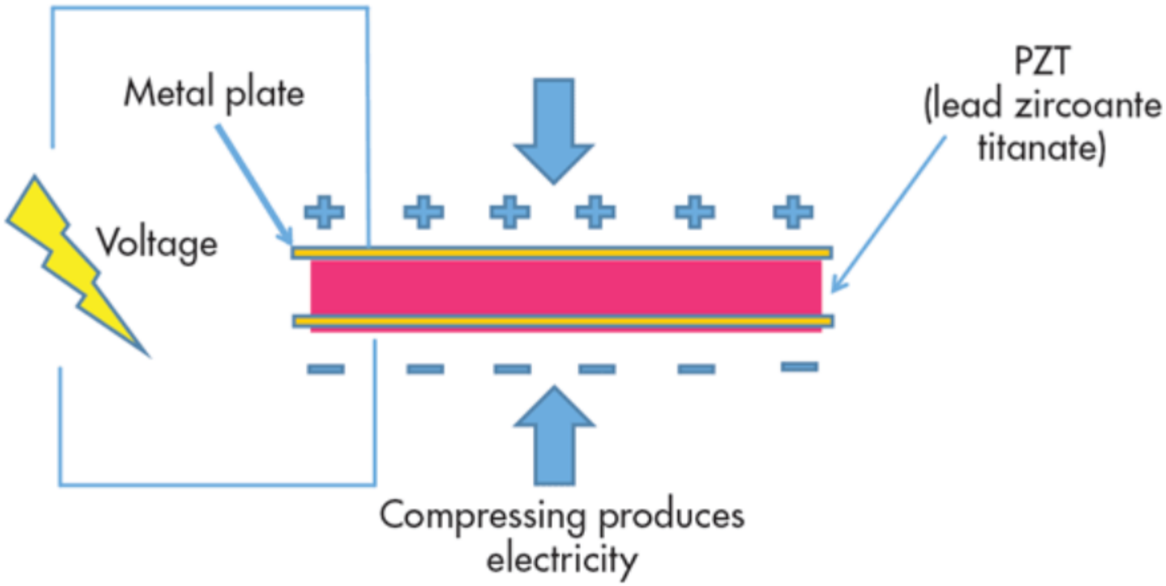
https://www.youtube.com/watch?v=eqZgxR6eRjo

Yaw- rate sensor (Micromechanical)

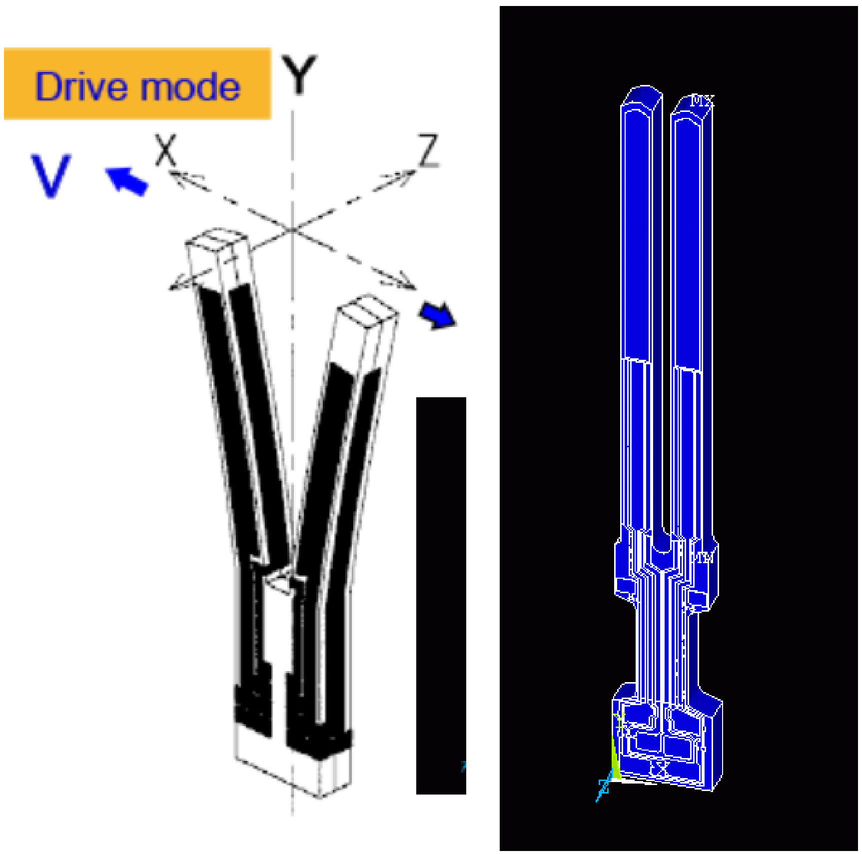


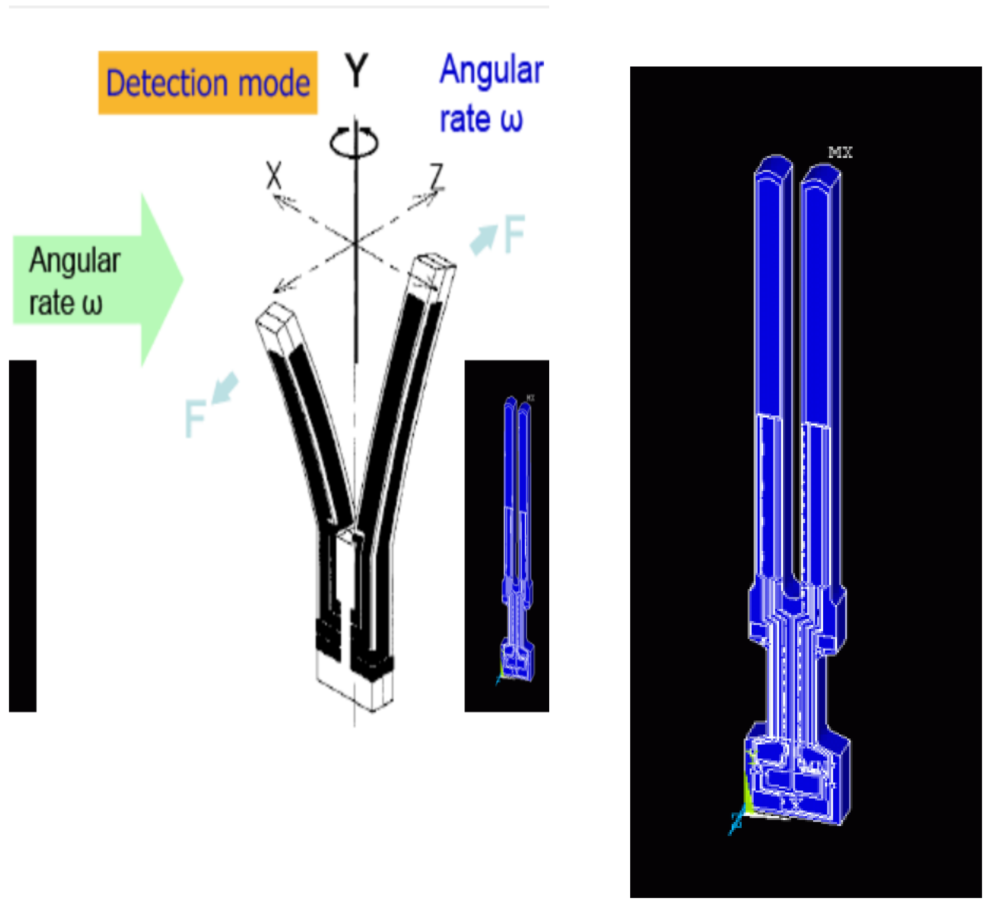
https://www.youtube.com/watch?v=XsjvaYAFN1M

Piezo electric



Yaw- rate sensor (Piezo electric)





Yaw- rate sensor (Piezo electric)

1 Piezoelectric “tuning-fork” yaw-rate sensor

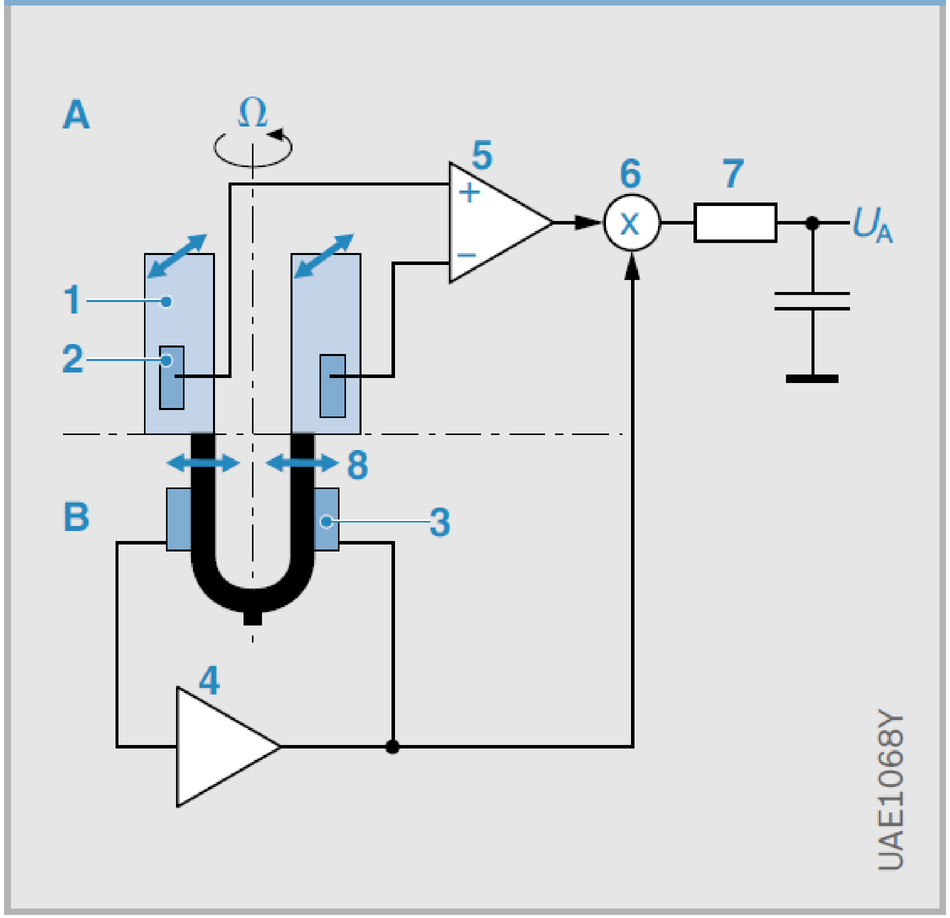
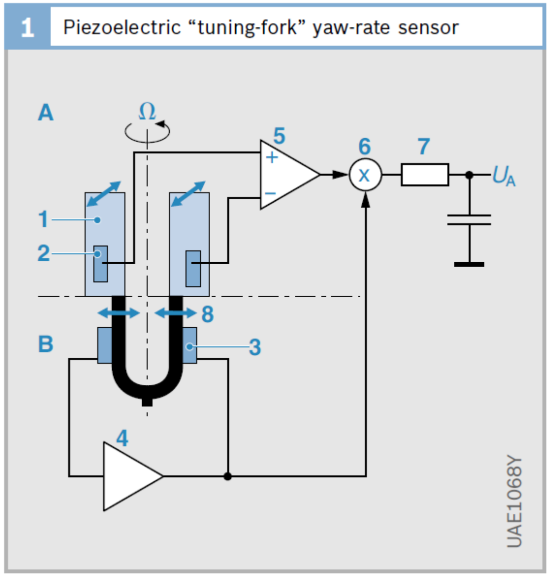
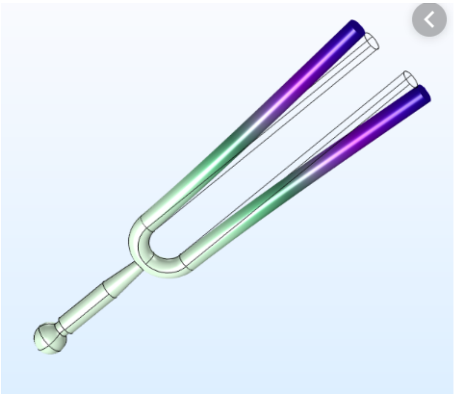


Fig. 1

- A Sensing section of the oscillating element
- B Stimulating section of the oscillating element
- 1 Oscillating element
- 2 Acceleration sensor
- 3 Actuator (piezoelectric element for vibration excitation)
- 4 Regulator for constant vibration excitation
- 5 Charge amplifier
- 6 Multiplication (demodulation)
- 7 Low pass
- 8 Vibration excitation
- U_A Output voltage (proportional to the yaw rate)
- Ω Yaw rate

Yaw- rate sensor (Piezo electric)





Straight-ahead driving

With the vehicle being driven in a straight line there are no Coriolis forces acting on the tuning fork, and since the upper piezo elements always oscillate in counter-phase and are only sensitive perpendicularly to the direction of oscillation, they do not generate a voltage.

Cornering

The rotational movement around the vehicle's vertical axis as it travels around a curve causes the upper portion of the tuning fork to leave the oscillatory plane so that an alternating voltage is generated in the upper piezo elements which is transferred to the navigation computer by an electronic circuit in the sensor housing.

The voltage-signal amplitude is a function of both the yaw rate and the oscillation velocity. Its sign depends on the direction (left or right) taken by the curve.

Piezoelectric Knock Sensors

- These are vibration sensors
- Knock occurs when uncontrolled combustion takes place
- Mass(2), due to oscillations, exerts a compressive force on piezoceramic element(1)
- This forces effect a charge transfer within ceramic element.
- An electrical voltage is generated at the element which is picked by the wire (6) and taken to ECU.

