



Unit -IV

Automotive Sensors & Actuators

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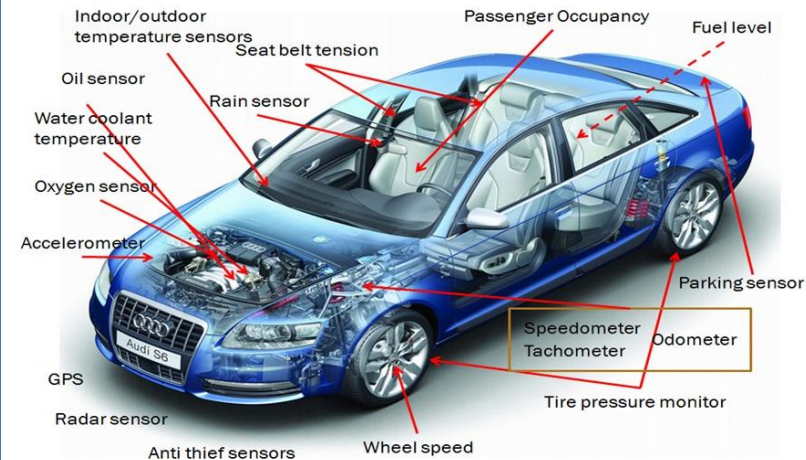


❖ Syllabus:

- Working principle of sensors, Types of sensors, Airflow rate sensor, Position sensor, Throttle angle sensor, Temperature sensor, MAP sensors, Knock/Detonation Sensor, Load cell, Lambda Sensor(Exhaust gas O₂ Sensor), yaw rate sensor, sensor feedback control, Electronic Control Unit (ECU), Principle of actuator, Types of actuators, engine control actuators, Solenoid actuators, motorized actuators (Stepper motors).

❖ Sensors:

- Sensors are the components of the system that provide the inputs that enable the computer (ECM) to carry out the operations that make the system function correctly.
- In the case of vehicle sensors it is usually a voltage that is represented by a code at the computer's processor. If this voltage is incorrect the processor will probably take it as an invalid input and record a fault.





❖ Types of Sensors used

1. Mass air flow (MAF) rate
2. Exhaust gas oxygen concentration (possibly heated)
3. Throttle plate angular position
4. Crankshaft angular position/RPM
5. Coolant temperature
6. Intake air temperature
7. Manifold absolute pressure (MAP)
8. Differential exhaust gas pressure
9. Vehicle speed
10. Transmission gear selector position



❖ **Mass air flow (MAF) rate sensor**

- Airflow sensors are used on engines with multiport electronic fuel injection. This is because the amount of fuel delivered by an EFI system is controlled by a computer (powertrain control module or PCM) which turns the fuel injectors on and off.
- The airflow sensor keeps the computer informed about how much air is being pulled into the engine past the throttle plates. This input along with information from other engine sensors allows the computer to calculate how much fuel is needed.
- The computer then increases or decreases injector duration (on time) to provide the correct air/fuel ratio.
- Types:
 1. Vane type Air Flow Rate Sensor
 2. Hot Wire type Air Flow Rate Sensor



❖ Vane type air flow (MAF) rate sensor

- An engine requires the correct air–fuel ratio to suit various conditions. With electronic fuel injection the ECM controls the air–fuel ratio and in order to do this it needs a constant flow of information about the amount of air flowing to the engine.
- With this information, and data stored in its memory, the ECM can then send out a signal to the injectors, so that they provide the correct amount of fuel.
- Air flow measurement is commonly performed by a ‘flap’-type air flow sensor. The air flow sensor shown in Figure A. uses the principle of the potential divider (potentiometer).

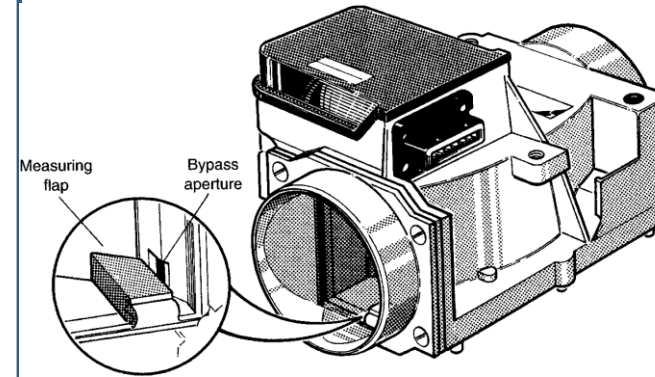


Fig. A

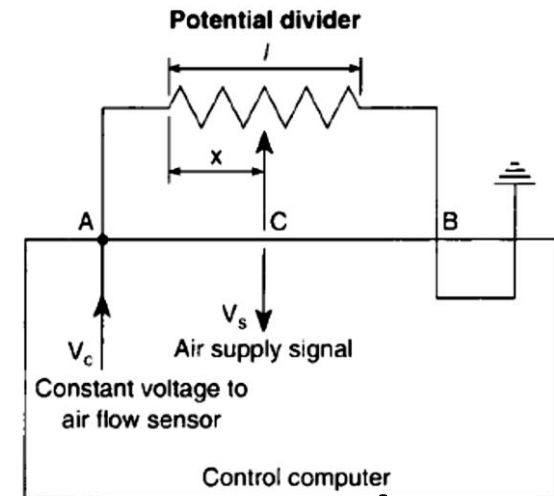


Fig. B



- Figure B. shows the theoretical form of a simple potential divider. A voltage, say 5 V, is applied across terminals A and B . C is a slider which is in contact with the resistor and a voltmeter is connected between A and C . The voltage V_{AC} is related to the position of the slider C in the form $V_{AC} = V_{AB} * x/l$.
- In the air flow sensor, the moving probe (wiper) of the potential divider is linked to the pivot of the measuring flap so that angular displacement of the measuring flap is registered as a known voltage at the potentiometer.

- Figure shows a simplified form of the air flow sensor. The closed position of the measuring flap will give a voltage of approximately zero, and when fully open the voltage will be 5 V.
- Intermediate positions will give voltages between these values. In practice, it is not quite as simple as this, because allowance must be made for other contingencies.
- A vane airflow sensor is located ahead of the throttle and monitors the volume of air entering the engine by means of a spring-loaded mechanical flap. The flap is pushed open by an amount that is proportional to the volume of air entering the engine.

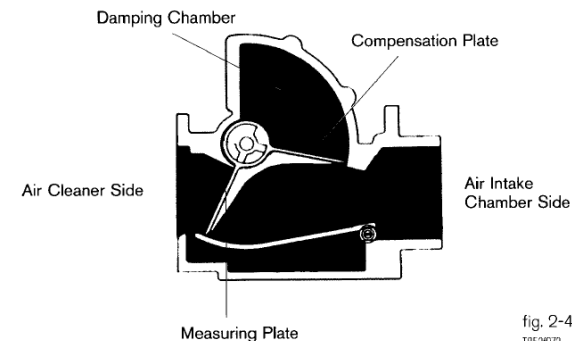
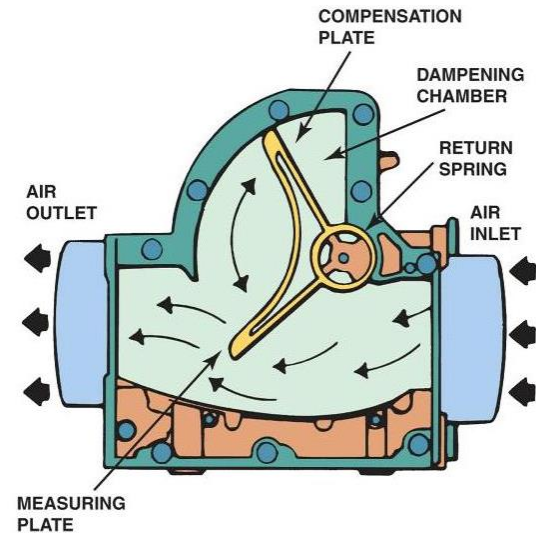


fig. 2-43
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- The flap has a wiper arm that rotates against a sealed potentiometer (variable resistor or rheostat), allowing the sensor's resistance and output voltage to change according to airflow.
- The greater the airflow, the further the flap is forced open. This lowers the potentiometer's resistance and increases the voltage return signal to the computer.
- A compensation plate acts as a shock absorber to prevent rapid movement or vibrations of the measuring plate.
- A sealed idle mixture screw is also located on the airflow sensor. This controls the amount of air that bypasses the flap, and consequently the richness or leanness of the fuel mixture.



❖ VANE AIRFLOW SENSOR PROBLEMS

- Vane airflow sensors as well as all the other types of airflow sensors **can't tolerate air leaks**. Air leaks downstream of the sensor can allow "unmetered" or "false" air to enter the engine. The extra air can lean out the fuel mixture causing a variety of driveability problems, including lean misfire, hesitation and stumbling when accelerating, and a rough idle.
- **Dirt can also cause problems**. Unfiltered air passing through a torn or poor fitting air filter can allow dirt to build up on the flap shaft of a vane airflow sensor causing the flap to bind or stick. The operation of the flap can be tested by gently pushing it open with a finger. It should open and close smoothly with even resistance. If it binds or sticks, a shot of carburetor cleaner may loosen it up otherwise the sensor will have to be replaced.



- **Backfiring in the intake manifold** can force the flap backwards violently, **often bending or breaking the flap**. Some sensors have a "backfire" valve built into the flap to protect the flap in case of a backfire by venting the explosion. But the anti-backfire valve itself can become a source of trouble if it leaks. A leaky backfire valve will cause the sensor to read low and the engine to run rich.

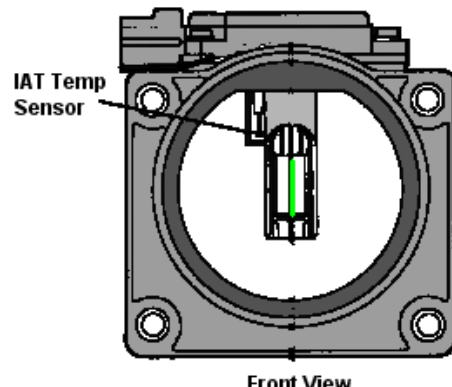
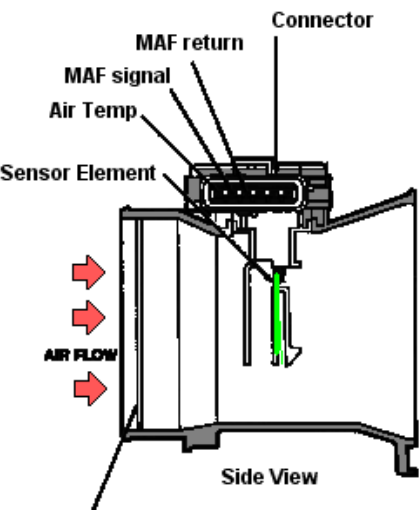
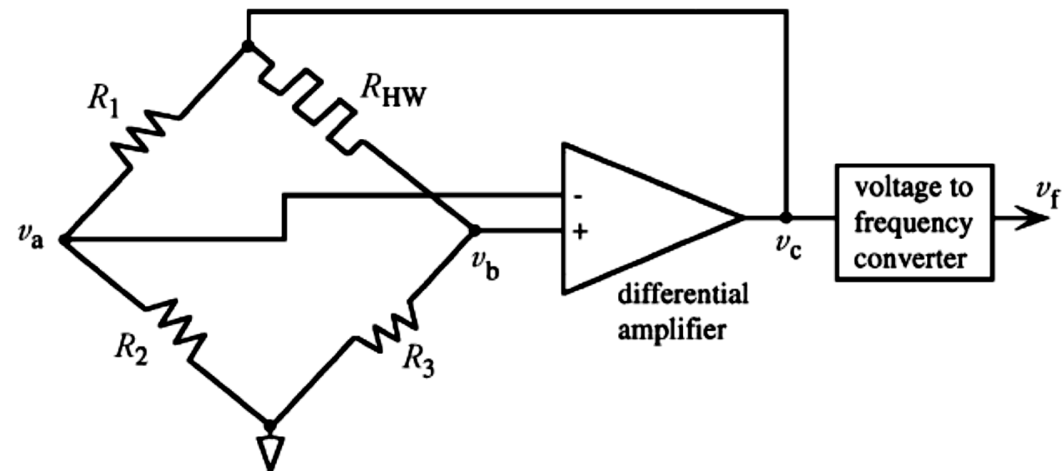


❖ Hot Wire Type MAF:

- The hot wire MAF sensor is a variation of a classic air flow sensor that was known as a hot wire anemometer and was used, for example, to measure wind velocity for weather forecasting.
- In this MAF, the hot-wire, or sensing, element is replaced by a hot-film structure mounted on a substrate.
- On the air inlet side is mounted a honeycomb flow straightener that “smooths” the air flow (causing nominally laminar air flow over the film element). At the lower portion of the structure is the signal processing circuitry.