2 Knock sensor (design and mounting)

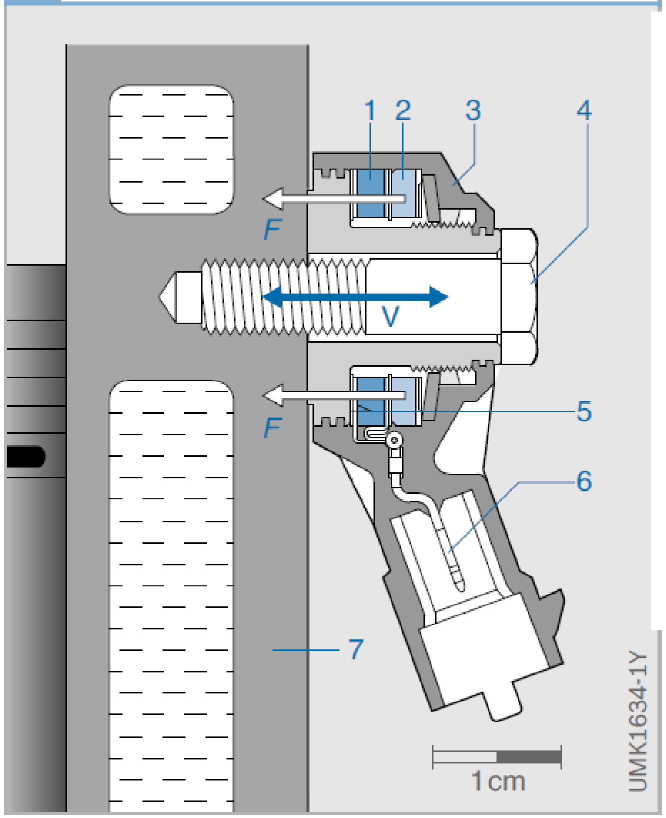
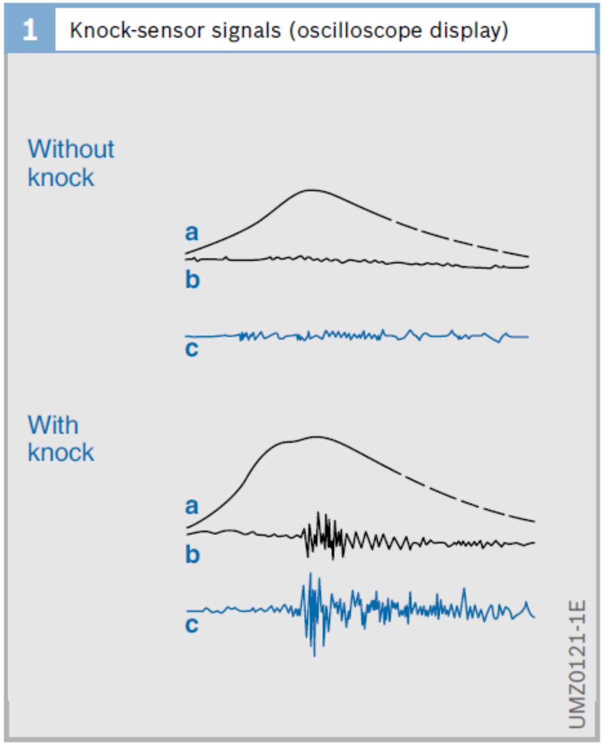


Fig. 2
1 Piezoceramic element
2 Seismic mass with compressive forces *F*
3 Housing
4 Bolt
5 Contact washer
6 Electric connection
7 Engine block
V Vibration

Piezoelectric Knock Sensors



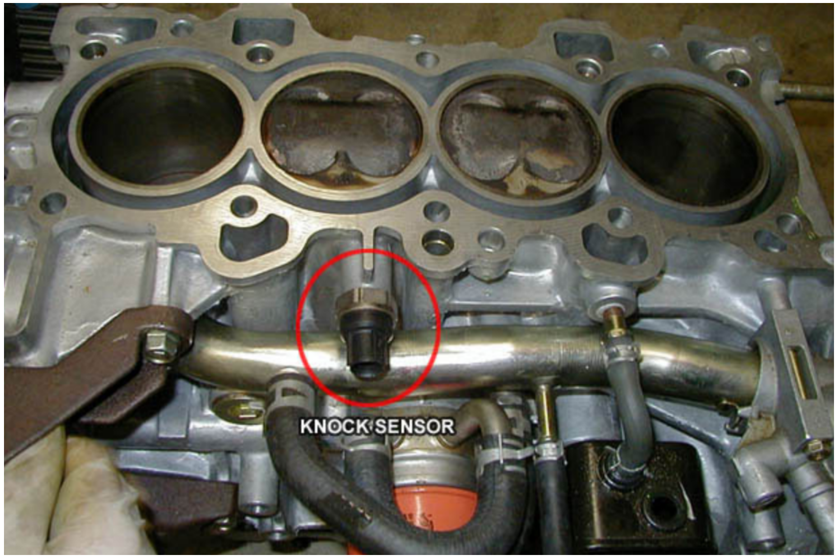


Fig. 1

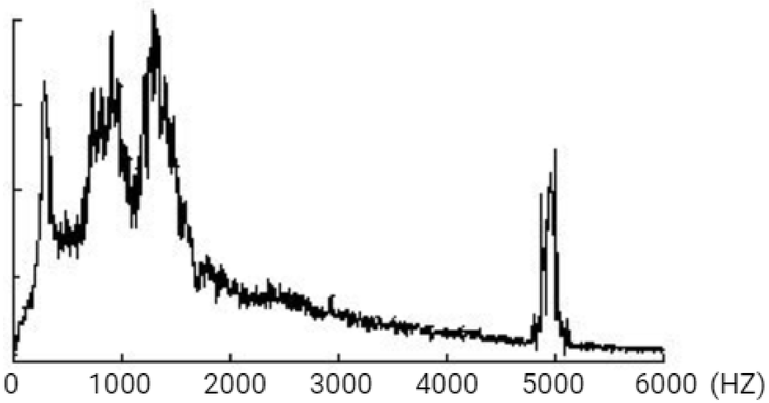
a Cylinder-pressure characteristic curve

b Filtered pressure signal

c Knock-sensor signal

6 cylinder engine requires 2 knock sensors

Piezoelectric Knock Sensors



When detonation occurs, the typical knock sound can be heard within the frequency spectrum. The frequency of this sound lies between 5 - 7 kHz, depending on the cylinder bore. The control unit filters all the frequencies and only acts on the knocking frequencies. As there can be engine vibrations in this same frequency range, the measurement is only carried out between 70° before TDC and 10° after TDC.

Pressure Sensors

External pressure acting on it makes center of the diaphragm to deflect by 10 to 1,000 µm).

The four strain-gage 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 shunts are arranged on the silicon chip so that when the diaphragm
is deformed, the resistance of two of them increases and that of the other
two decreases. These measuring shunts are arranged in a Wheatstone bridge circuit (Fig. 1b) and a change in their resistance values leads to a change in the ratio of

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

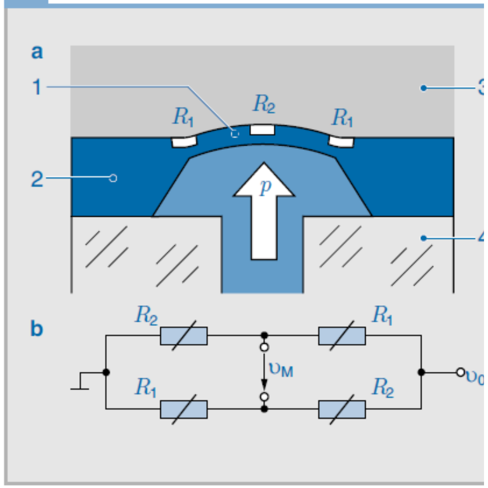
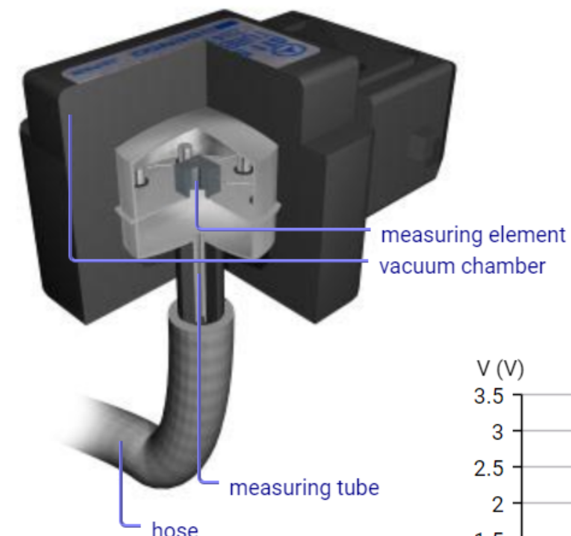


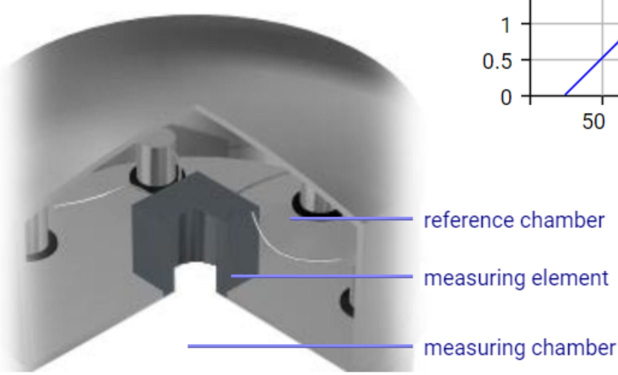
Fig. 1

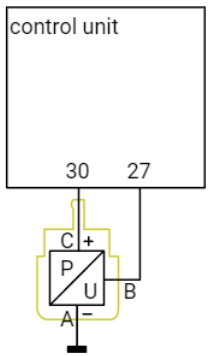
a Sectional drawing
b Bridge circuit

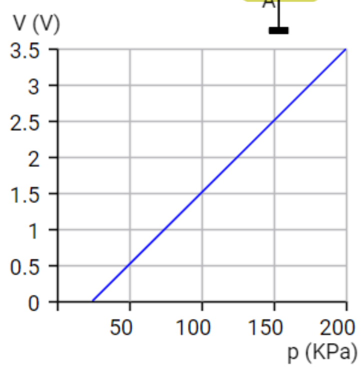
1 Diaphragm
2 Silicon chip
3 Reference vacuum
4 Glass (Pyrex)
p Measured pressure
U_0 Supply voltage
U_M Measurement voltage
R_1 Strain-gage resistor (compressed)
R_2 Strain-gage resistor (elongated)

Pressure sensor (Manifold- MAP)









P (KPa)	V (V)
50	0.5
100	1.5
150	2.5
200	3.5

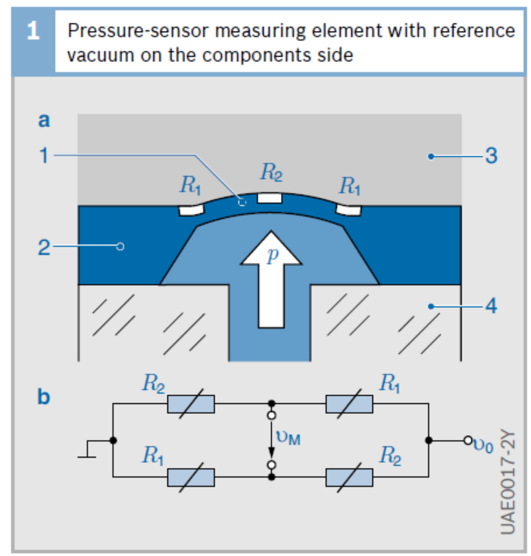


Fig. 1

- 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 Measurement voltage
- R_1 Strain-gage resistor (compressed)
- R_2 Strain-gage resistor (elongated)

Pressure sensor

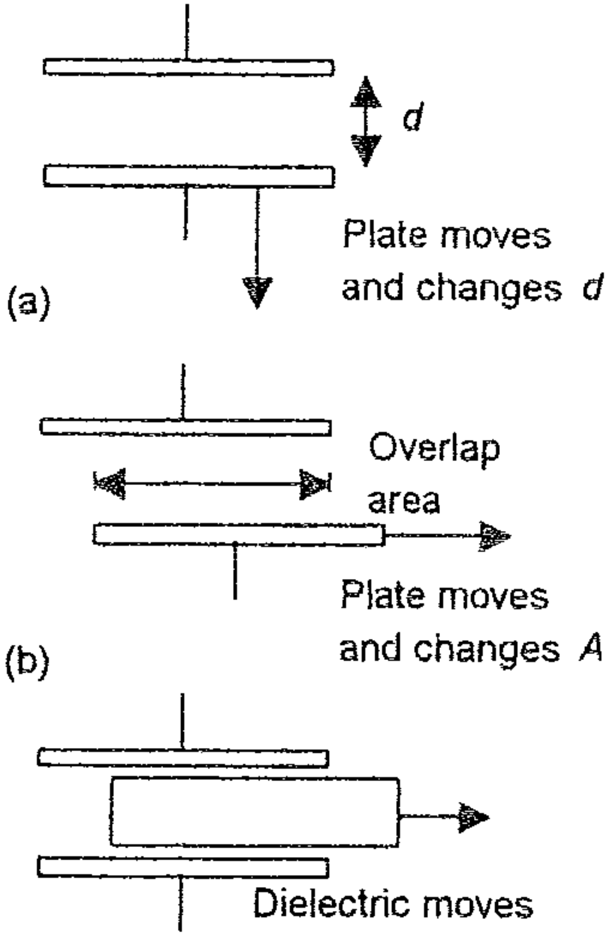
- Intake-manifold or boost pressure (1 to 5 bar) for gasoline injection
- Brake pressure (10 bar) on electropneumatic brakes
- Air-spring pressure (16 bar) on pneumatic-suspension vehicles
- Tire pressure (5 bar absolute) for tire-pressure monitoring
- Hydraulic reservoir pressure (approximately 200 bar) for ABS and power-assisted steering
- Shock-absorber pressure (approximately 200 bar) for chassis and suspension control
- Coolant pressure (35 bar) for air-conditioning systems
- Modulation pressure (35 bar) for automatic transmissions
- Brake pressure in master cylinder and wheel-brake cylinder (200 bar), and automatic yaw-moment compensation on the electronically-controlled brake
- Overpressure/underpressure of the tank atmosphere (0.5 bar)
- Combustion-chamber pressure (100 bar, dynamic) for detection of misfiring and knock detection
- Element pressure on the diesel fuel-injection pump (1,000 bar, dynamic) for electronic diesel control
- Fuel pressure on the diesel common rail (up to 2,000 bar)
- Fuel pressure on the gasoline direct injection system (up to 200 bar)

Capacitive Sensor principles

The capacitance C of a parallel plate capacitor is given by

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d}$$

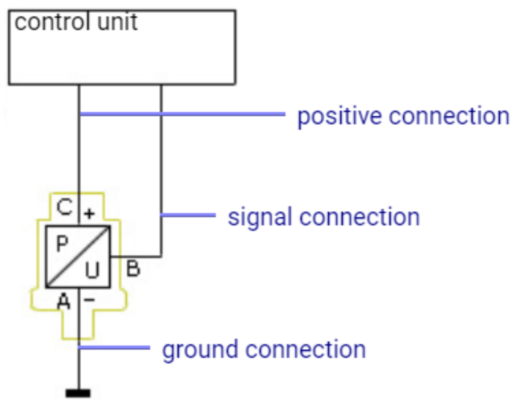
where ε_r is the relative permittivity of the dielectric between the plates, ε_0 a constant called the permittivity of free space, A the area of overlap between the two plates and d the plate separation.



Modification of capacitance is possible by,

- Changing the distance between the two parallel electrodes.
- Changing the dielectric constant, permittivity of dielectric medium .
- Changing the area of the electrodes, *A.*

Oil pressure sensor



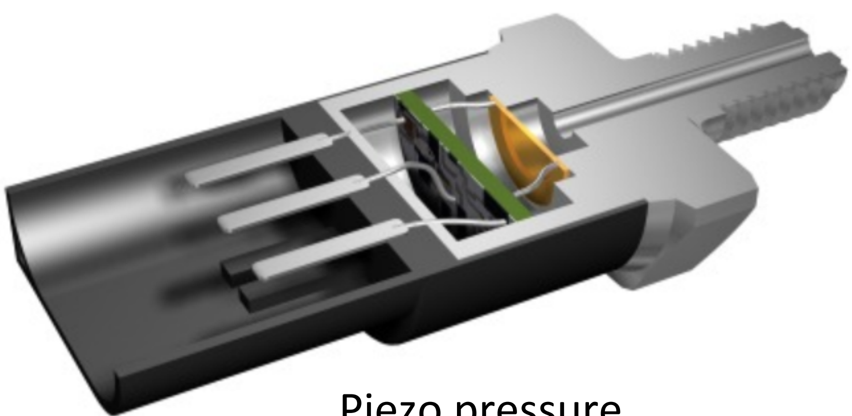
Oil pressure sensor

An oil pressure sensor can not only measure low oil pressure, but can also determine actual oil pressure.

These sensors are connected to an ECU and have a positive, ground and signal wire. Each sensor is provided with a circuit to convert the measured signal to a recognisable unit for the ECU.

The oil pressure can be determined with two types of sensors:

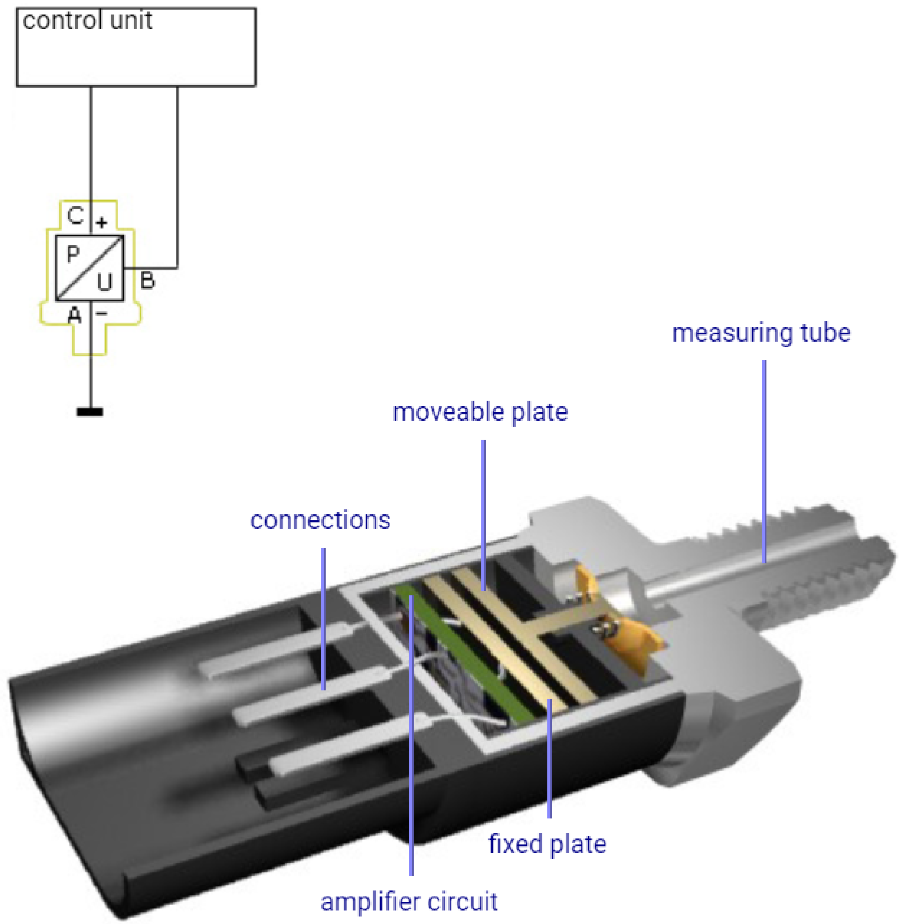
- Piezo-pressure sensor:
  A measuring element is placed on a membrane. Membrane pressure deforms the measuring element. This also changes the resistance value.
- Capacitive pressure sensor:
  This sensor has both a fixed and movable plate. Pressure alters the distance between the two plates, and this changes the capacitor's capacitance.



Piezo pressure sensor

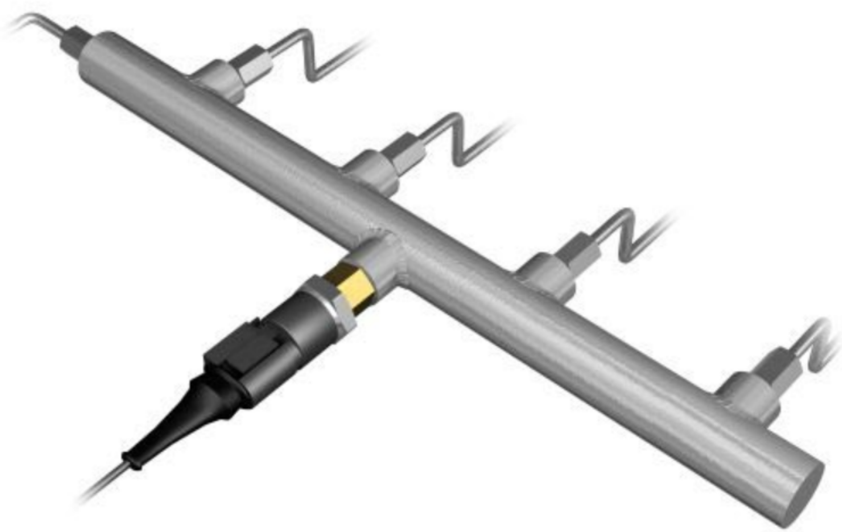
Diaphragms are made of thick steel, thickness being proportional to pressures.

Oil pressure sensor

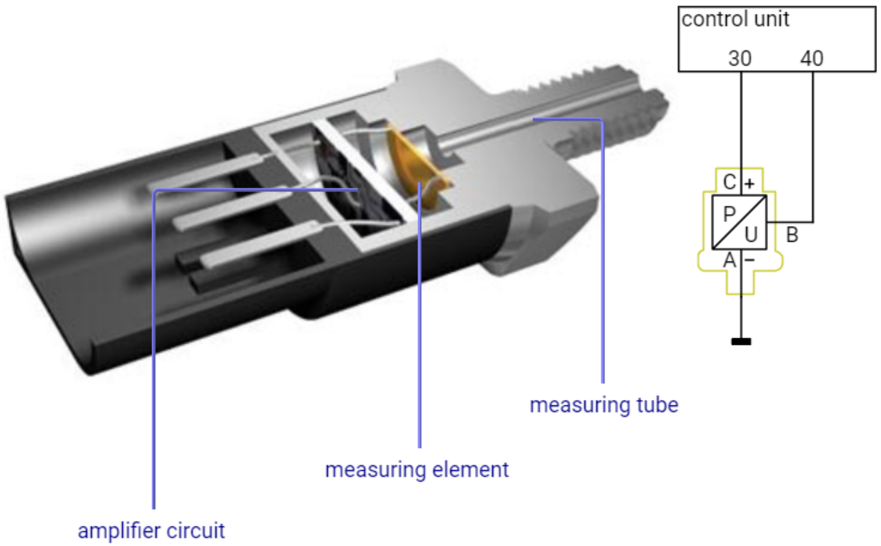


Capacitive pressure sensor

Fuel pressure sensor

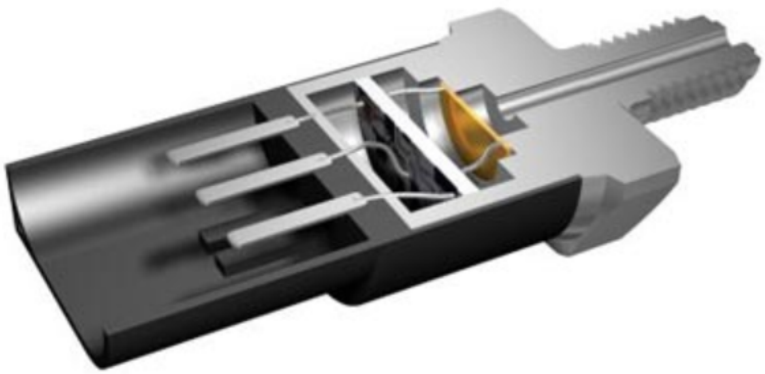


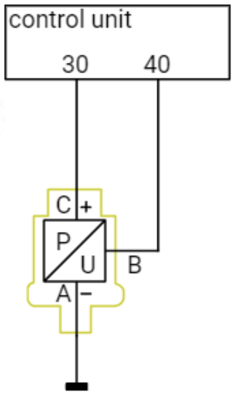
High pressure measurement upto 160 MPa

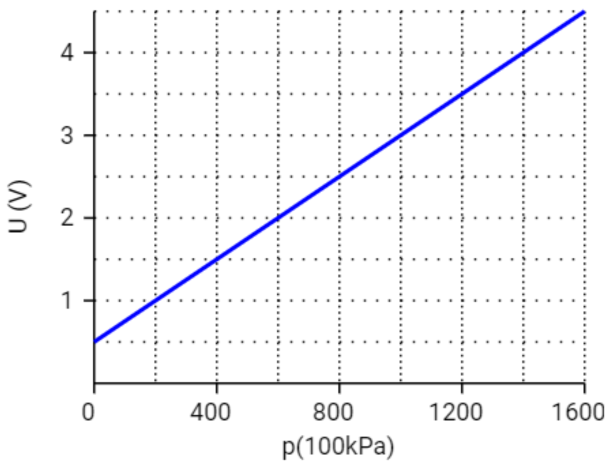


Diaphragms are made of thick steel, thickness being proportional to pressures.

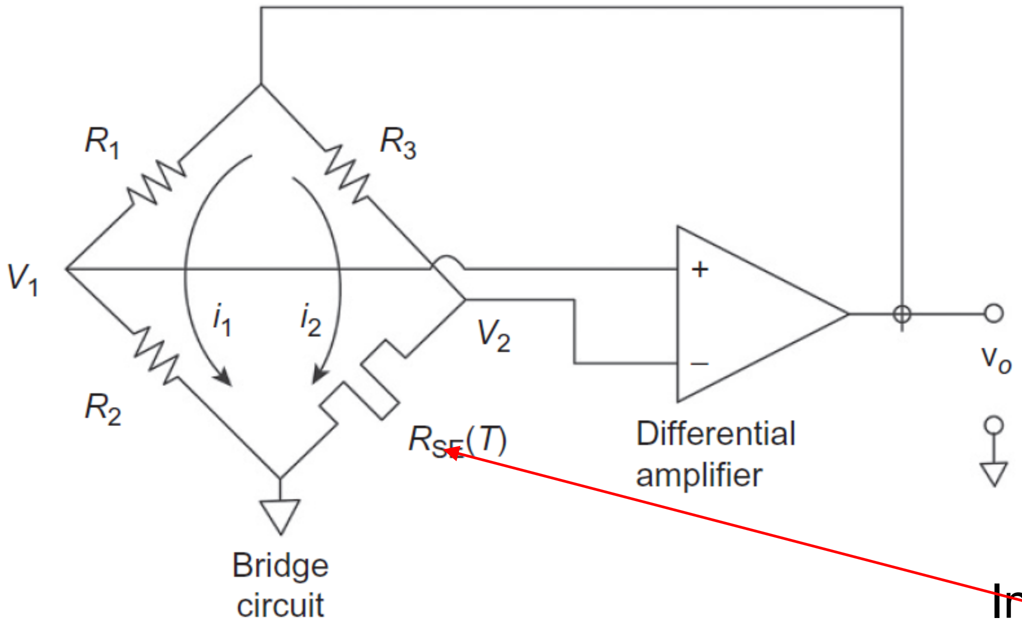
Fuel pressure sensor







Mass air flow sensor



$$v_o(\dot{M}_a) = \left[v_o^2(0) + K_{MAF}\dot{M}_a\right]^{1/2}$$

V_0 – Output voltage
K_{MAF} is constant for a configuration
M_a = Mass of air flow.