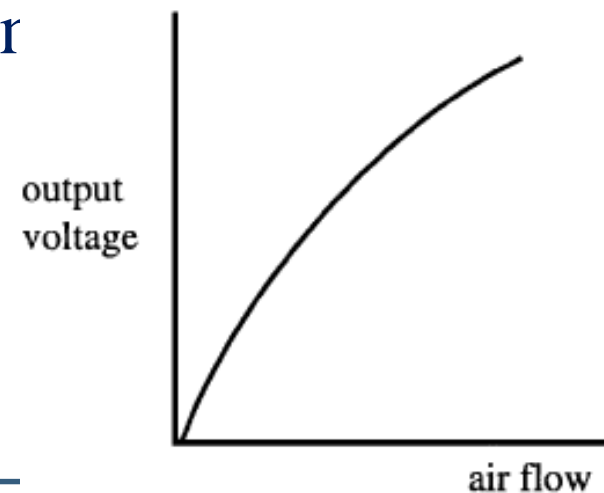
- The film element is electrically heated to a constant temperature above that of the inlet air.
- The hot-film element is incorporated in a Wheatstone bridge circuit (Figure at top).
- The power supply for the bridge circuit comes from an amplifier.





- The Wheatstone bridge consists of three fixed resistors R_1 , R_2 , and R_3 and a hot-film element having resistance R_{HW} . With no air flow the resistors R_1 , R_2 , and R_3 are chosen such that voltage v_a and v_b are equal (i.e., the bridge is said to be balanced).
- As air flows across the hot film, heat is carried away from the film by the moving air. The amount of heat carried away varies in **proportion to the mass flow rate of the air**.
- The heat lost by the film to the air tends to cause the resistance of the film to vary, which unbalances the bridge circuit, thereby producing an input voltage to the amplifier.
- The output of the amplifier is connected to the bridge circuit and provides the power for this circuit. The amplified voltage changes the resistance in such a way as to maintain a fixed hot-film temperature relative to the inlet temperature.

- The amplifier output voltage v_c varies with MAF and serves as a measure of (Mass flow rate of air) R_m . Typically the conversion of MAF to voltage is slightly nonlinear, as indicated by the calibration curve depicted in Figure.
- Fortunately, a modern digital engine controller can convert the analog bridge output voltage directly to mass air flow by simple computation





- Hot Wire MAF sensors have no moving parts. Unlike a vane airflow meter that uses a spring-loaded flap, mass airflow sensors use electrical current to measure airflow.
- The sensing element, which is either a **platinum wire (hot wire) or nickel foil grid (hot film)**, is heated electrically to keep it a certain number of degrees hotter than the incoming air.
- In the case of **hot film MAFs, the grid is heated to 75°C** above incoming ambient air temperature. With the **hot wire sensors, the wire is heated to 100 °C** above ambient temperature.
- As air flows past the sensing element, it cools the element and increases the current needed to keep the element hot. Because the cooling effect varies directly with the temperature, density and humidity of the incoming air, the amount of current needed to keep the element hot is **directly proportional to the air "mass" entering the engine**



❖ **Positions Sensors:**

- The positions sensors are generally speed sensors of different working principle used for detecting the position of different parameters.
- Parameters Measured,
 1. Crankshaft Position Sensor
 2. Camshaft Position Sensor
 3. ABS Wheel Sensors
 4. Vehicle Speed Sensor
- Working Principles used,
 1. Magnetic Reluctance (Variable Reluctance) type
 2. Hall Effect type
 3. Optical Type



❖ **Crankshaft Position Sensor:**

- A **crank position sensor** is a component used in an internal combustion engine to monitor the position or rotational speed of the crankshaft. This information is used by engine management systems to control ignition system timing and other engine parameters.

❖ Magnetic Reluctance (or Variable Reluctance) type sensor

- This type of sensor is used in many vehicle applications, such as ignition systems, engine speed sensors for fuelling, and wheel speed sensors for anti-lock braking etc.
- Air has a greater reluctance (resistance to magnetism) than iron and this fact is made use of in many sensors. The basic principle of operation of a variable reluctance type sensor (Fig. 5.1) may be understood from the following description.
- The principal elements of the sensor are:
 - an iron rotor with lobes on it;
 - a permanent magnet;
 - a metallic path (the pole piece) for carrying the magnetic flux;
 - a coil, wound around the metallic path, in which a voltage is induced.

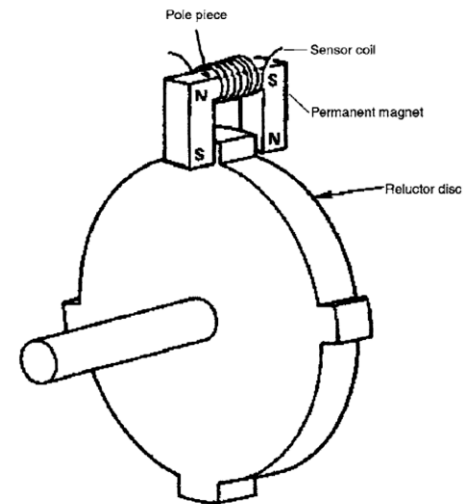


Fig. 5.1 The basic principle of the variable reluctance sensor



- The reluctor disc has a number of tabs on it and these tabs are made to move through the air gap in the magnetic circuit.
- The movement of the reluctor tabs, through the air gap is achieved by rotation of the reluctor shaft. The voltage induced in the sensor coil is related to the rate of change of magnetic flux in the magnetic circuit.
- The faster the rate of change of magnetic flux the larger will be the voltage that is generated in the sensor coil. When the metal tab on the reluctor rotor is outside the air gap, the sensor voltage is zero.
- As the tab moves into the air gap the flow of magnetism (flux) increases rapidly. This causes the sensor voltage to increase, quite quickly, to a maximum positive value. Figure 5.2 shows the approximate behavior of the voltage output as the reluctor is rotated.

- Figure 5.2(a) shows the reluctor tab moving into the air gap. As the metal tab moves further into the gap the voltage begins to fall and, when the metal tab is exactly aligned with the pole piece, the sensor voltage falls back to zero (Although the magnetic flux is strongest at this point, it is not changing and this means that the voltage is zero.)

- Figure 5.2(b) shows that there is zero voltage when the reluctor tab is in alignment with the pole piece.

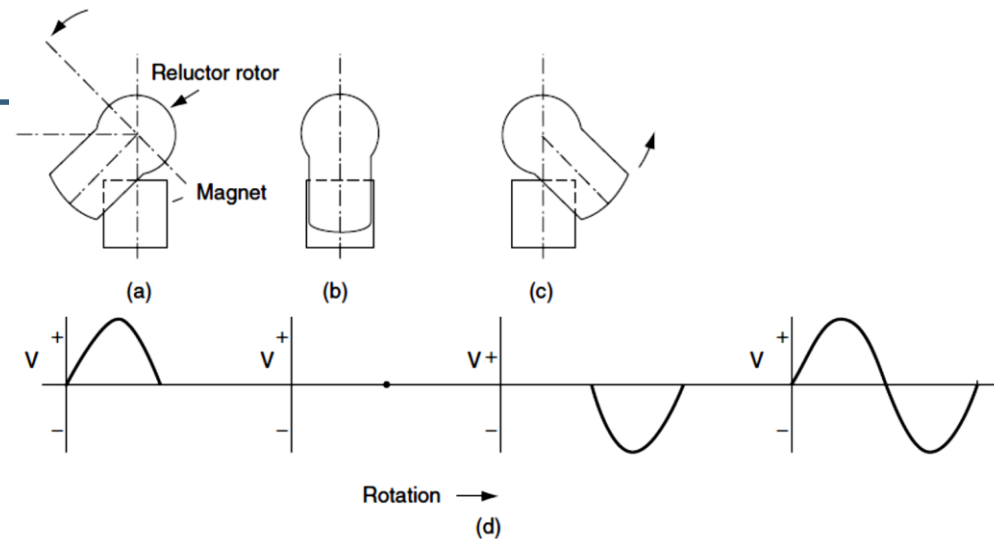


Fig. 5.2 The voltage pattern from a variable reluctance sensor



- As the metal tab continues to rotate out of the air gap and away from the pole piece, the rate of change of the magnetic flux is rapid, but opposite in direction to when the tab was moving into the air gap.
- This results in the negative half of the voltage waveform as shown in Fig. 5.2(c). When the tab has moved out of the air gap the sensor voltage returns to zero. While the rotor shaft continues to turn another tab will enter the air gap and the above process will be repeated.
- If the sensor coil is connected to an oscilloscope the pattern observed will be similar to that shown in Fig. 5.2(d).

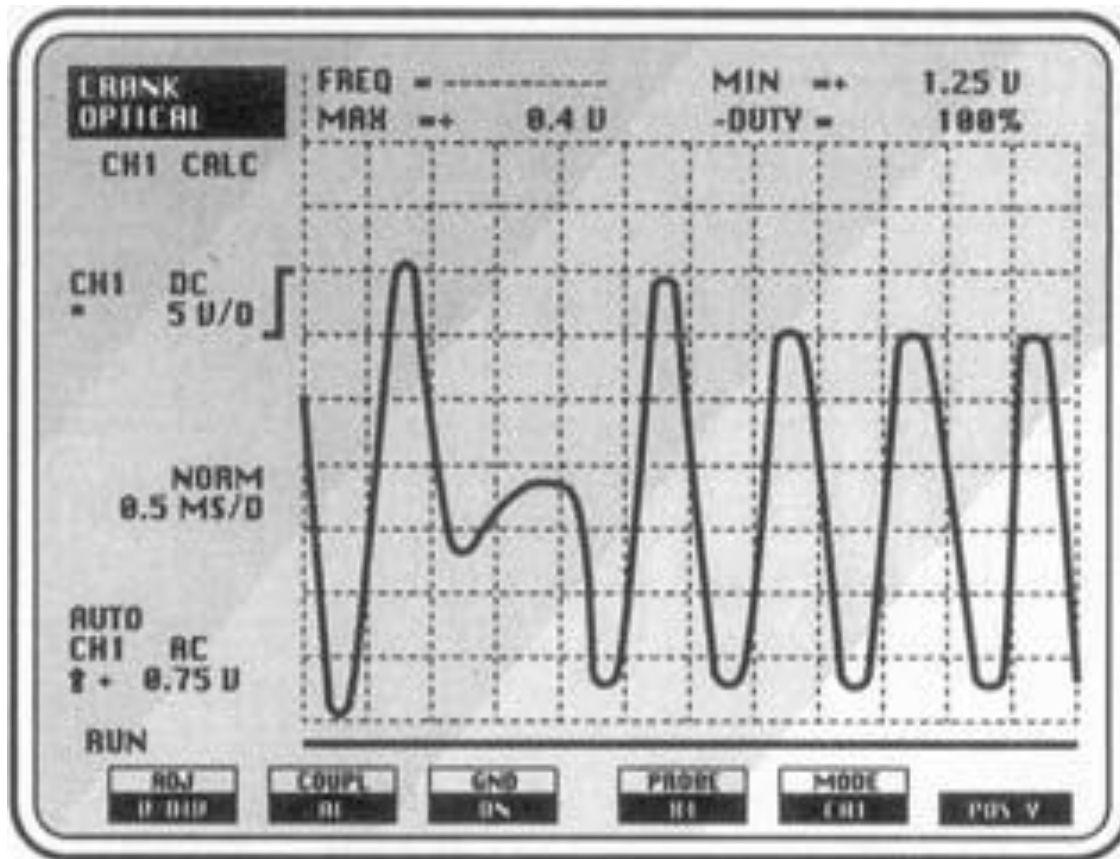
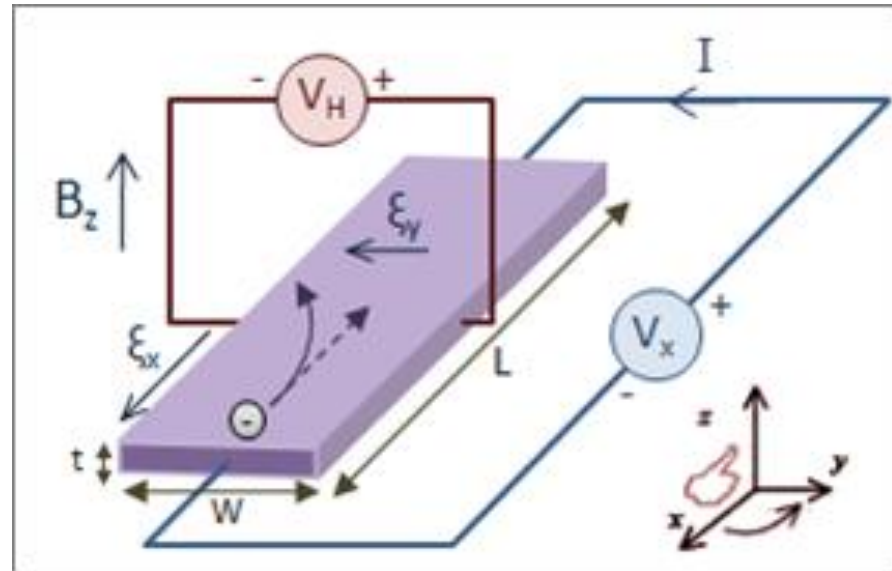