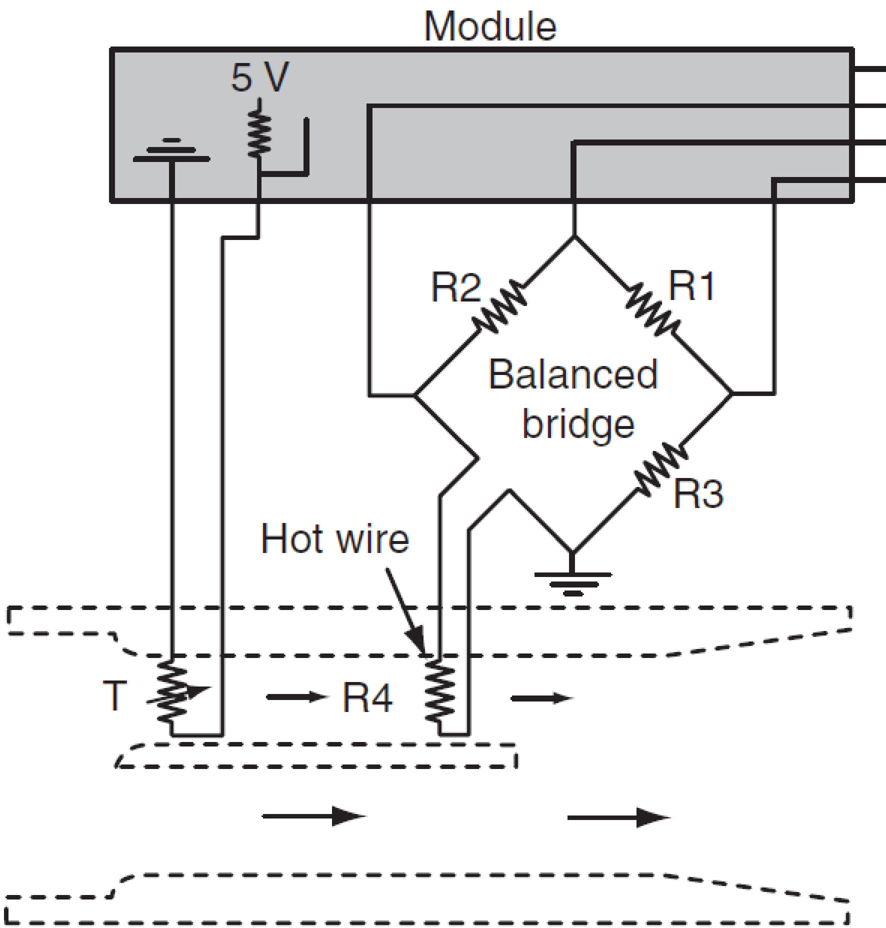
$V_2 = R_{SE}/(R_{SE}+R_3)$

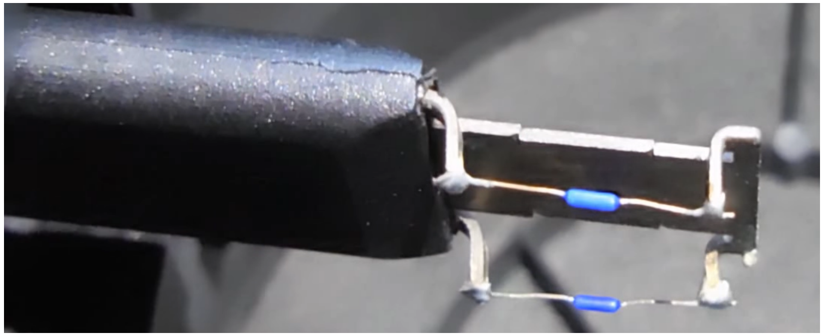
Amplifier output = G (V_1-V_2)

In this bridge circuit, only that sensing element (R_{SE}) is placed in the moving airstream whose mass flow rate is to be measured.

The other three resistances are mounted such that they are at the same ambient temperature (T_a) as the moving air.

Mass air flow sensor

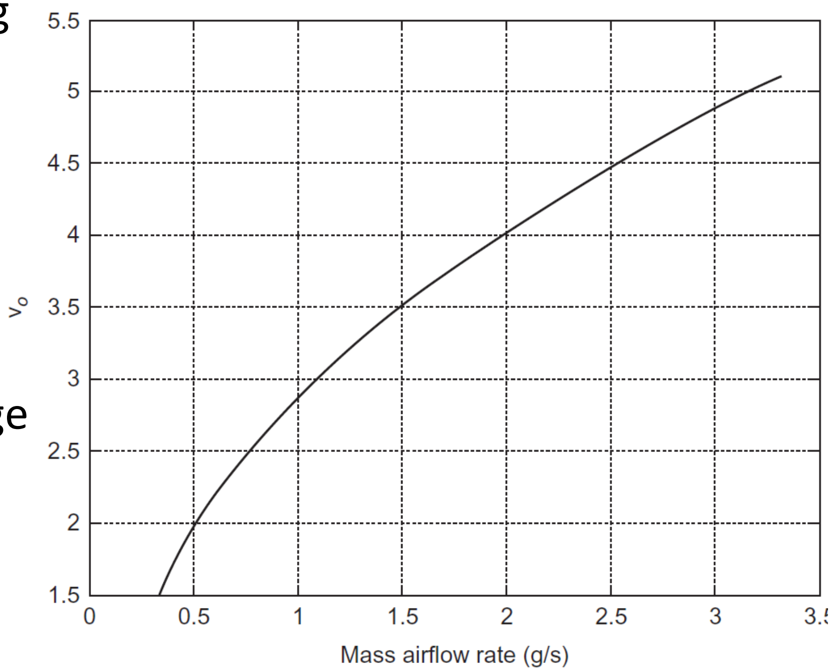




Mass air flow sensor

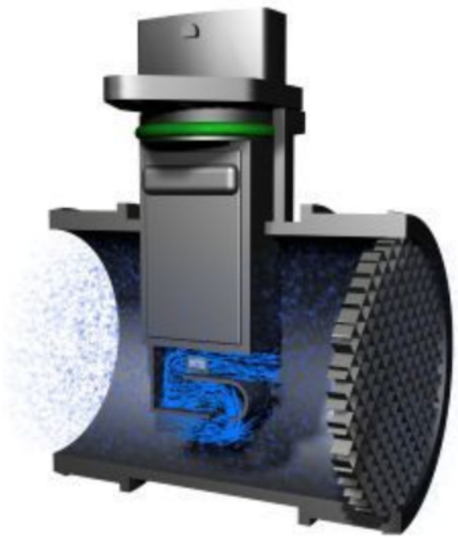
Typically the analog output voltage is converted to frequency(f) proportional to the input voltage.

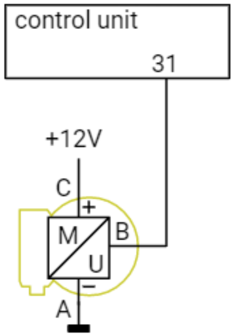
The device is voltage to frequency converter.



During the start of engine, the wires are heated just to clean the dirt / debris.

Mass air flow sensor



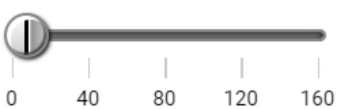


The mass air flow meter can be found in the air intake duct, directly after the air filter.

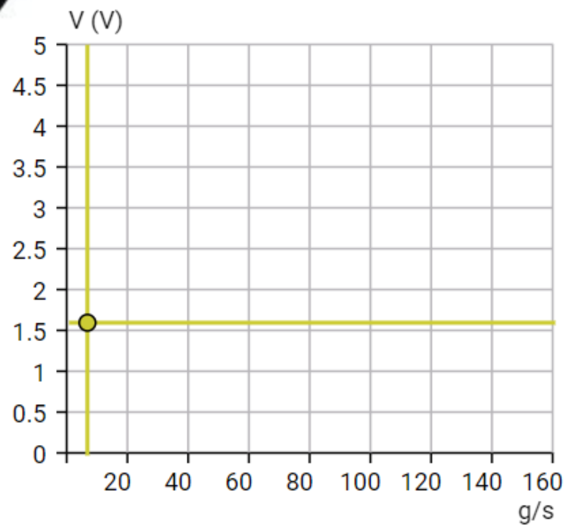
The mass air flow meter is a sensor that measures the volume of the air flow and converts it into a voltage.

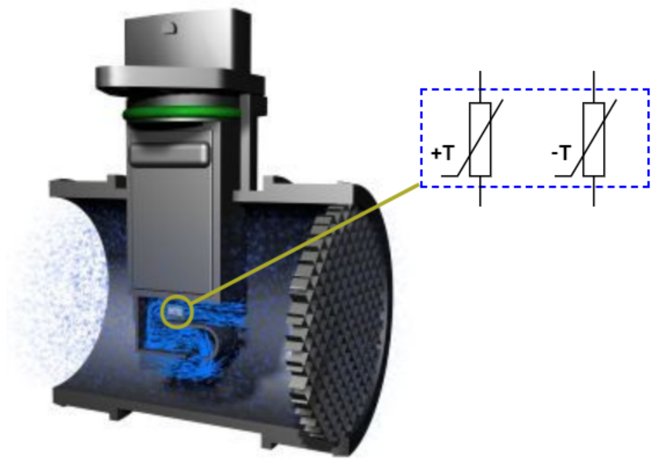
The control unit measures the size of this voltage and thus determines the mass of air drawn in.

The airflow drawn in by a 2000 cc 4-cylinder 4-stroke engine is approximately 3.6 g/s when the engine is idling and increases to about 120 g/s when the engine is at full load.

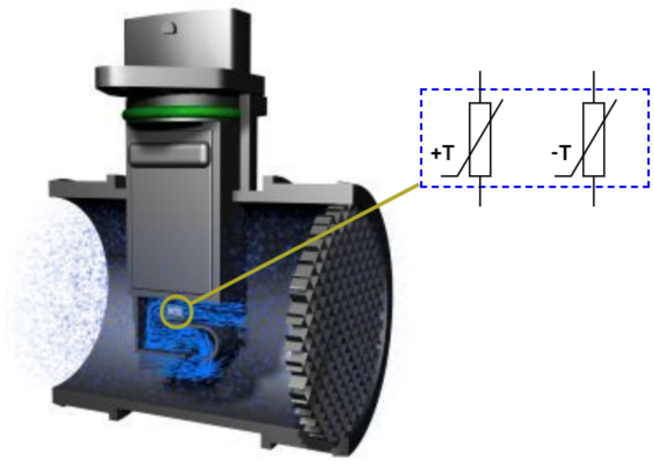


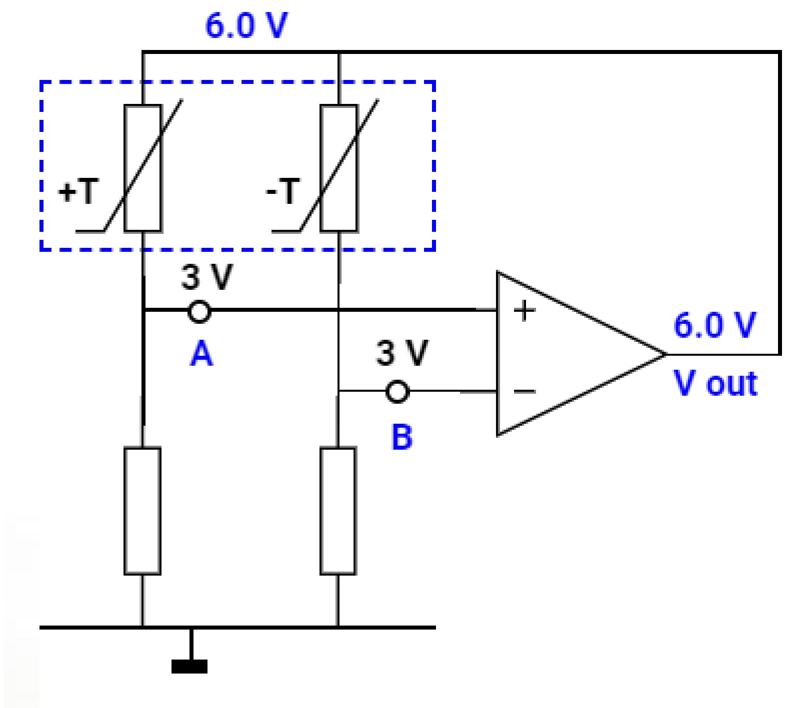
g/s	V (V)
0	0
5	
10	
20	
40	
60	
80	
100	
120	
150	





Mass air flow sensor

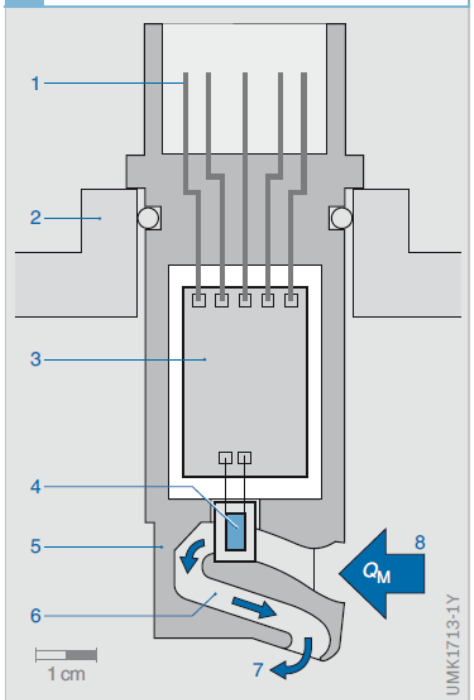




Hot film air sensor

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

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



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

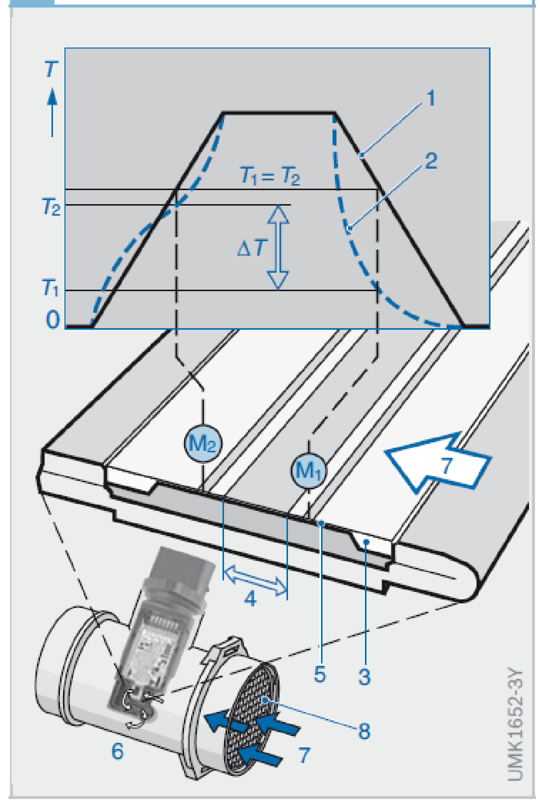
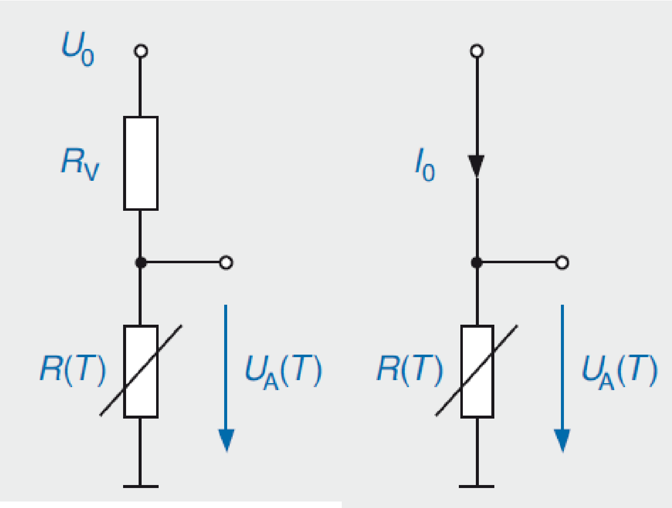