Fig. 5.4 A crank sensor voltage pattern

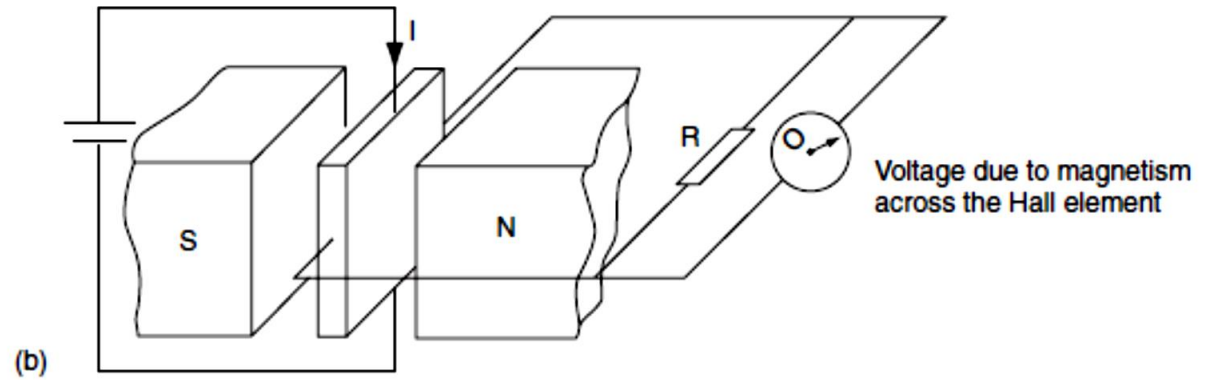
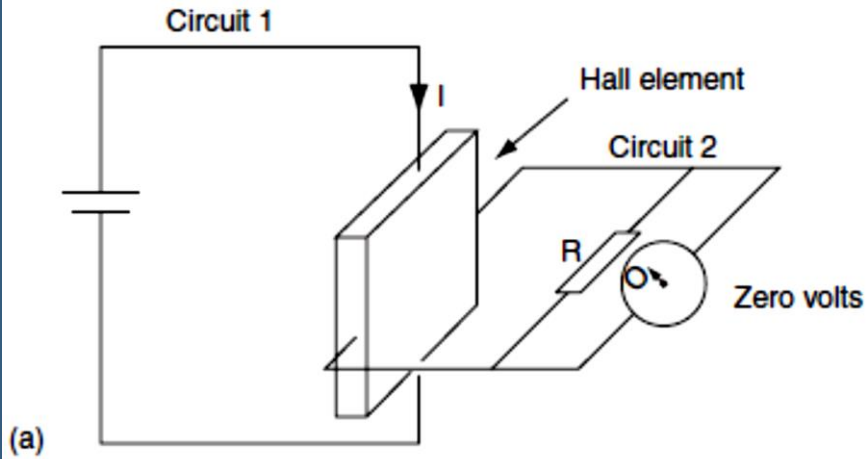
❖ Hall Effect:

- The **Hall effect** is the production of a **voltage difference** (the **Hall voltage**) across an electrical conductor, transverse to an electric current in the conductor and to an applied **magnetic field perpendicular** to the current. It was discovered by Edwin **Hall** in 1879.

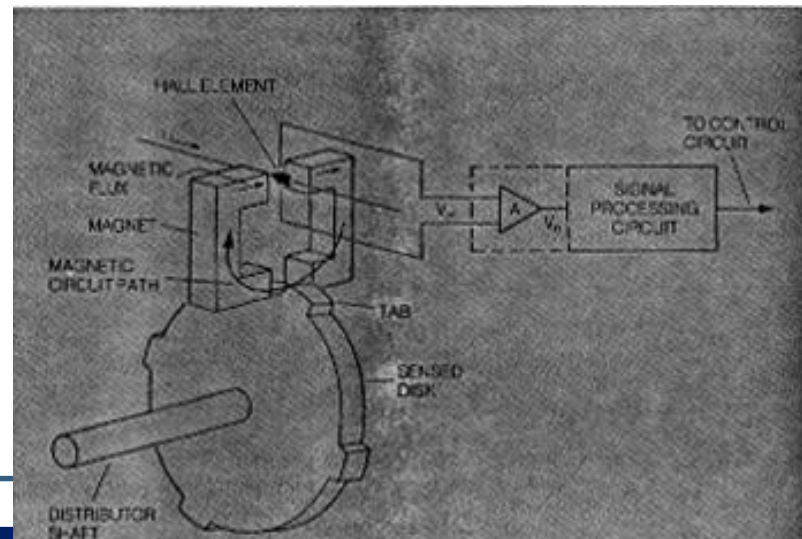


2. Hall Effect type sensor:

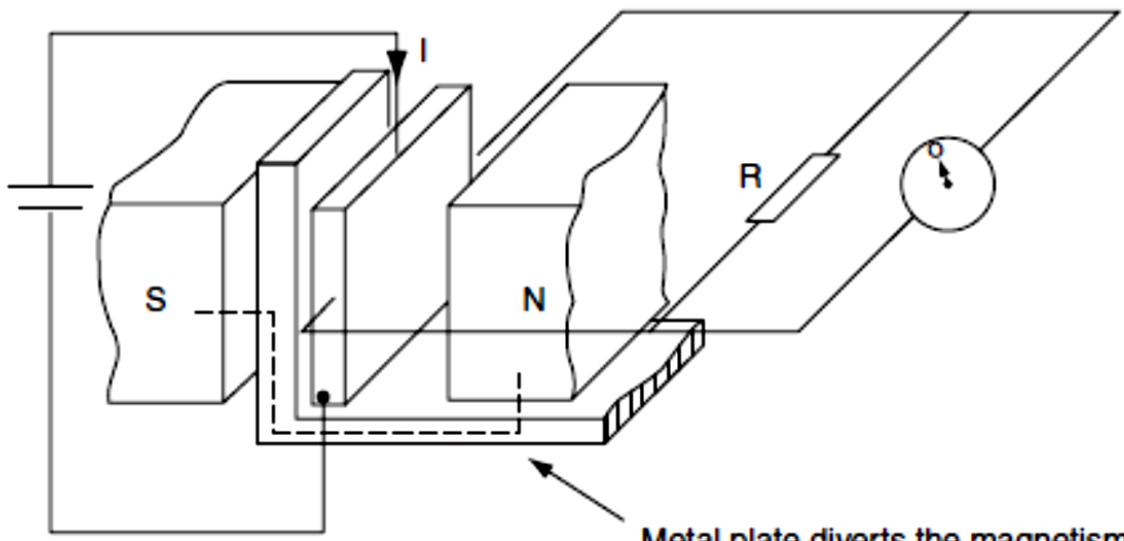
- Figure shows the principle of a Hall type sensor. The Hall element is a small section of semiconductor material such as silicon.
- When connected as shown in Fig.(a), the battery will cause current to flow through the semiconductor Hall element and battery circuit, but there will be no current in the circuit which is at right angles to the battery circuit, as shown by a zero reading on the voltmeter.



- When a magnetic field is imposed on the Hall element, as shown in Fig. (b), a current will flow in circuit 2.
- When the magnetic effect is prevented from reaching the Hall element, as in Fig.(c), the current will cease to flow in circuit 2.
- The result is that the current in circuit 2 can be switched on and off by shielding the Hall element from the magnetic field.

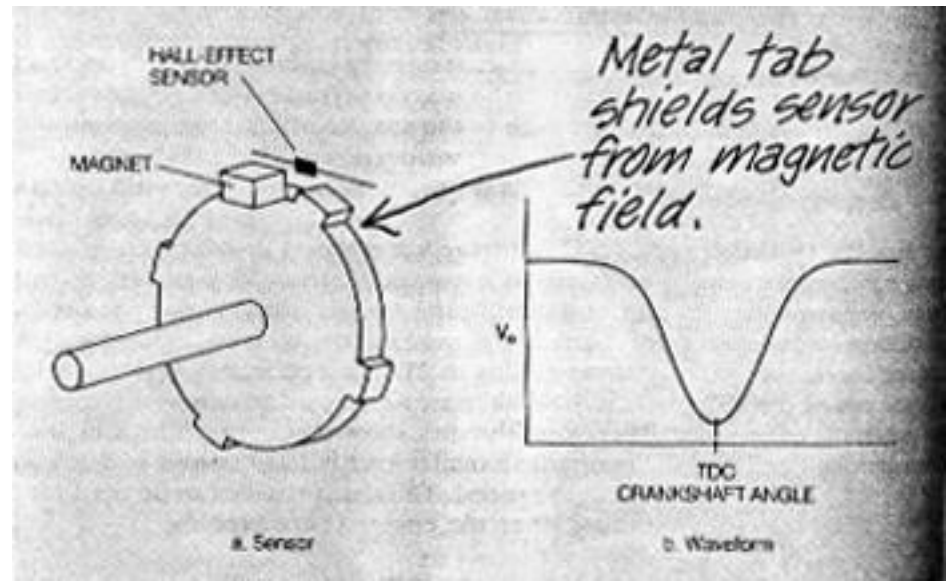


(c)



Zero volts, because magnetism is removed from the Hall element

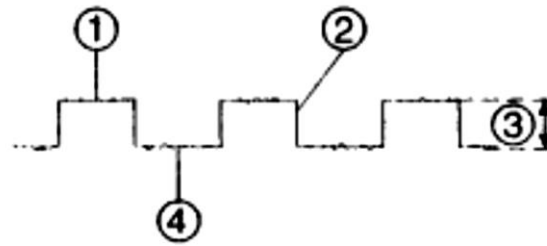
Metal plate diverts the magnetism away from the Hall element





- When the metal plate that is inserted between the magnet and the Hall element is mounted on a rotating shaft, the Hall current can be switched on and off at any desired frequency.
- The Hall type sensor produces an output power that is virtually constant at all speeds.
- Hall effect sensors are used wherever other electromagnetic sensors are used, e.g. engine speed and crank position, ABS wheel sensors, camshaft (cylinder) identification (for ignition and fuelling) etc.

- The voltage from a Hall element is quite small and it is common practice for Hall type sensors to incorporate an amplifying and pulse-shaping circuit. The result is that the sensor produces a digital signal, i.e. it is a rectangular waveform as shown in Fig. 5.7.



- 1 The upper horizontal lines should reach reference voltage.
- 2 Voltage transitions should be straight and vertical.
- 3 **Peak-Peak** voltages should equal reference voltage.
- 4 The lower horizontal lines should almost reach ground.

The duty cycle of the signal remains fixed, determined by the spacing between shutter blades.

Frequency of the signal increases as the speed of the engine increases.

Fig. 5.7 A Hall sensor output signal

❖ Optical Sensor:

- In a sufficiently clean environment a shaft position can also be sensed using optical techniques. Figure below illustrates such a system. Again, as with the magnetic system, a disk is directly coupled to the crankshaft.
- This time, the disk has holes in it that correspond to the number of tabs on the disks of the magnetic systems.
- Mounted on each side of the disk are fiber-optic light pipes. The hole in the disk allows transmission of light through the light pipes from the light-emitting diode (LED) source to the phototransistor used as a light sensor.
- **Light would not be transmitted from source to sensor when there is no hole because the solid disk blocks the light.**



- As shown in Figure below, the pulse of **light is detected by the phototransistor** and coupled to an amplifier to obtain a satisfactory signal level. The output pulse level can very easily be standard transistor logic levels of +2.4 V for the high level and +0.8 V for the low level.
- One of the **problems with optical sensors is that they must be protected from dirt and oil; otherwise, they will not work properly.**
- They have the advantages that they can sense position without the engine running and that the pulse amplitude is constant with variation in speed.

Rotation of disk causes alternate blocking and transmission of light.

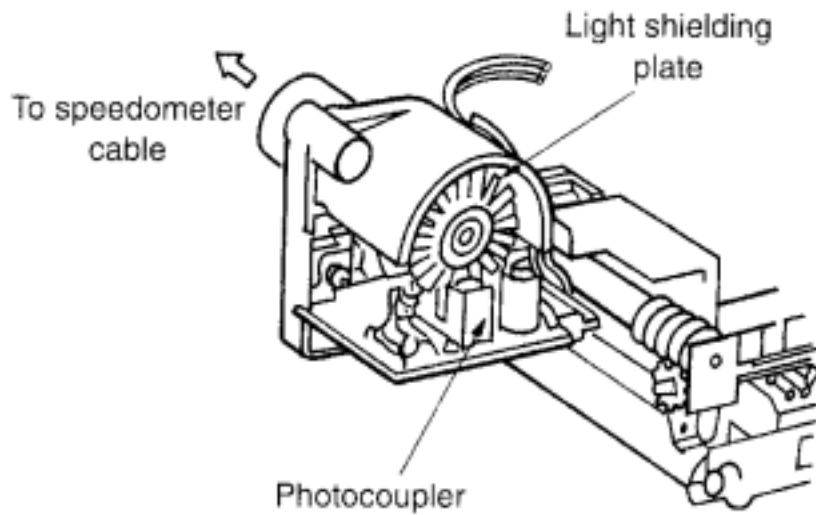
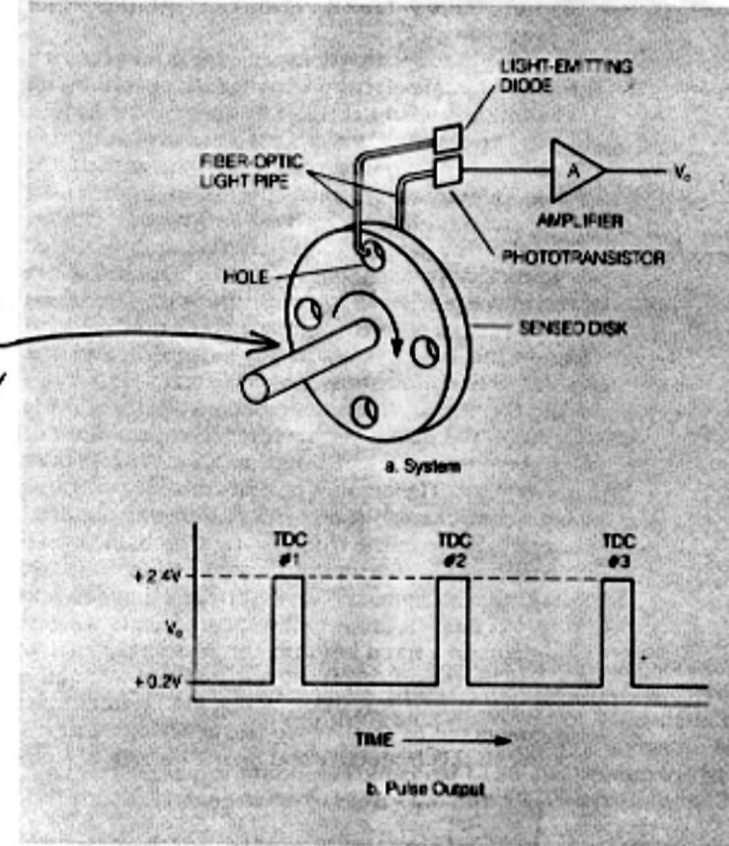
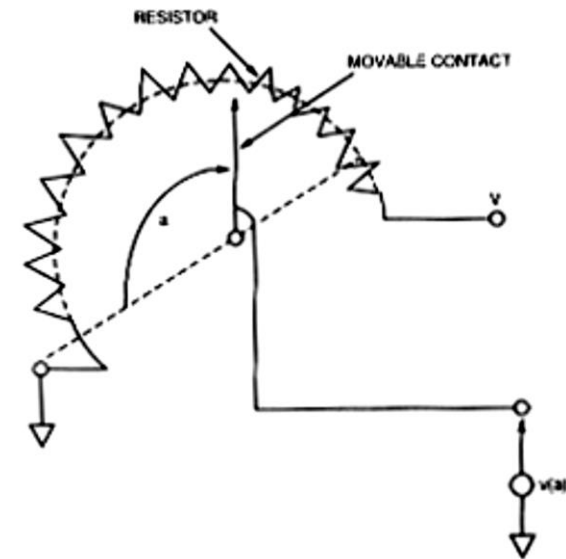


Fig. 5.8 An optoelectronic sensor

❖ Throttle Position Sensor:

- When an engine is idling the exhaust gas scavenging of the cylinders is poor. This has the effect of diluting the incoming mixture.
- The ECU must detect when the throttle is in the idling position, so that alteration of the air–fuel ratio can occur to ensure that the engine continues to run smoothly.
- At full engine load and full throttle, the mixture (air–fuel ratio) needs enriching, so the ECU also needs a signal to show that the throttle is fully open.



- These duties are performed by the throttle position switch. Figure 5.12 shows how the action of a throttle position sensor is based on the principle of the potential divider.
- The sensor produces a voltage which is related to throttle position. The voltage signal is conducted to the ECU where it is used, in conjunction with other inputs, to determine the correct fuelling for a given condition.

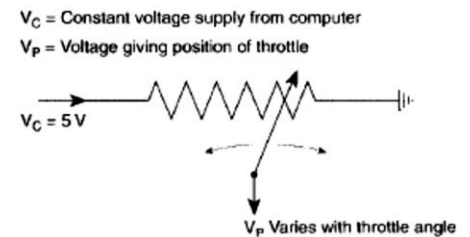
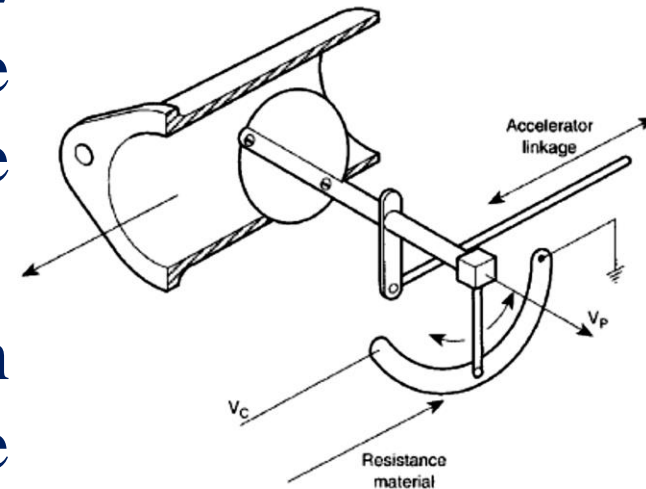


Fig. 5.12 The principle of the throttle position sensor



❖ Thermistor:

- Thermistors are of two opposite fundamental types:
- With **NTC** thermistors, resistance *decreases* as temperature rises. An NTC is commonly used as a temperature sensor, or in series with a circuit as an inrush current limiter.
- With **PTC** thermistors, resistance *increases* as temperature rises. PTC thermistors are commonly installed in series with a circuit, and used to protect against *overcurrent* conditions, as resettable fuses
- Thermistors differ from resistance temperature detectors (RTDs) in that the material used in a thermistor is generally **a ceramic or polymer**, while RTDs use pure metals. The temperature response is also different; RTDs are useful over larger temperature ranges, while thermistors typically achieve a greater precision within a limited temperature range, **typically $-90\text{ }^{\circ}\text{C}$ to $130\text{ }^{\circ}\text{C}$**

❖ Temperature sensor

- A commonly used device used for sensing temperature is **the thermistor**. A thermistor utilizes the concept of **negative temperature coefficient**.
- Most electrical conductors have a **positive temperature coefficient**. This means that the **hotter the conductor gets the higher is its electrical resistance**.
- This thermistor operates differently; its **resistance gets lower as its temperature increases and this is a characteristic of semiconductor materials**.

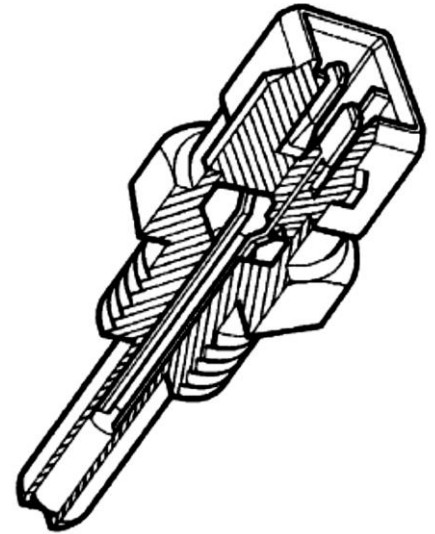


Fig. 5.17 An engine coolant temperature sensor

- There is a well-defined relationship between temperature and resistance.
- This means that current flow through the thermistor can be used to give an accurate representation of temperature.
- Figure shows the approximate relationship between temperature and resistance.
- The coolant temperature sensor provides the ECU with information about engine temperature and thus allows the ECU to make alterations to fuelling for cold starts and warm-up enrichment.

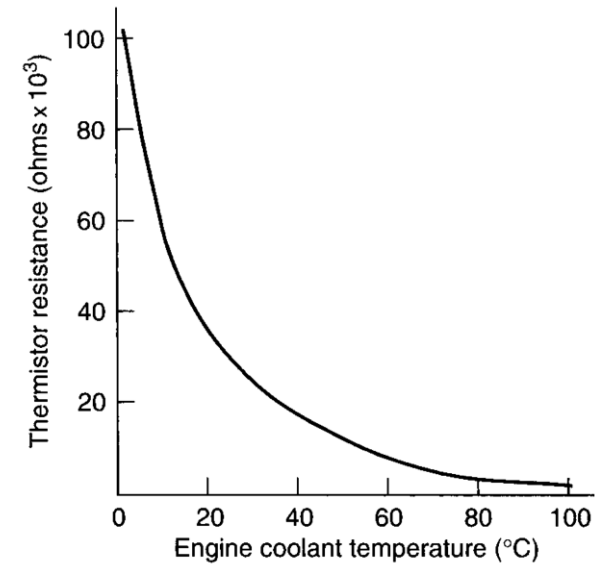


Table 5.1 Temperature and corresponding resistance for a coolant sensor

Temperature (°C)	Resistance (ohms)	Voltage
0	6000	4.5
20	2500	3.2
30	1400	3.1
60	800	2.4
80	280	1.2

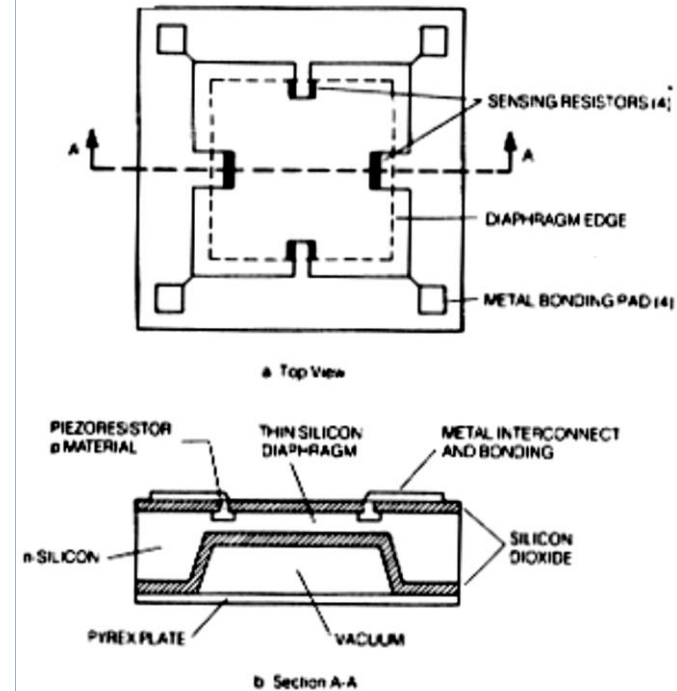


❖ **Manifold Absolute Pressure (MAP) Sensor:**

- Several MAP sensor configurations have been used in automotive applications.
- The earliest sensors were derived from aerospace instrumentation concepts, but these proved more expensive than desirable for automotive applications and have been replaced with more cost-effective designs.
- It is interesting to note that none of the MAP sensors in use measure manifold pressure directly, but instead measure the displacement of a diaphragm that is deflected by manifold pressure.
- The details of the diaphragm displacement and the measurement of this displacement vary from one configuration to another.