Fig. 3
1 Temperature profile without air flow
2 Temperature profile with air flow
3 Measuring cell
4 Heating zone
5 Sensor diaphragm
6 Measuring tube with air-mass meter
7 Intake-air flow
8 Wire mesh
M_1, M_2 Measuring points
T_1, T_2 Temperature values at measuring points M_1 and M_2
ΔT Temperature difference

Temperature Sensor

1	Temperature measuring points in the motor vehicle
Measuring point	**Temperature range °C**
Intake/charge air	−40 to 170
External environment	−40 to 60
Interior	−20 to 80
Exhaust air/heating system	−20 to 60
Evaporator (air-conditioning system)	−10 to 50
Cooling water	−40 to 130
Engine oil	−40 to 170
Battery	−40 to 100
Fuel	−40 to 120
Tire air	−40 to 120
Exhaust gas	100 to 1,000
Brake caliper	−40 to 2,000

Resistive Sensors:
Temperature- dependent electrical resistors are particularly suitable for temperature measurement.

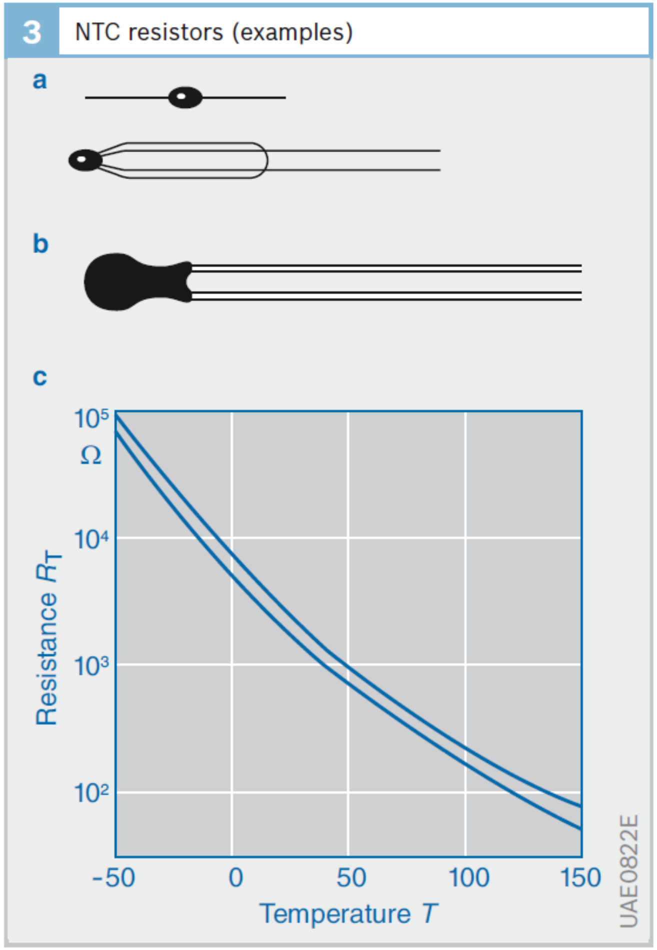


$$U(T) = U_0 \cdot \frac{R(T)}{R(T) + R_V}$$

$$U(T) = I_0 \cdot R(T)$$

Temperature Sensor

Negative temperature Coefficient sensors



$$R(T) = R_0 \cdot e^{B \cdot \left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

Where $R_0 = R(T_0)$,

B = 2,000 to 5,000 K = const,

T absolute temperature

Temperature Sensor

PTC thin-film/thick-film metallic resistors

- Positive temperature coefficient sensors – Resistance is directly proportional to tempe

$$R(T) = R_0 (1 + \alpha \cdot \Delta T + \beta \cdot \Delta T^2 + ..)$$

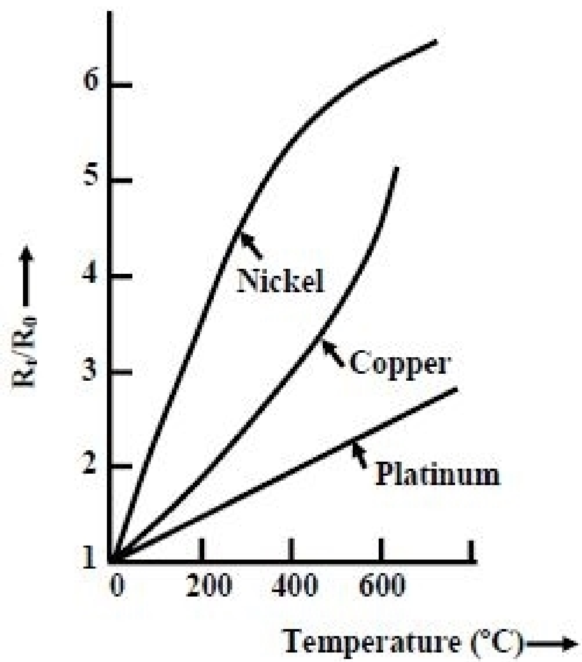
where $\Delta T = T - T_0$ and
$T_0 = 20$ °C (reference temperature),
α linear temperature coefficient (TC),
β square temperature coefficient.

R_0 is resistivity at 20°C

PT100 – 100 Ohms at 20°C
PT1000- 1000 ohms at 20 °C

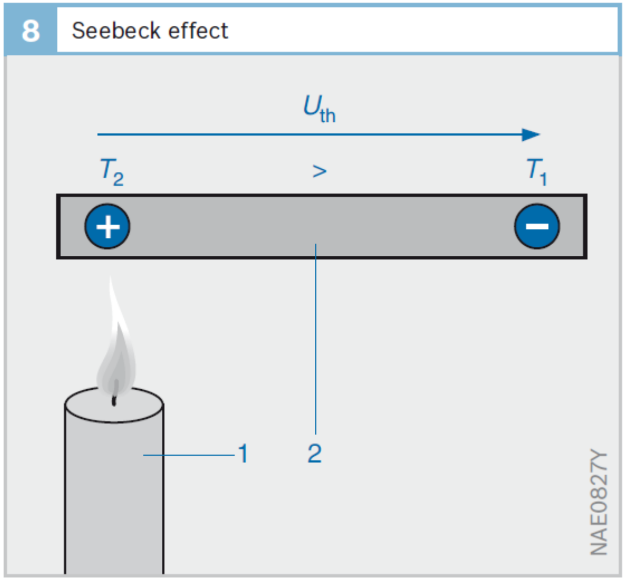
-Very precise

-Best Aging stability



Temperature Sensor

Thermocouple

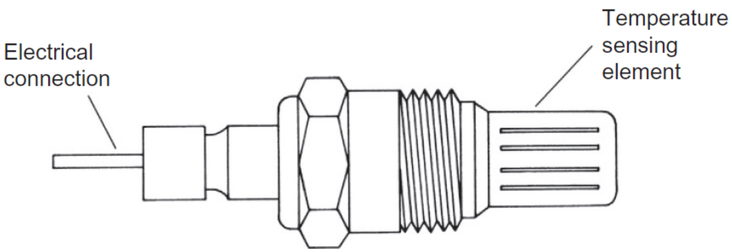


Thermocouples are used in particular for measuring ranges ≥ 1,000 °C. They rely on the Seebeck effect, according to which there is a voltage across the ends of a metallic
conductor when these are at different temperatures T_1 and T_2.

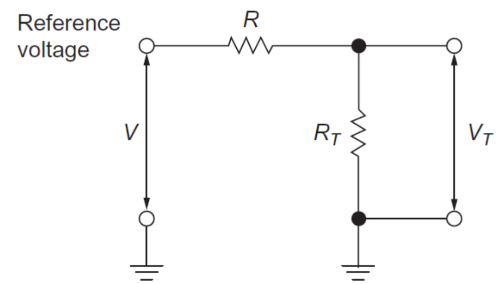
$$U_{th} = c\,(T_2 - T_1) = c\,\Delta T,$$

Temperature Sensor

- Temperature of the coolant
- Temperature of inlet air
- Temperature of Exhaust gas



NTC device- Temperature is inversely proportional to resistance



$$V_T = V \frac{R_T}{R + R_T}$$

$$T = A / \{B + \ln[V_T R / (V - V_T)]\}$$

represents the thermistor resistance R_T as a logarithmic function of T is given by

$$\ln(R_T) = \frac{A}{T} - B \qquad (5.59)$$

where, for an exemplary sensor, the coefficients are approximately $A \cong 5000$ and $B \cong 3.96$, and T is absolute temperature (K).