❖ Strain Gauge MAP Sensor

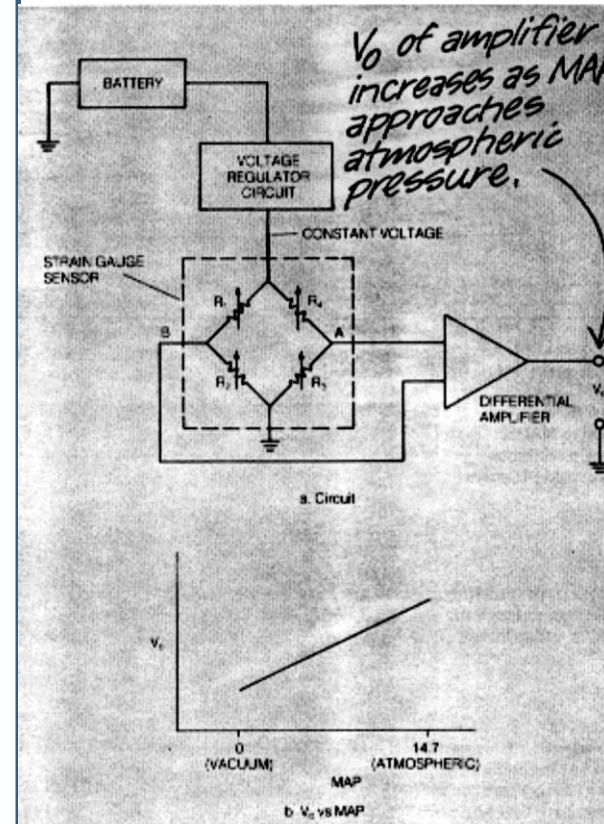
- One relatively inexpensive MAP sensor configuration is the silicon diaphragm diffused strain gauge sensor shown in Figure.
- This sensor uses a silicon chip that is approximately 3 millimeters square. Along the outer edges, the chip is approximately 250 micrometers (1 micrometer = 1 millionth of a meter) thick, but the center area is only 25 micrometers thick and forms a diaphragm.
- The edge of the chip is sealed to a pyrex plate under vacuum, thereby forming a vacuum chamber between the plate and the center area of the silicon chip.





- A set of sensing resistors is formed around the edge of this chamber, as indicated in Figure. The resistors are formed by diffusing a doping impurity into the silicon.
- External connections to these resistors are made through wires connected to the metal bonding pads. This entire assembly is placed in a sealed housing that is connected to the intake manifold by a small-diameter tube.
- Manifold pressure applied to the diaphragm causes it to deflect.
- The resistance of the sensing resistors changes in proportion to the applied manifold pressure by a phenomenon that is known as **piezoresistivity**.
- Piezoresistivity occurs in certain semiconductors so that the actual resistivity (a property of the material) changes in proportion to the strain (fractional change in length).

- The strain induced in each resistor is proportional to the diaphragm deflection, which, in turn, is proportional to the pressure on the outside surface of the diaphragm. This pressure is the manifold pressure.
- An electrical signal that is proportional to the manifold pressure is obtained by connecting the resistors in a circuit called a Wheatstone bridge, as shown in the schematic of Figure a.
- The voltage regulator holds a constant dc voltage across the bridge.





- The resistors diffused into the diaphragm are denoted R_1 , R_2 , R_3 , and R_4 in Figure a.
- When there is no strain on the diaphragm, all four resistances are equal, the bridge is balanced, and the voltage between points A and B is zero. When manifold pressure changes, it causes these resistances to change in such a way that **R_1 and R_3 increase by an amount that is proportional to pressure; at the same time, R_2 and R_4 decrease by an identical amount.**
- This unbalances the bridge and a net difference voltage is present between points A and B. The differential amplifier generates an output voltage proportional to the difference between the two input voltages (which is, in turn, proportional to the pressure), as shown in Figure b.

❖ Variable-Capacitance type MAP Sensor

- Figure below gives an indication of the principle of operation of the variable capacitance type of MAP sensor.
- Capacitance $C = e_o A/d$, where e_o = permittivity in a vacuum, A = area of the metallized plates and d = the distance between the plates.
- The metallized plates of the capacitor are placed on each side of an evacuated capsule.
- This capsule is placed in a chamber which is connected to manifold pressure and, as the manifold pressure changes, the distance d between the capacitor plates changes.
- This change in distance between the capacitor plates causes the value of the capacitance C to change. The capacitor is connected into an electronic circuit that converts changes in capacitance into an electrical signal.

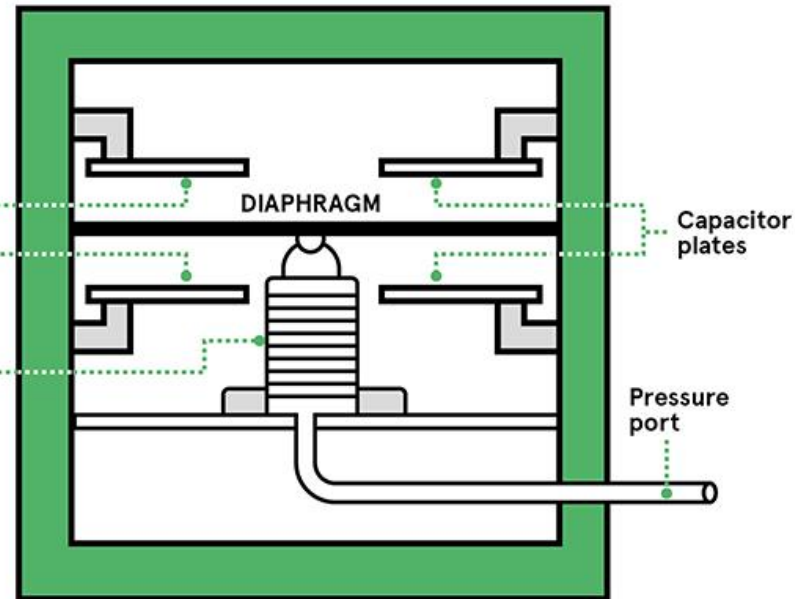
Manifold pressure chamber. This forms part of the sensor body

Metallised area in quartz diaphragm that makes the capacitor plates. One on each side of the capsule

Electronic circuit that converts MAP into electrical signal of varying frequency

Connection to induction manifold

Flexible walls to evacuated capsule. This allows the capacitor plates to move closer together or further apart with changes in MAP





❖ **Variable-Inductance type MAP Sensor:**

- The variable-inductance type of MAP sensor relies on the principle that the inductance of a coil is altered by varying the position of an iron cylinder placed in the center of the coil. Figure illustrates the principle involved.
- In this simplified version, the iron cylinder moves in or out of the coil under the influence of the diaphragm and spring.

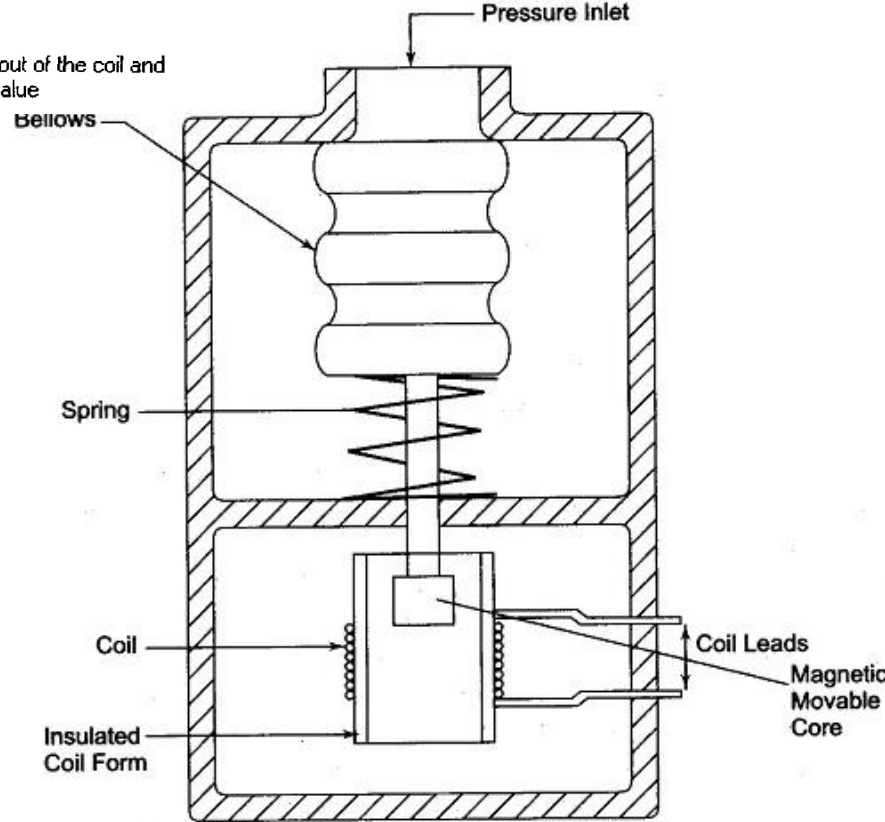
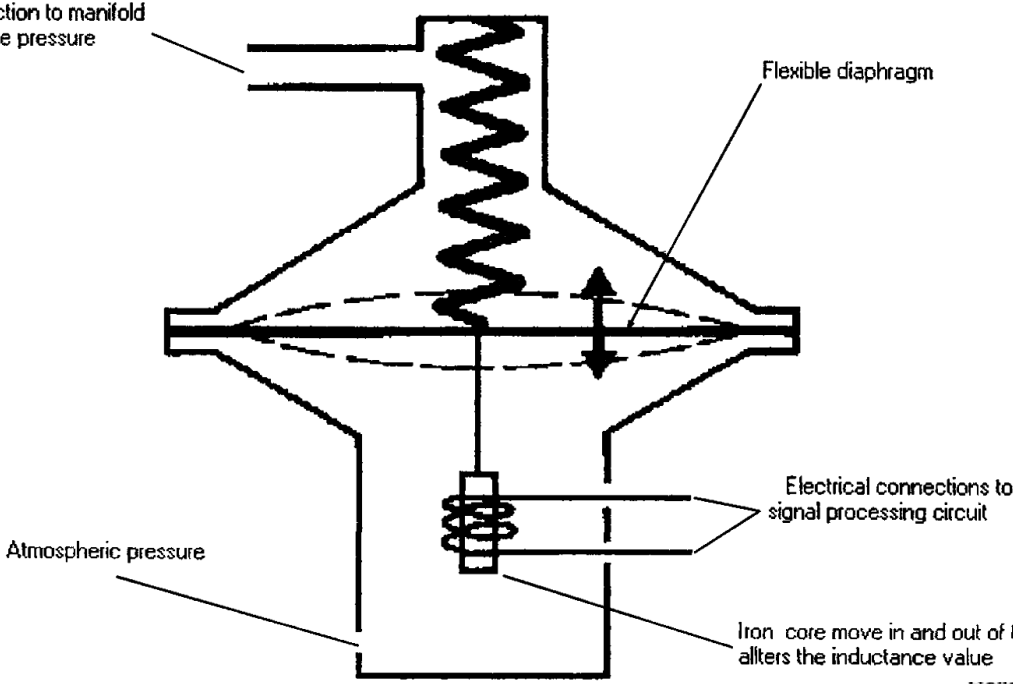


Fig. 13.22 Pressure Inductive Transducer

- Variations in manifold absolute pressure increase or decrease the 'suction' force acting on the diaphragm and the resultant changes in inductance are related to the manifold absolute pressure.
- The coil (inductance) forms part of an electronic circuit and this circuit is designed so that the changes in frequency of the square-wave output are accurate representations of manifold absolute pressure. Figure shows the approximate form of the variable frequency output of sensors of this type.

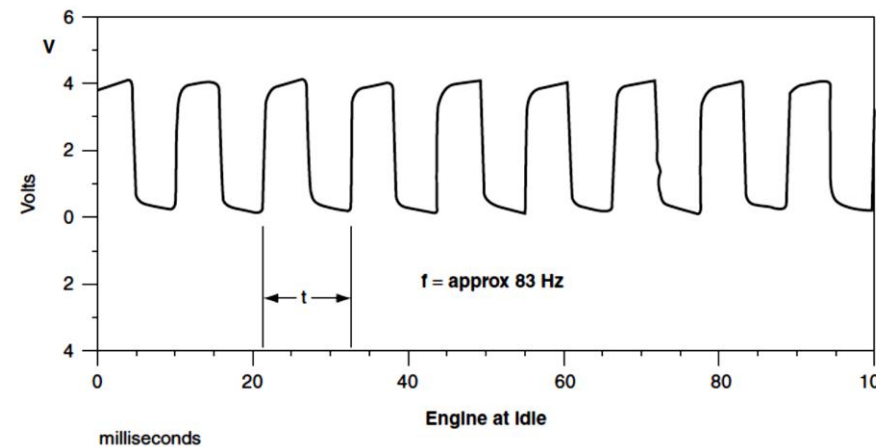
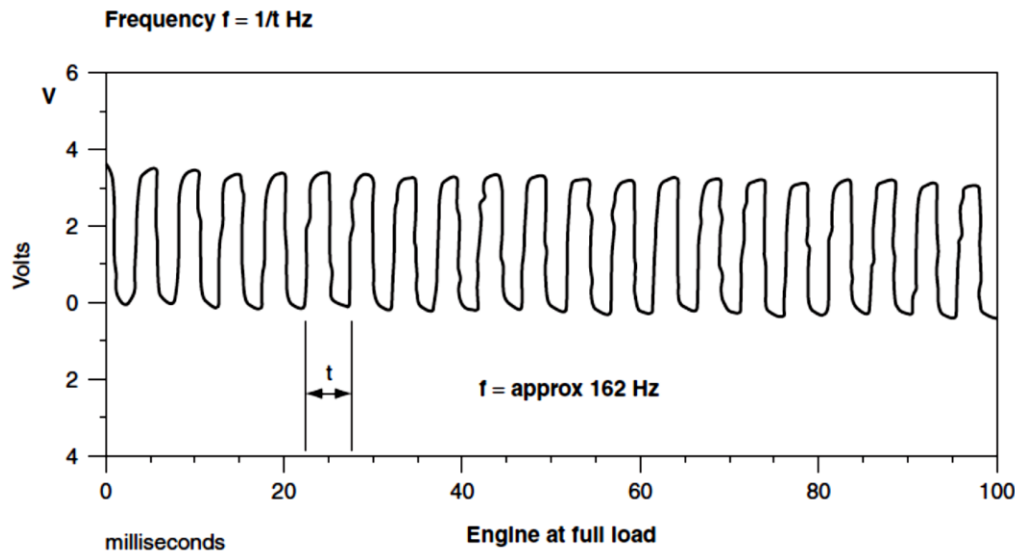


Fig. 5.25 Frequency patterns for a MAP sensor at full load and idle

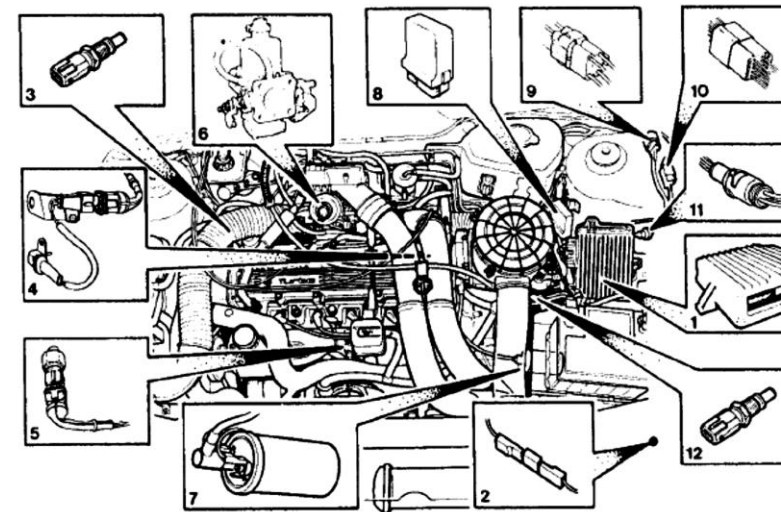


❖ **Knock Sensor:**

- A knock sensor that is commonly used in engine control systems utilizes the piezoelectric generator effect, i.e. the sensing element produces a small electric charge when it is compressed and then relaxed.
- Materials such as quartz and some ceramics like PZT (a mixture of platinum, zirconium and titanium) are effective in piezoelectric applications.
- In the application shown, the knock sensor is located on the engine block adjacent to cylinder number 3 (Fig. 5.10). This is the best position to detect vibrations arising from combustion knock in any of the four cylinders.
- Because combustion knock is most likely to occur close to TDC in any cylinder, the control program held in the ECM memory enables the processor to use any knock signal generated to alter the ignition timing by an amount that is sufficient to eliminate the knock.

- When knock has ceased the ECM will advance the ignition, in steps, back to its normal setting. The mechanism by which vibrations arising from knock are converted to electricity is illustrated in Fig. 5.11.

- The sensor is accurately designed and the center bolt that pre-tensions the piezoelectric crystal is accurately torqued. The steel washer that makes up the seismic mass has very precise dimensions.



- | | | |
|---|----------------------------------|--------------------------------|
| 1. ERIC ECU | 5. Knock sensor | 10. 13-way connector—engi |
| 2. Ambient air temperature sensor
(located behind horns) | 6. Carburetter | 11. Serial Diagnostic Link con |
| 3. Coolant temperature sensor | 7. Ignition coil | 12. Inlet air sensor |
| 4. Crankshaft sensor | 8. Engine MFU | |
| | 9. 4-way connector—engine / main | |

Fig. 5.10 The knock sensor on the engine

- When combustion knock occurs, the resulting mechanical vibrations are transmitted by the seismic mass, to the piezoelectric crystal. The ‘squeezing up’ and relaxing of the crystal in response to this action, produces a small electrical signal that oscillates at the same frequency as the knock sensor element.
- The electrical signal is conducted away from the crystal by wires that are secured to suitable points on the crystal.

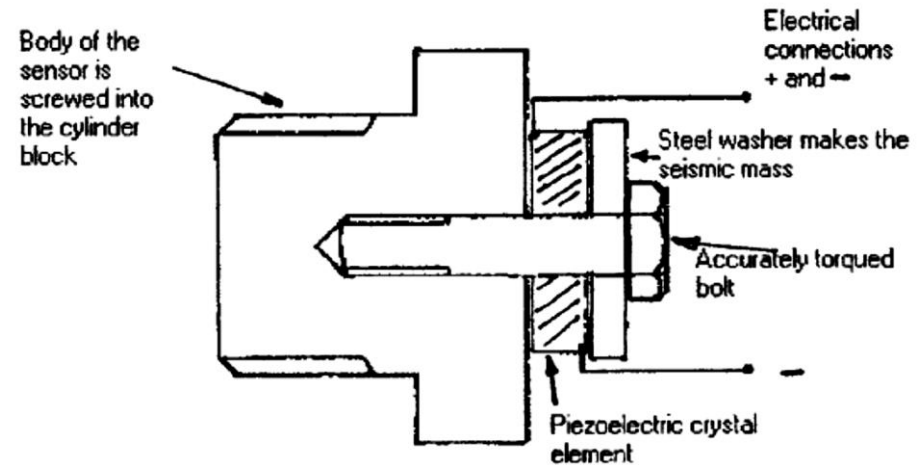


Fig. 5.11 The principle of the piezoelectric combustion knock sensor

- The tuning of the sensor is critical because it must be able to distinguish between knock from combustion and other knocks that may arise from the engine mechanism. This is achieved because combustion knock produces vibrations that fall within a known range of frequencies.



Knock sensor



❖ **Lambda Sensor (Exhaust Gas Oxygen Sensor)**

- In order for the exhaust emissions catalyst to operate correctly, the air–fuel ratio must be kept close to 15:1 (by mass), and it is the exhaust gas oxygen (EGO) sensor that assists the ECM to keep the air–fuel ratio within the required limits.
- The EGO sensor constantly monitors the oxygen content of the exhaust gas, and hence the air–fuel ratio at the engine intake, since the percentage of oxygen in the exhaust gas is an accurate measure of the air–fuel ratio of the mixture entering the engine cylinders.
- Figure 5.26 shows the relation between the oxygen content of the exhaust gas and the air–fuel ratio of the mixture entering the combustion chambers of the engine.

- The information (voltage) from the EGO sensor is fed back to the ECM so that the amount of fuel injected into the engine may be changed to ensure that the air-fuel ratio is kept within the required limits.

- It is common practice to refer to the air-fuel ratio that gives chemically correct combustion as $\lambda = 1$.

- If the mixture is rich, λ is less than 1 (probably $\lambda = 0.97$), and if the mixture is weak, λ is greater than 1 (probably $\lambda = 1.03$). For this reason, the exhaust gas oxygen sensor is often referred to as a λ sensor.

$$\lambda = \frac{\text{actual air-fuel ratio}}{\text{chemically correct air-fuel ratio}}$$

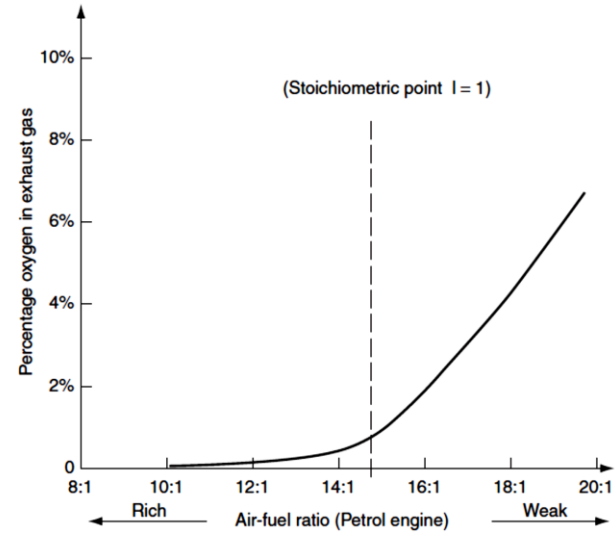
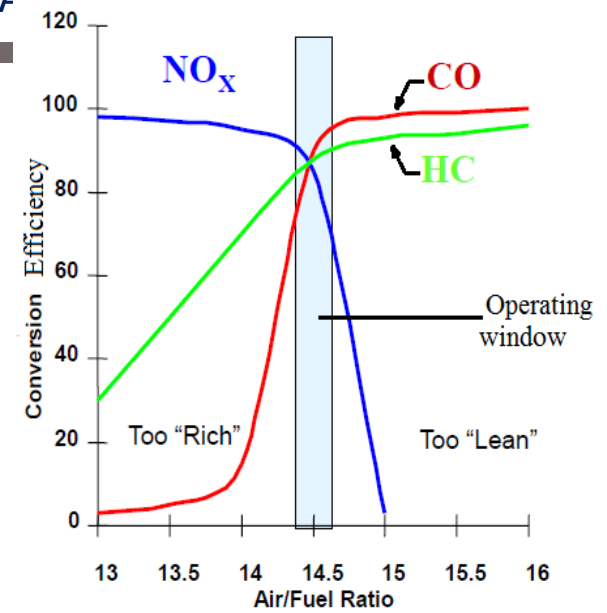


Fig. 5.26 Oxygen in exhaust versus air - fuel ratio



❖ THE VOLTAIC-TYPE EGO SENSOR

- The voltaic, or zirconia (ZrO_2), type oxygen sensor operates on the basis of a difference between the oxygen partial pressure of atmospheric air and the partial pressure of oxygen in the exhaust gas.
- At sea level, atmospheric air contains approximately 21% oxygen by weight, and this gives the oxygen a partial pressure of approximately 0.2 bar.
- The oxygen content of exhaust gas varies from zero in a rich mixture, to about 10% in a weak mixture, as shown in Fig.5.26.
- The partial pressure of the oxygen in the exhaust gas therefore ranges from near zero to approximately 0.01 bar.