Torque Sensor

8 Determining torque by measuring angular difference

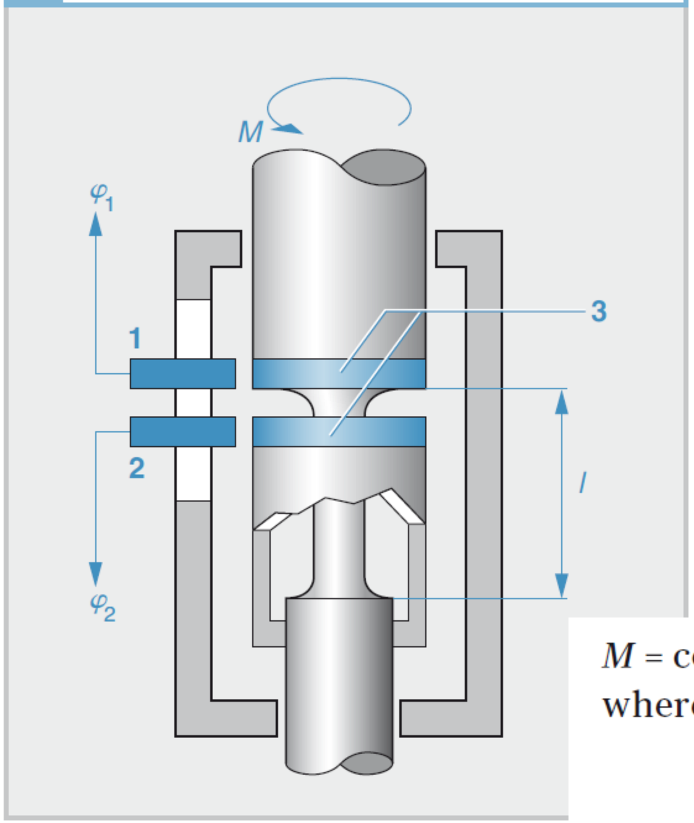


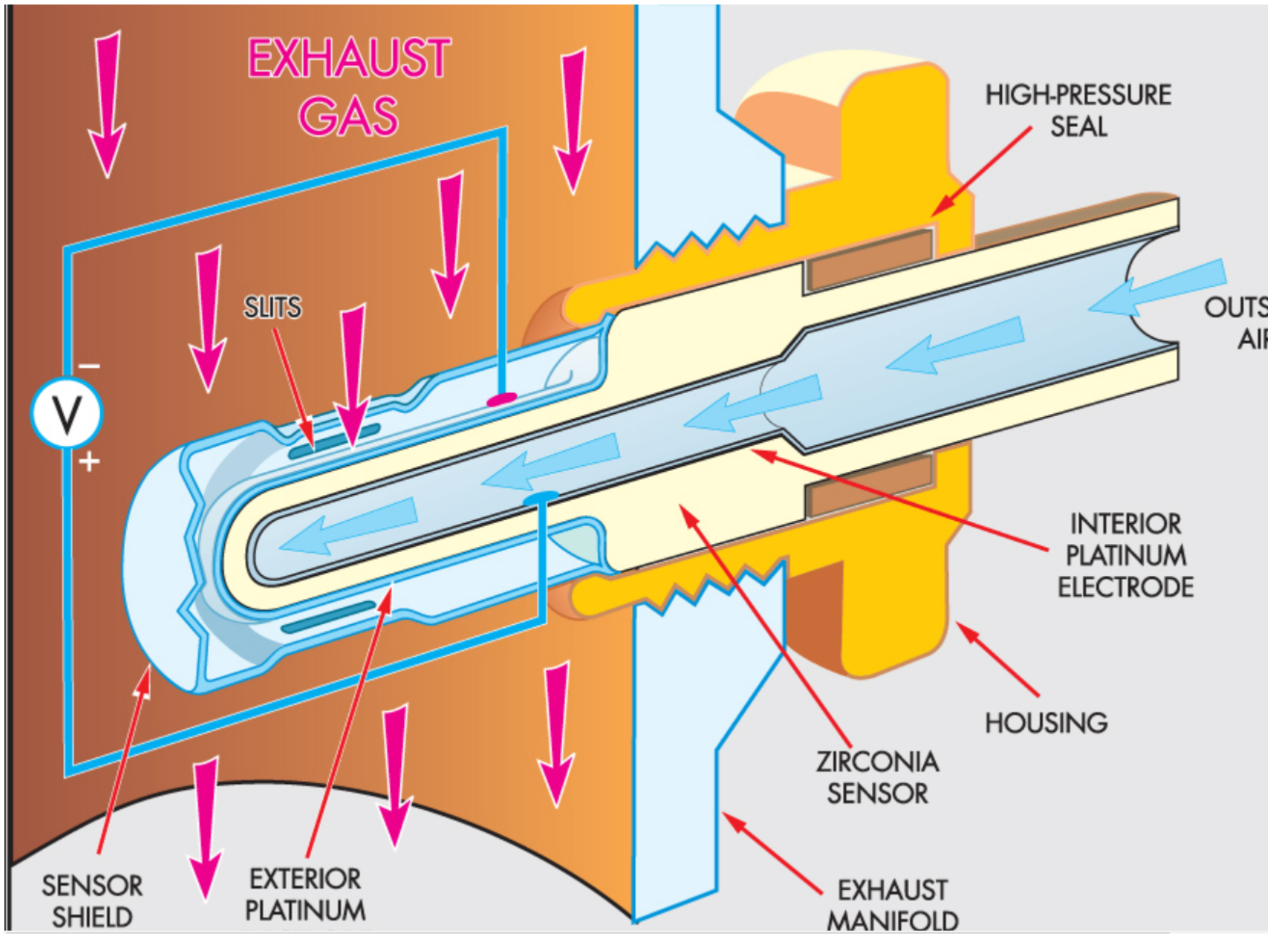
Fig. 8

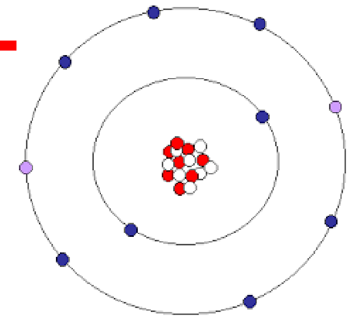
1, 2 Angle/speed sensors
3 Angle markings
l Torsion-measurement section
M Torque to be measured
$\varphi_{1,2}$ Angle signals

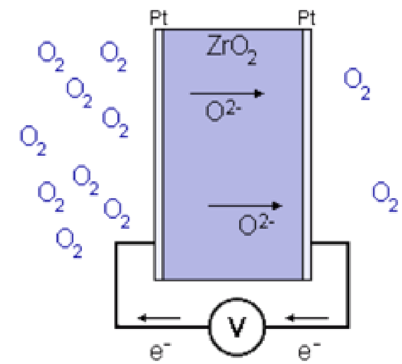
$M = \text{const}\cdot L\cdot(\varphi_2 - \varphi_1)$

where L = length of the section subject to torsion

Exhaust Gas (Lambda Sensor)







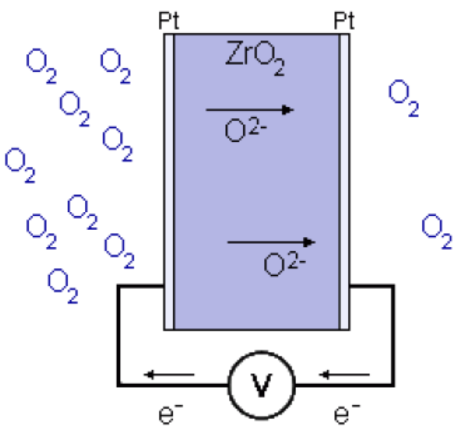
$$U_s = (RT/4F)\ ln(p_{ref}/\ p_{exh})$$

where:

- U_s - sensor signal, V
- T - temperature, K
- p - partial pressure of oxygen
- R - gas constant = 8.314 J/mol
- F - Faraday constant = 96,485 sA/mol

Exhaust Gas (Lambda Sensor)

ZrO_2 behaves like an electrolyte. If two different oxygen pressures exist on either side of a piece of ZrO_2, a voltage (Nernst voltage) is generated across it.

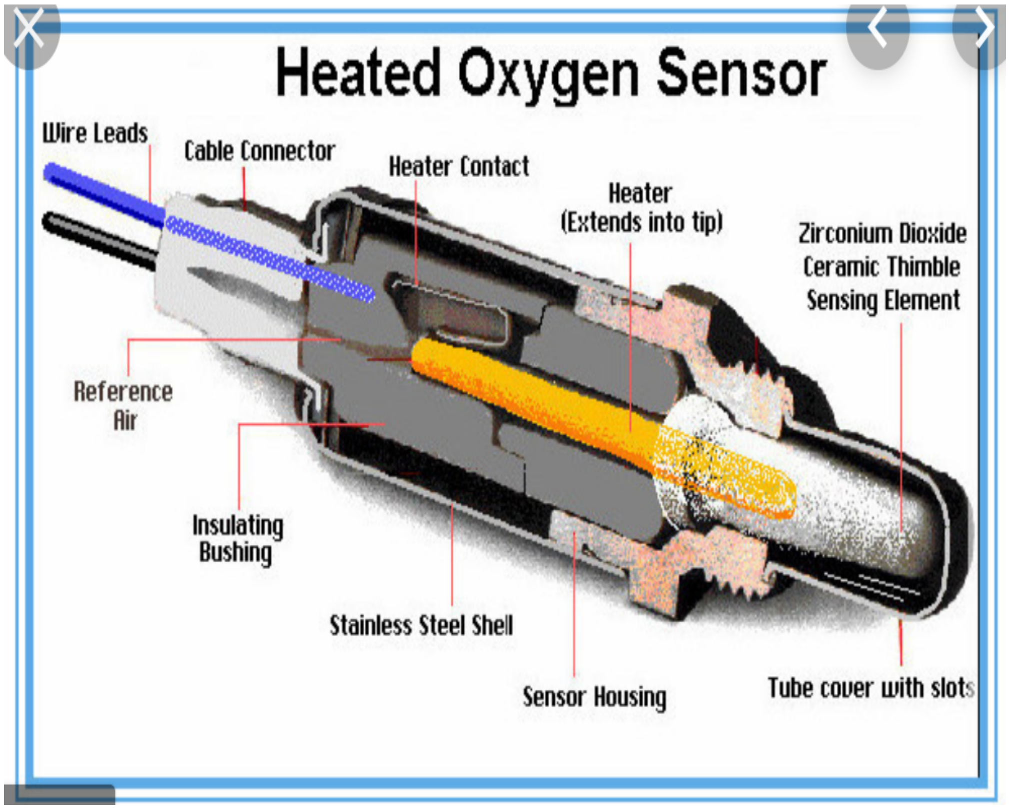


Narrow band

Wide band

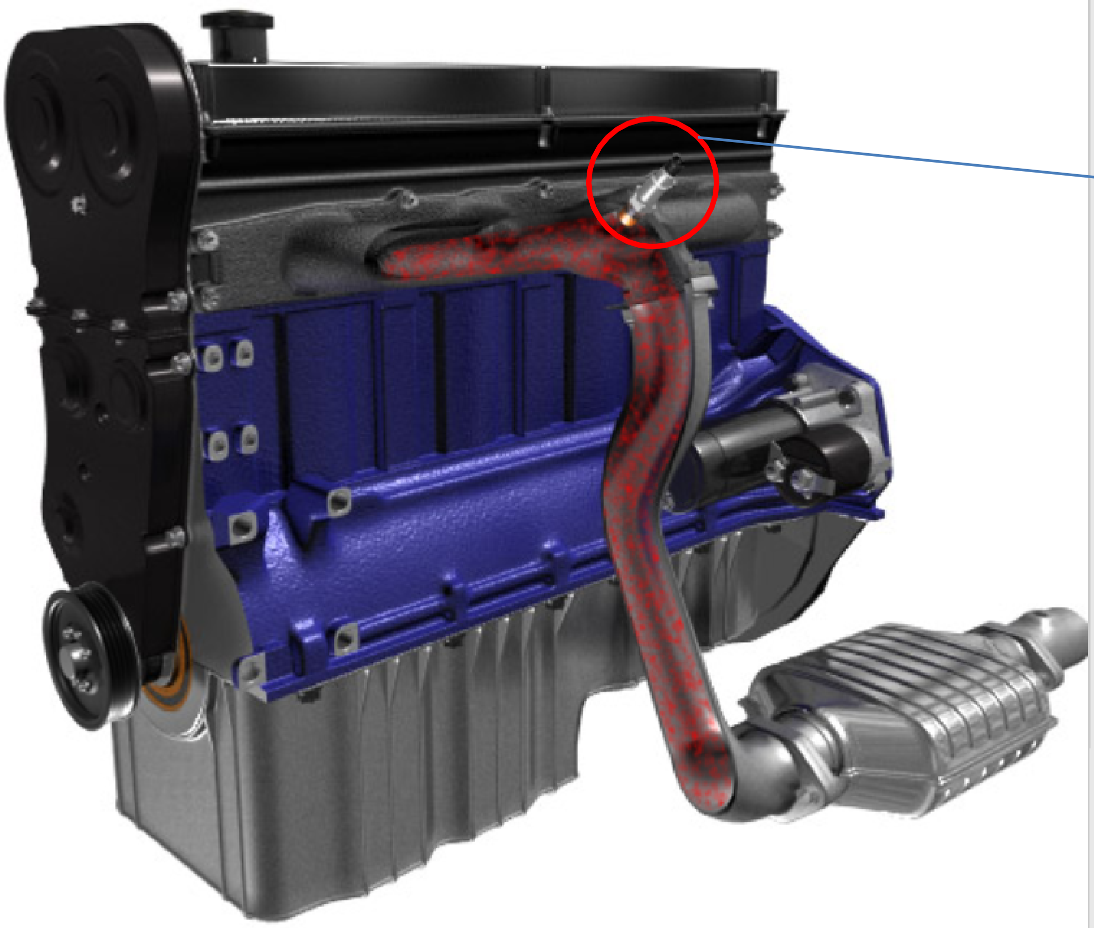
The output voltage of the zirconium sensor is 1000 mV for a rich mixture and 100 mV for a lean mixture. The change takes place at λ=1.

Exhaust Gas (Lambda Sensor)



Oxygen Concentration	Measured Ip
0.0%	0.00mA
3.0%	0.34mA
6.0%	0.68mA
8.29%	0.95mA
12.0%	1.40mA
20.9%	2.55mA

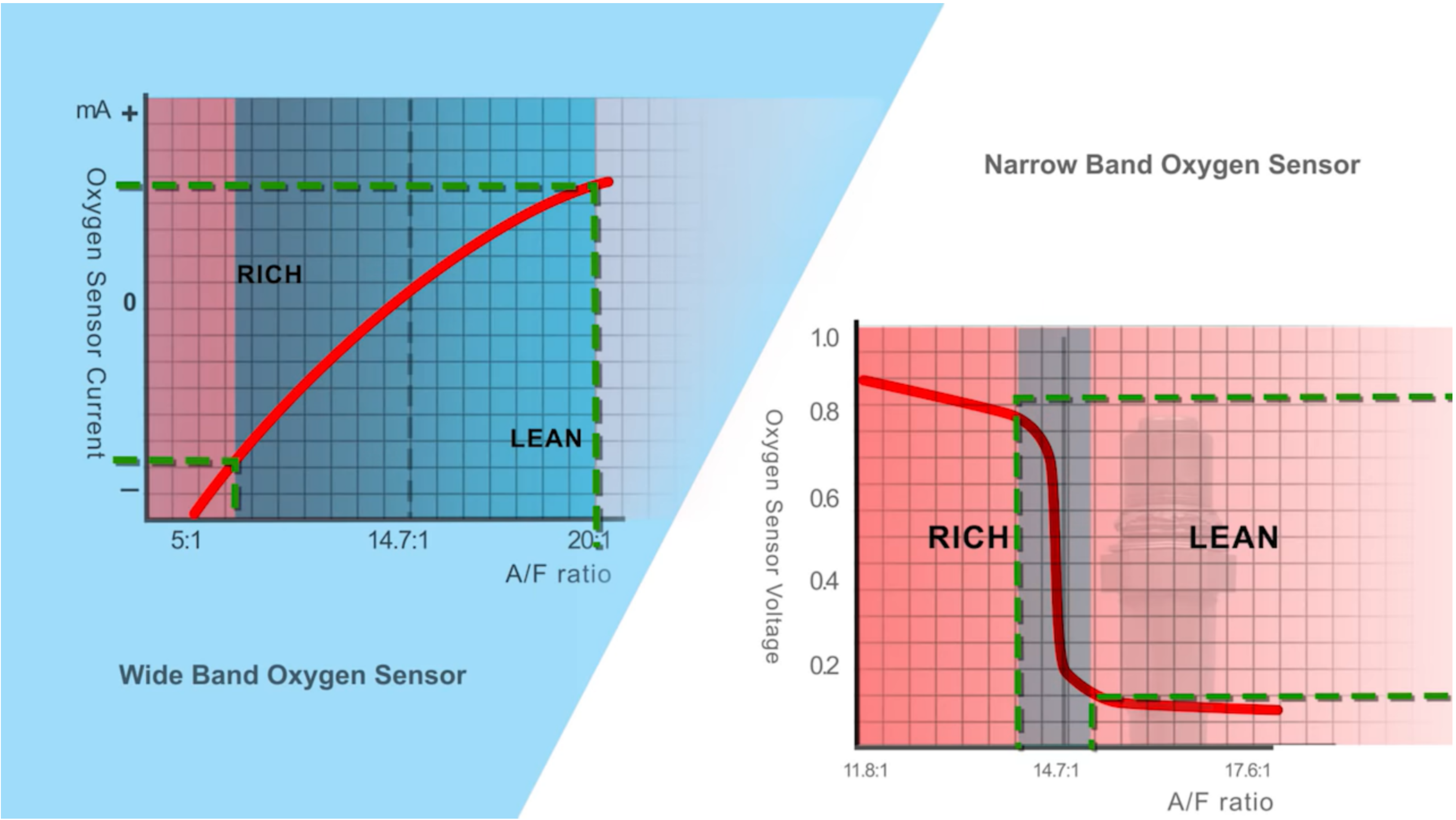
Exhaust Gas (Lambda Sensor)