- Figure 5.27 shows that the sensor element is essentially a cell (battery). The plates are made from platinum and they have a layer of ceramic zirconia between them which acts as an electrolyte.
- The platinum plates act as catalysts for the oxygen which makes contact with them, and they are also used to conduct electricity away from the sensor.

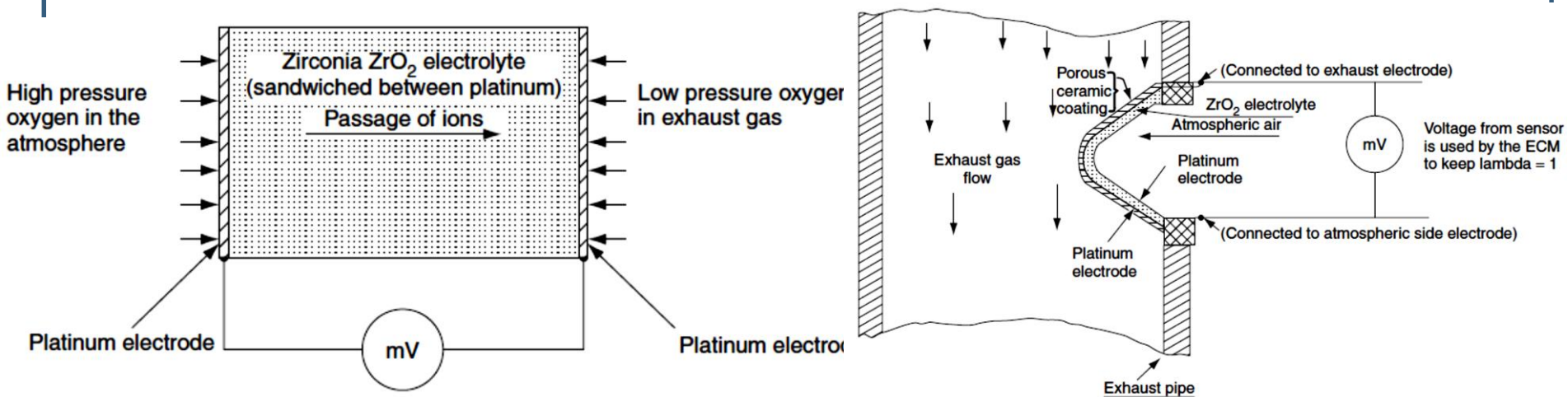


Fig. 5.27 The EGO sensor as a voltaic cell



- The catalyzing action that takes place when oxygen contacts the platinum plates causes the transport of oxygen ions through the electrolyte and this creates the electric current that gives rise to the e.m.f. (voltage) of the sensor.
- This sensor voltage is an accurate representation of the oxygen content of the exhaust gas.
- In practice the sensing element is formed into a thimble shape as shown in Fig. 5.28.
- This type of construction exposes the maximum area of platinum to the exhaust gas on one side and to the atmospheric air on the other side. The platinum that is exposed to the exhaust gas is covered with a porous ceramic material.
- This allows the oxygen through to the platinum but protects the platinum against harmful contaminants in the exhaust products.

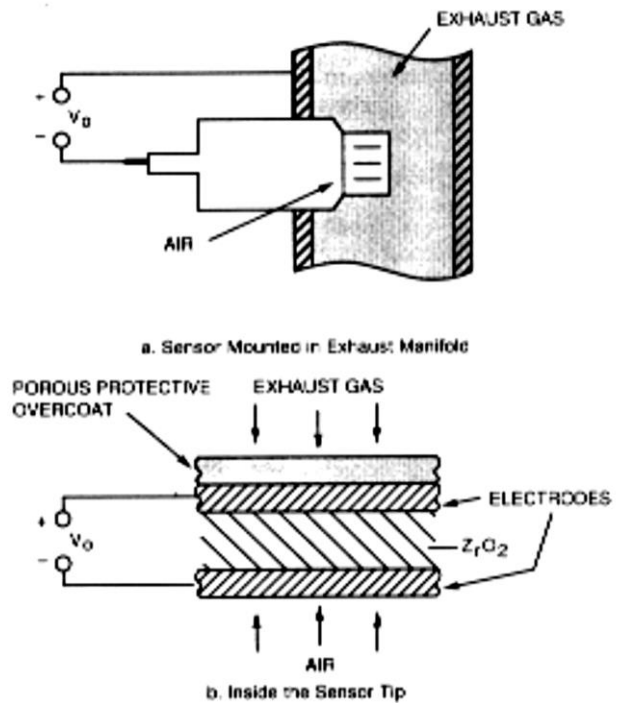
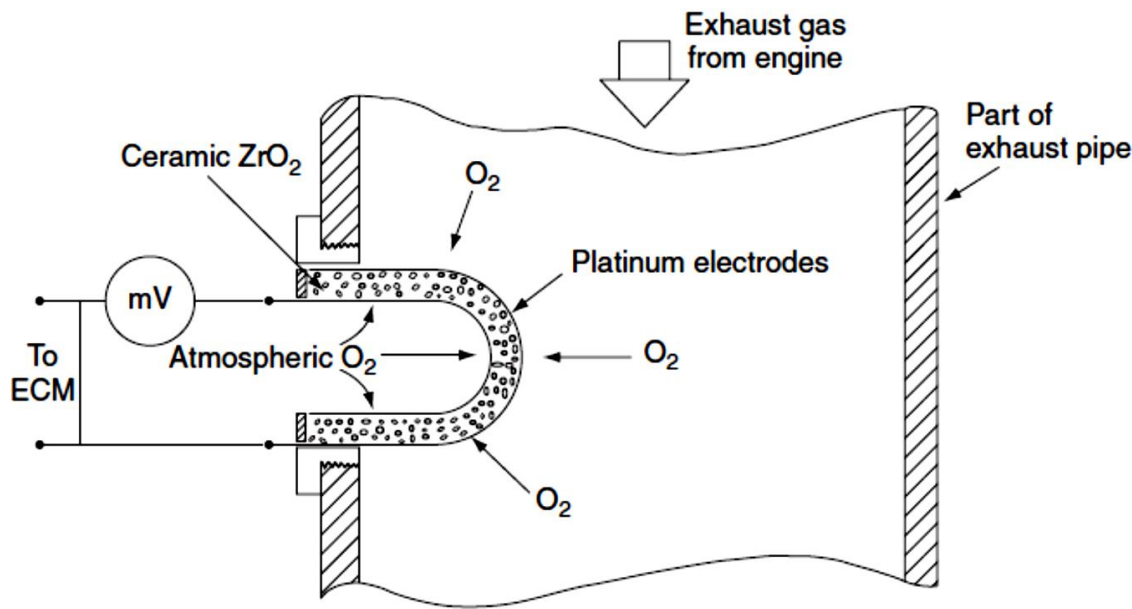


Fig. 5.28 Diagrammatic representation of the oxygen sensor in the exhaust pipe



- The greater the difference in oxygen levels between the atmospheric air and the exhaust gas, the greater is the voltage produced by the EGO sensor.
- When the air–fuel ratio changes from slightly rich, say 14:1 $\lambda = 0.93$ to slightly weak, 16:1 $\lambda = 1.06$, there is a marked change in the oxygen partial pressure of the exhaust gas and this leads to a step change in the EGO sensor voltage because the ceramic electrolyte (zirconia) is very sensitive to oxygen levels, as shown in Fig. 5.29.
- This sudden change in sensor voltage is used to trigger an action by the ECM, that will alter the fuelling, to maintain $\lambda=1$ (chemically correct air–fuel ratio).

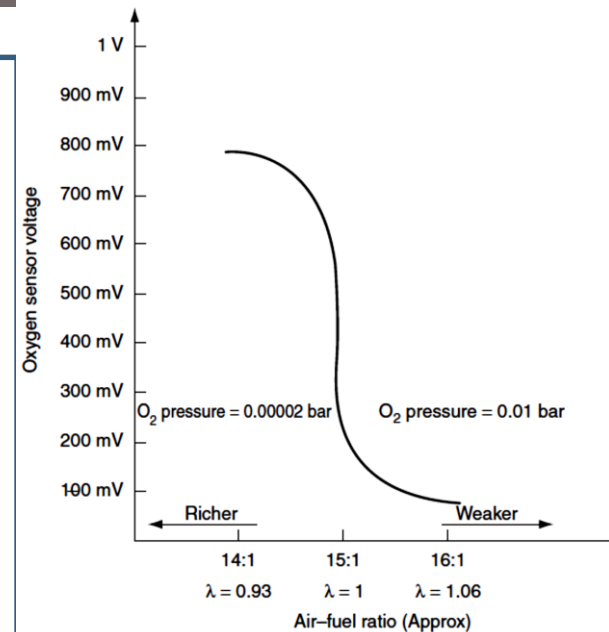


Fig. 5.29 Change in sensor voltage as air-fuel ratio changes

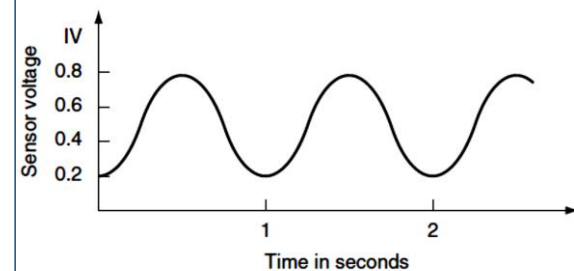


Fig. 5.30 The voltage waveform of an EGO sensor



- The result of this action is that the EGO sensor output cycles up and down, at a frequency that ensures that the engine runs smoothly and the exhaust catalyst is kept functioning correctly.
- The actual frequency is determined by the program that the designer places in the ROM of the ECM. All of this means that a voltaic-type EGO produces a standard type of output that can be measured by means of equipment that is readily available to vehicle repairers
- The approximate shape of the voltage waveform from the EGO sensor when in operation is shown in Fig. 5.30. This waveform arises from the way that the ECM alters the amount of fuel injected, i.e. lowering and raising the amount of fuel injected, in an ordered way, so as to keep the air–fuel ratio within the required limits.