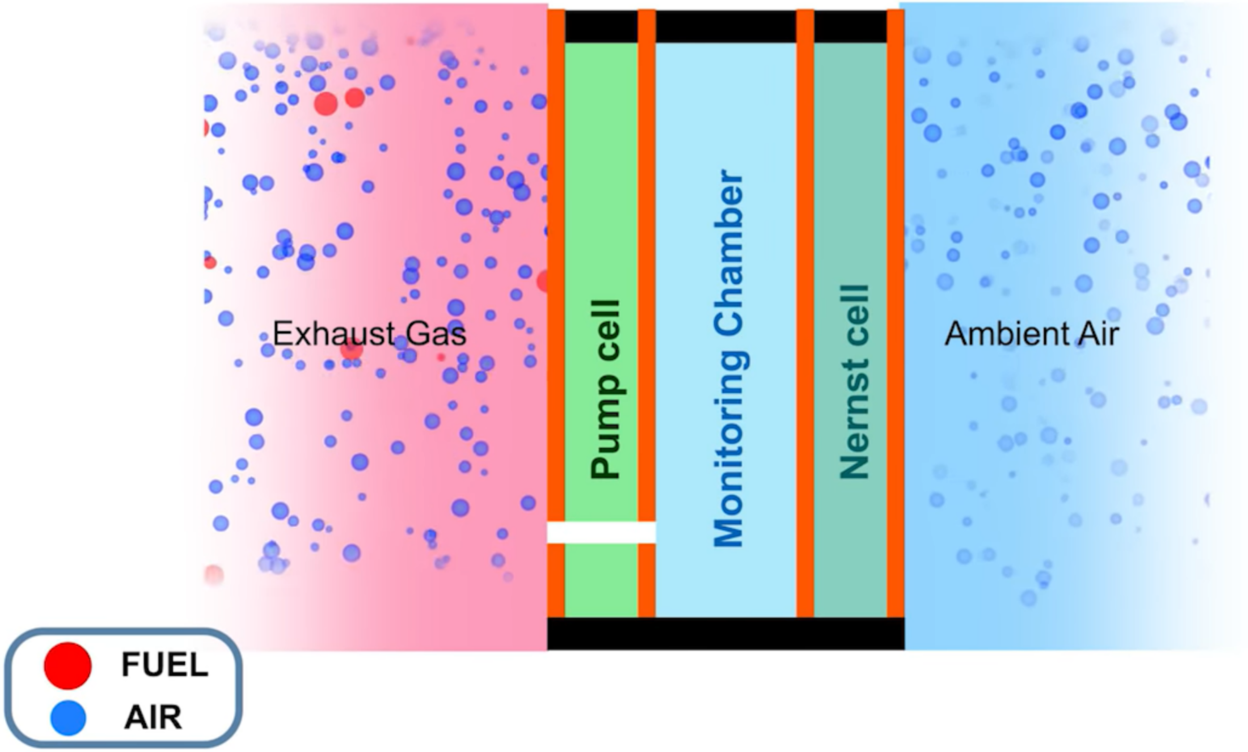
Non heated
Oxygen sensor.

3-4 wire sensor

Exhaust Gas (Lambda Sensor)

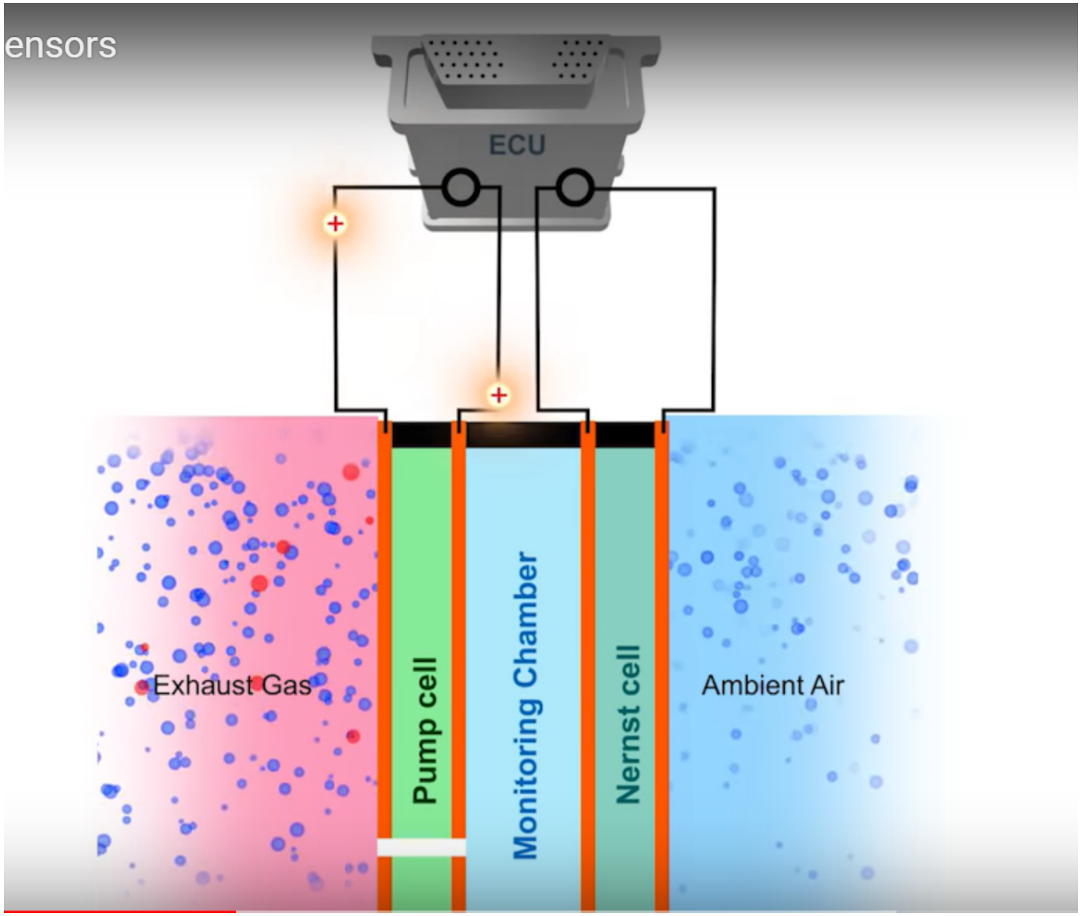


Exhaust Gas (Wideband Lambda Sensor)



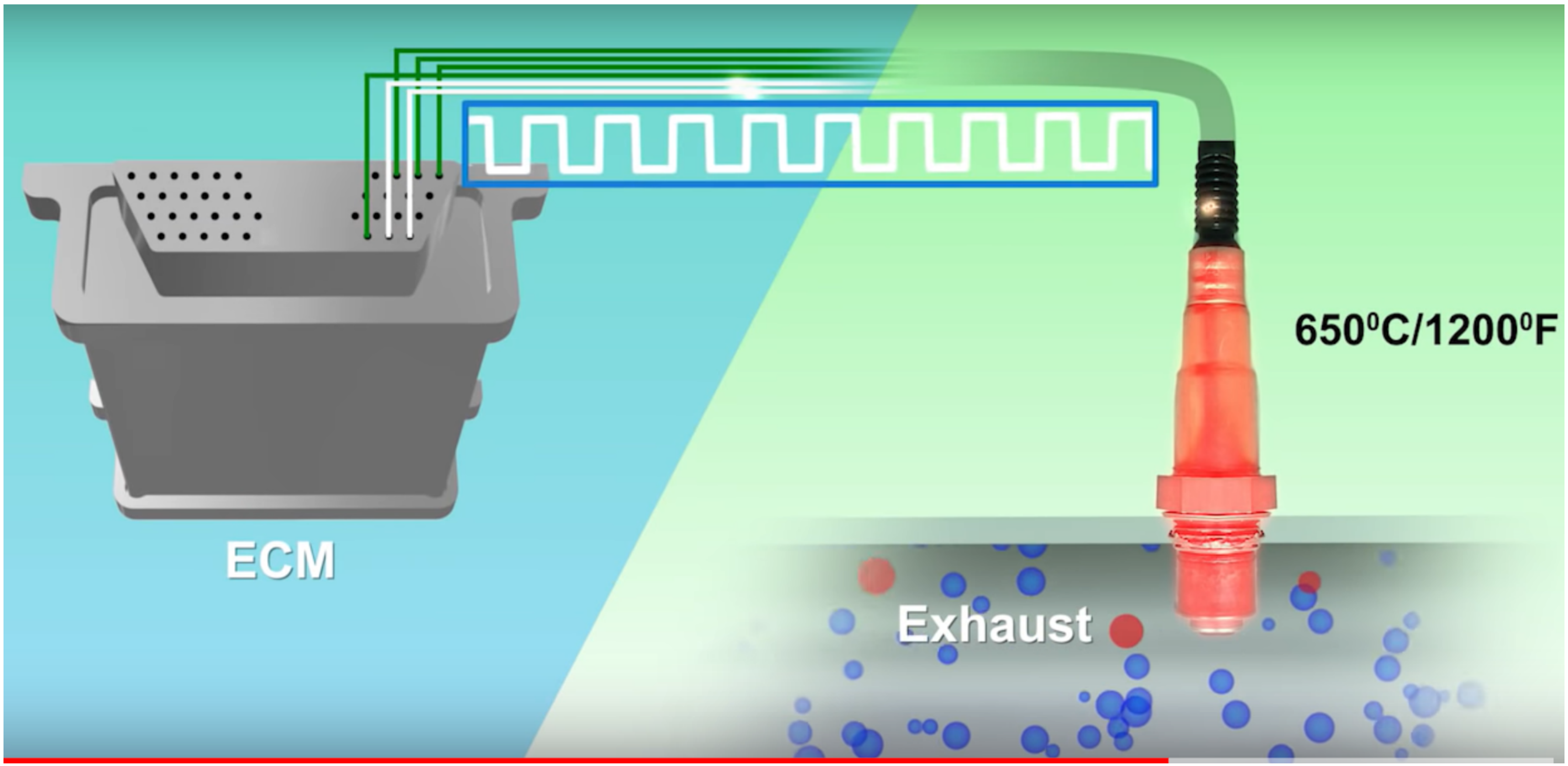
https://www.youtube.com/watch?v=zjefDrFH_6c

Exhaust Gas (Wideband Lambda Sensor)

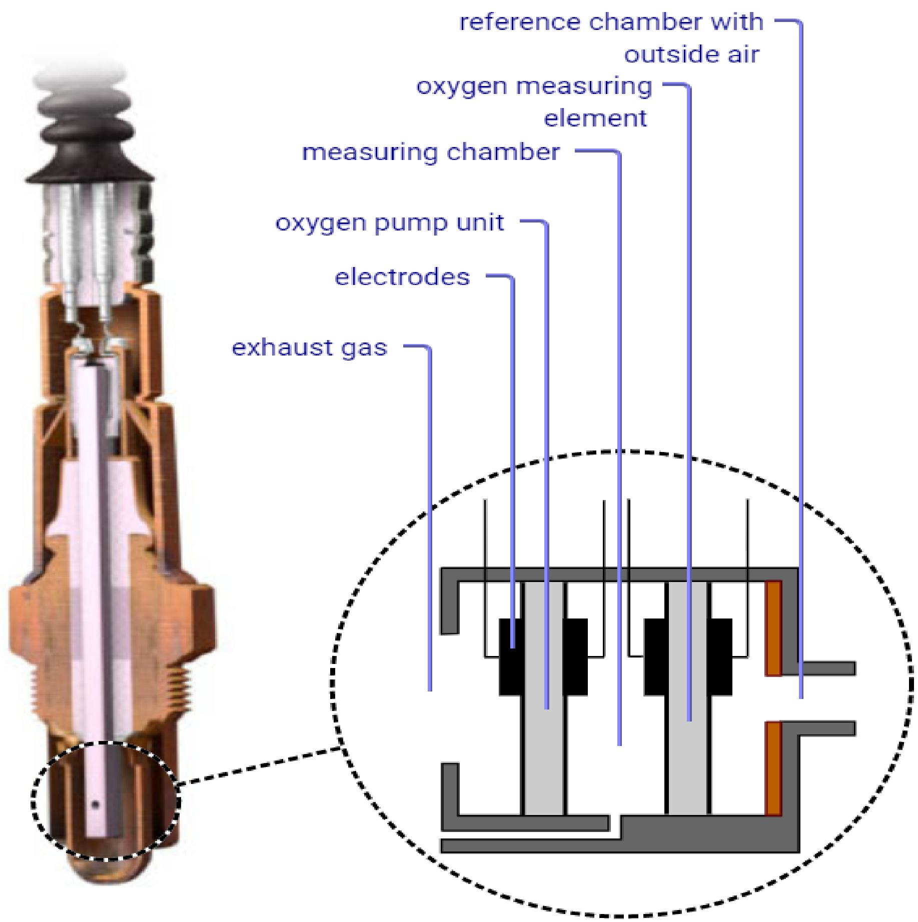


Exhaust Gas (Wideband Lambda Sensor)

Exhaust sensor needs to be heated up

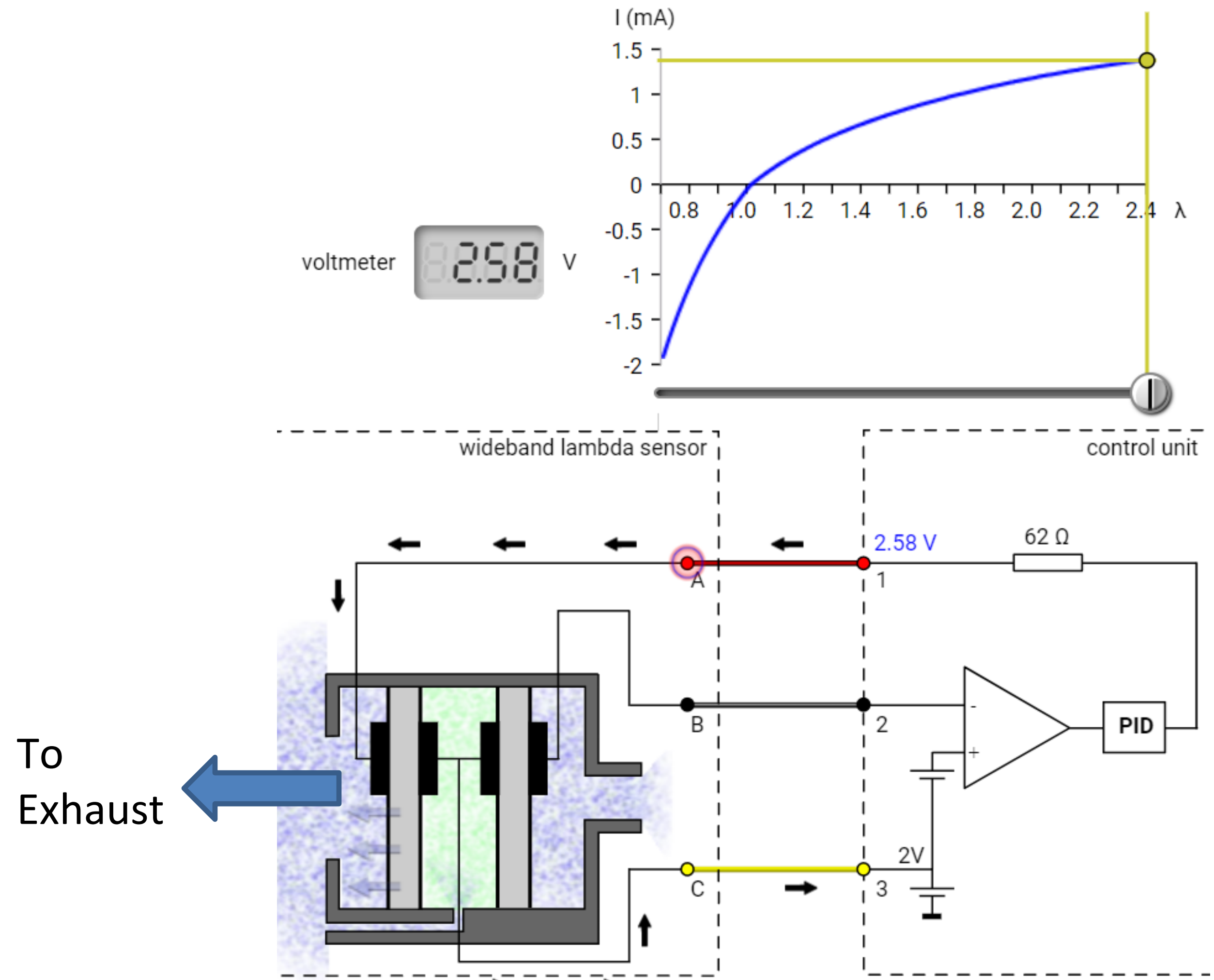


Exhaust Gas (Lambda Sensor)

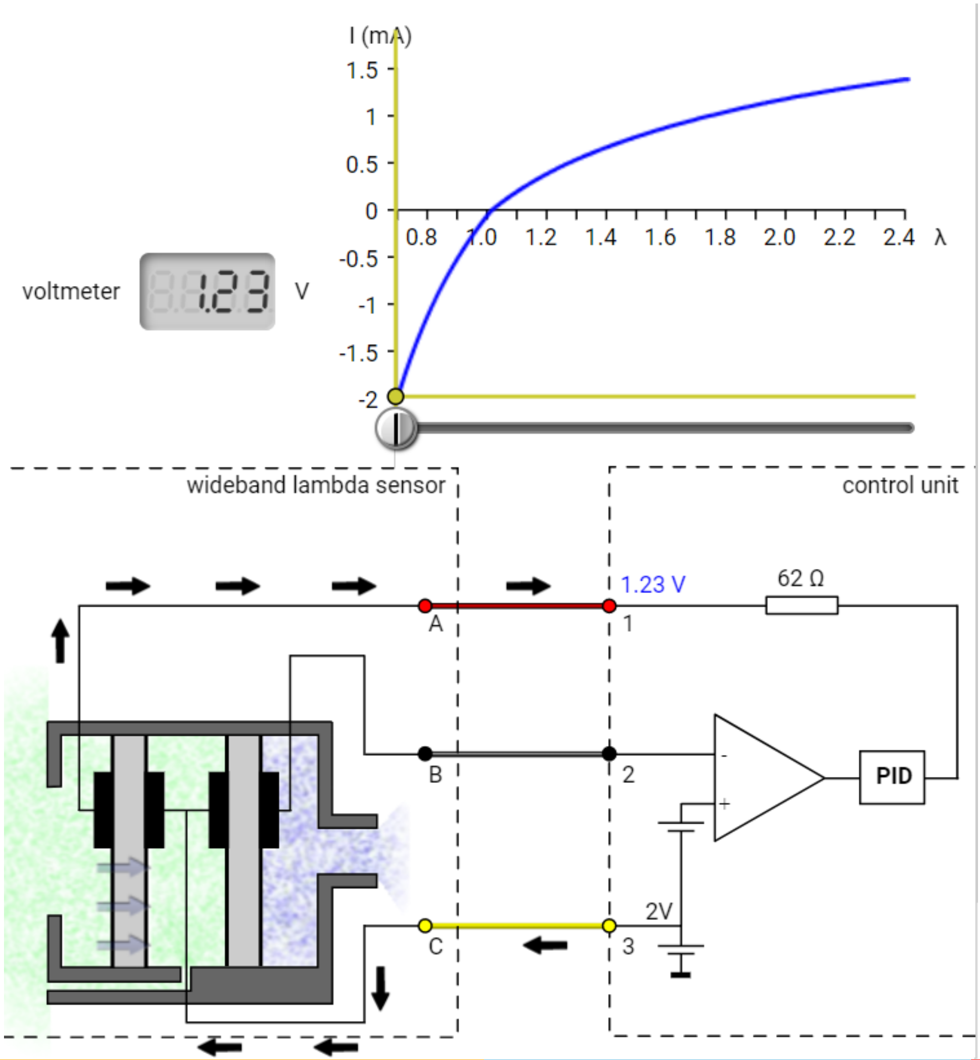


Wideband sensors have two cells: A measurement cell and a pump cell. In the measurement cell the oxygen content of the exhaust gas flow is compared to a set value of 450 mV. In the event of a deviation in this value, use is made of a pump current to pump oxygen ions into or out of the measurement chamber until a voltage value of 450 mV is obtained between the electrode on the reference air side and the measurement chamber electrode. **This pump current is the measurement quantity which almost linearly describes the exact lambda value of the mixture**. With a stoichiometric mixture it is equal to zero, as the oxygen partial pressure in the measurement chamber corresponds to the set value of 450 mV.

Lambda Sensor – Lean(λ)



Lambda Sensor – Rich(λ)



From Exhaust

NOx sensors

NOx sensors include at least two oxygen pump cells (Figure 1)—one to remove excess oxygen from the exhaust gas, and another to measure the concentration of oxygen released from the decomposition of NOx.

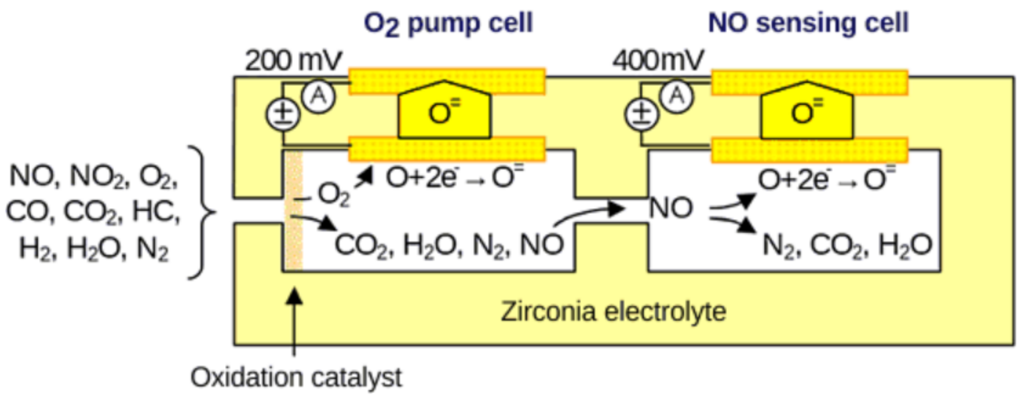


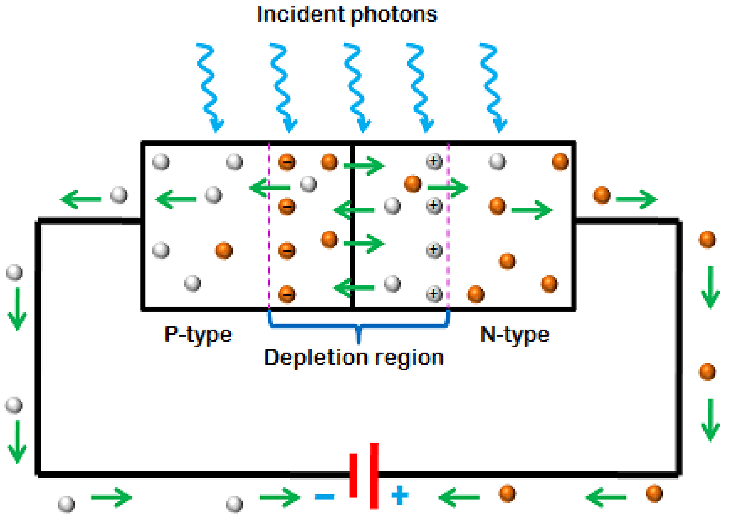
Figure 1. Schematic representation of an amperometric NOx sensor

The O_2 in the first cell is reduced and the resulting O ions are pumped through the zirconia electrolyte by applying a bias of approximately -200 mV to -400 mV. The pumping current is proportional to the O_2 concentration.

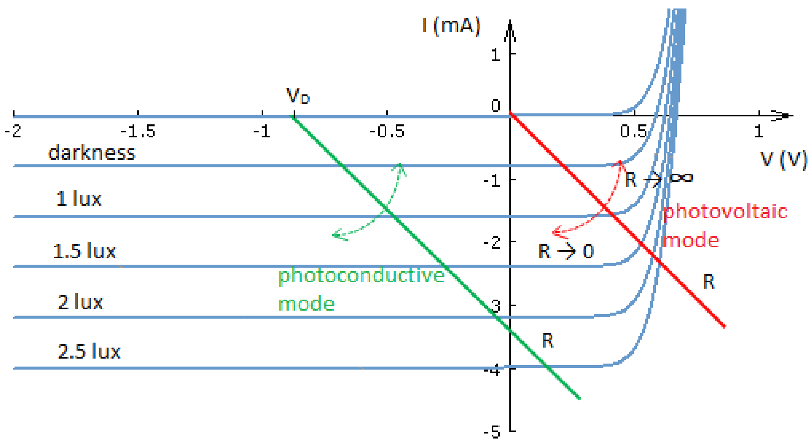
The remaining gases diffuse into the second cell where a reducing catalyst (Iridium) causes NOx to decompose into N_2 and O_2.

As with the first cell, a bias of -400 mV applied to the electrode dissociates the resulting O_2 which is then pumped out of the cell; the pumping current of the second cell is proportional to the amount of oxygen from the NOx decomposition. An additional electrochemical cell can be used as a Nernstian lambda sensor to help control the NOx sensing cell

Photodiodes



PN Junction photodiode



Without light, @ reverse bias of 3V, current could be 25µA, Resistance is 120KΩ,

With light of 25K Lumes/Sqm , the current raises to 375µA, Resistance is 8KΩ

Rain Sensor / Light Sensor

Application of the light sensor

A light sensor is also incorporated in the rain sensor, it may be used to control the low beam. This can detect the various situations (e.g. twilight, driving into and out of a tunnel, driving under long bridges) and switch the low beam on or off accordingly. The light sensor can also be used to control all the lighting functions on the vehicle. These functions include adjusting the brightness of the instrument cluster lighting, “coming home leaving home” or selectively switching on the rear lamps.

A rain sensor comprises an optical transmission and reception path (Fig. 1). An
LED (6) emits light at a determined angle into the windshield (2) which is reflected on the outer boundary layer (glass/play) (total reflection) and then is evaluated on an aligned receiver (photodiode, 4). If there is moisture on the sensitive outer surface, a part of the light is coupled out as a function of the droplet size and number, which attenuates the return signal.

1 Rain/light sensor for windshields

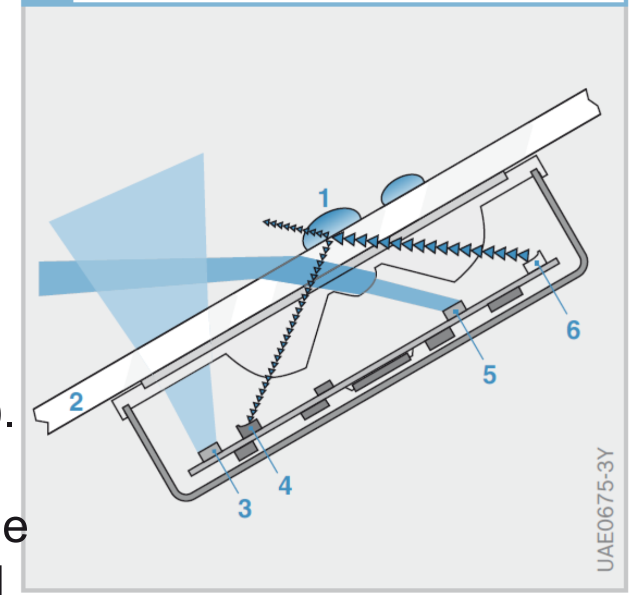


Fig. 1

1 Raindrops
2 Windshield
3 Ambient-light sensor
4 Photodiode
5 Light sensor set up for distance
6 LED

Thank you