- The action of the oxygen sensor is dependent on its temperature. The sensor needs to reach a **temperature of around 250°C** before it starts to function at its best.
- In order to assist the sensor to reach this temperature as quickly as possible, from a cold start, it is common practice to equip the sensor with a resistive-type heating element as shown in Fig. 5.31.
- This means that most oxygen sensors will be equipped with four wires: a signal wire and an earth for the sensor element, and a feed wire and an earth for the heating element.
- This type of sensor is known as a **heated exhaust gas oxygen sensor (HEGO)**

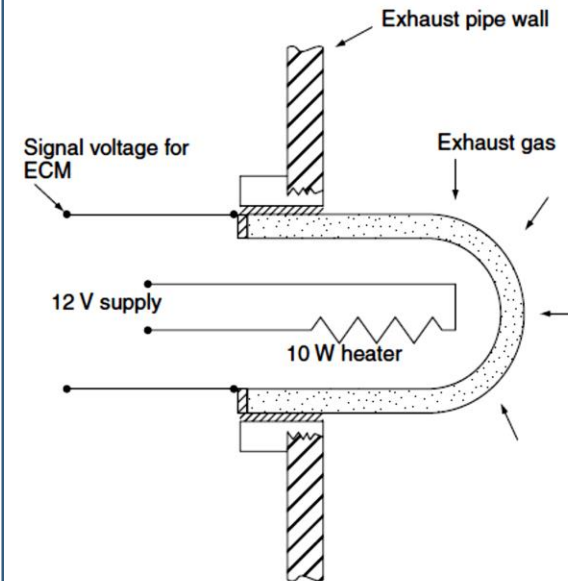


Fig. 5.31 A resistive-type heating element

❖ *ON-BOARD MONITORING OF THE CATALYTIC CONVERTER*

- The USA OBDII and impending European legislation requires that vehicle emissions systems are equipped with the facilities to illuminate a warning lamp (malfunction indicator lamp or MIL) should the catalytic converter cease to function correctly. In order to meet this requirement it is current practice to fit a second oxygen sensor downstream of the catalyst, as shown in Fig. 5.34.

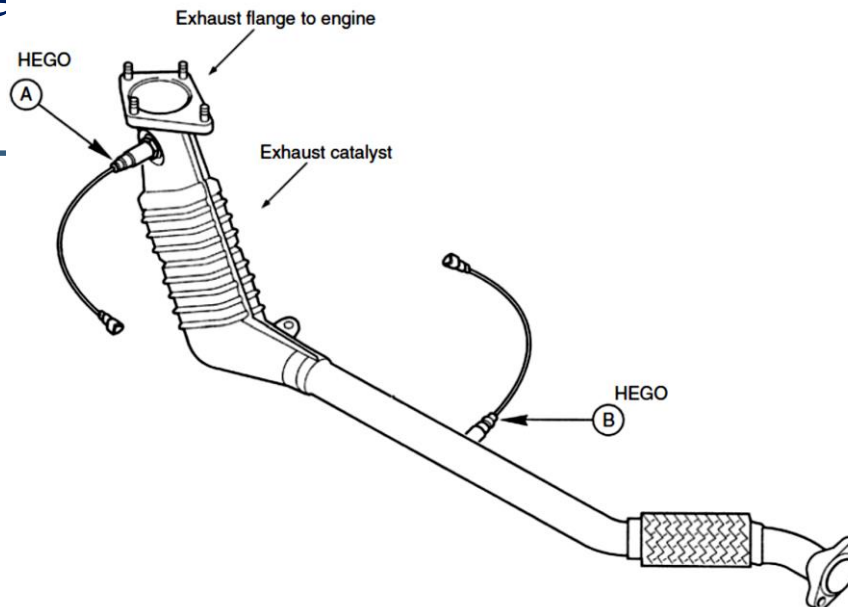


Fig. 5.34 The downstream oxygen sensor that monitors the catalyst

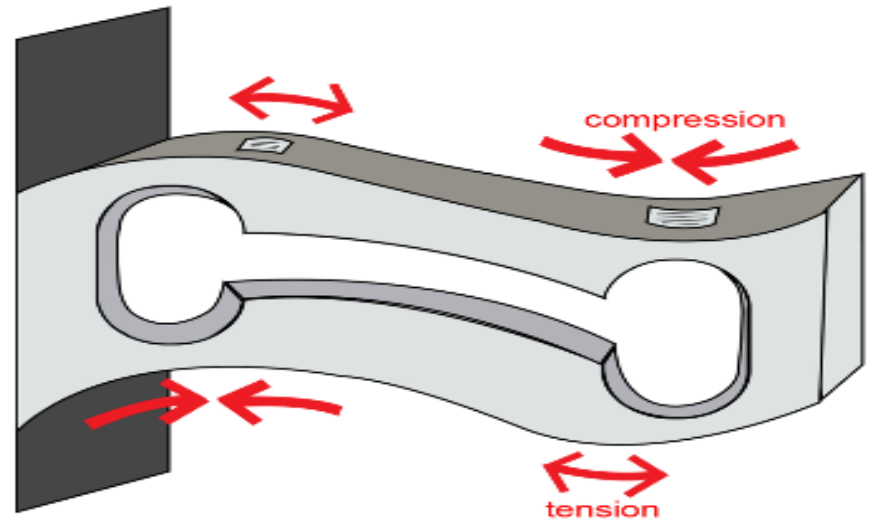


- In Fig. 5.34, A represents the upstream oxygen which is on the engine side of the catalyst.
- It is this sensor that provides the feedback signal that the ECM uses to control the air–fuel ratio within the required limits.
- The second sensor at B sends a signal to the ECM that is used to determine the efficiency of the catalyst. The voltage amplitude of this second sensor signal is the key to assessing the catalyst efficiency.
- As the catalyst ages, or is damaged by incorrect fuel etc., the voltage amplitude of this second sensor increases.



❖ Load Cell

- A **load cell** is a transducer that is used to create an electrical signal whose magnitude is directly proportional to the force being measured.
- The various types of load cells include hydraulic load cells, pneumatic load cells and **strain gauge load cells**.





- The strain gauge measures the deformation (strain) as a change in electrical resistance, which is a measure of the strain and hence the applied forces.

$$\frac{\Delta R}{R} = K \times \varepsilon$$

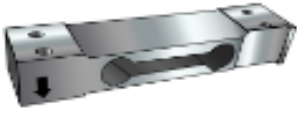
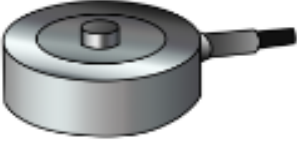

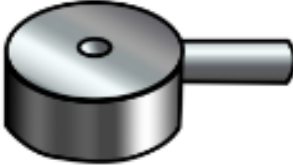


Where,

R : Initial resistance of the strain gauge

ΔR : Resistance change caused by elongation or contraction

K : Proportional constant (called the “gauge factor”)
($\Delta R/R/\Delta L/L$)

ε : Strain

Single Point Load Cells	Button Load Cells	S-Beam Load Cells	Miniature Load Cells	Through Hole Load Cells	Pancake Load Cells
					
<p>Generally used to build scales and in applications where space is not limited. They offer excellent off-center loading compensation.</p>	<p>Ideal for measuring compression forces that are applied axially. They are compact and easy to use.</p>	<p>Ideal for tension (pull) or Universal (push and pull) force measurement applications</p>	<p>Smallest miniature load cells we offer for compression force measurements only. Ideal for cramped locations.</p>	<p>Rugged, industrial load cells for compression and/or tension force measurements. Has a through hole with threads to attach accessories</p>	<p>High Capacity load cells with capacities up to 100K lbs for compression and/or tension load cell measurements.</p>



- The working principle is based on the strain/resistance relationship of electrical conductors.
- Any electrical conductor changes its resistance with mechanical stress, e.g. through tension or compression forces. The resistance change is partially due to the conductor's deformation and partially due to the change in the resistivity of the conductor material as a result of microstructural changes.

- **Operating Principle:**

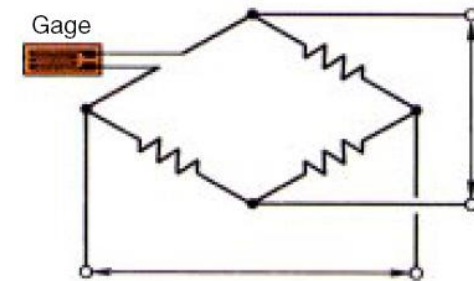
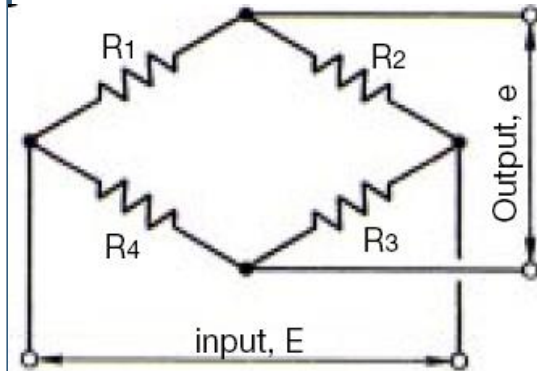
Welded Sensor utilizes bonded strain gages connected in Wheatstone bridge circuit. The output is derived from imbalance in the bridge circuit as load is sensed by sensor.

❖ Wheatstone Bridge:

- Wheatstone bridge is an electric circuit suitable for detection of minute resistance changes, therefore used to measure resistance changes of a strain gage
- The bridge is configured by combining four resistors as shown in Fig.
- Initially $R_1=R_2=R_3=R_4$, in this condition no output voltage is there, $e=0$
- When one of the Resistances is replaced by strain Gauge attached to the object whose strain is to be measured and load is applied, then there is small change in the resistance of gauge, hence some output voltage is there which can be related to strain as

$$e = \frac{1}{4} \cdot \frac{\Delta R}{R} \cdot E$$

- From this, strain can be easily determined using the relation



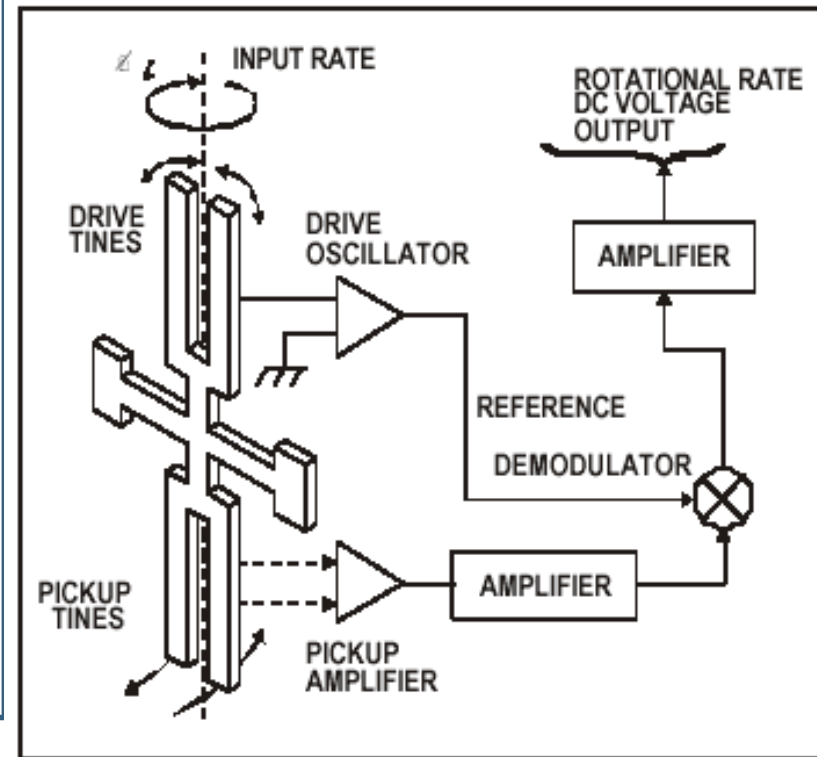
$$e = \frac{1}{4} \cdot K \cdot \epsilon \cdot E$$



❖ Yaw Rate Sensor:

- The drive portion looks and acts exactly like a simple tuning fork. Because the drive tines are constructed of crystalline quartz, it is possible to electronically “ring” this tuning fork.
- Each fork tine has a mass and an instantaneous radial velocity which changes sinusoidally as the tine moves back and forth.
- As long as the fork’s base is stationary the momenta of the two tines exactly cancel one another and there is no energy transfer from the tines to the base. In fact, it takes only $\sim 6\mu\text{W}$ of power to keep the fork ringing.

- As soon as the tuning fork is rotated around its axis of symmetry, however, the Coriolis principle exerts a profound influence on the behavior of this mechanism.
- By convention, (the “right-hand rule”), the rotational vector, ω_i , is described by an arrow that is aligned with the axis of rotation.
- The instantaneous radial velocity of each of the tines will, through the Coriolis effect, generate a vector cross product with this rotation vector.





- The net effect is that each tine will generate a force perpendicular to the instantaneous radial velocity of each of the tines:

$$F = 2m\omega_i * V_r$$

where:

- m = tine mass
- ω_i = rotation rate
- V_r = radial velocity
- Note that this force is directly proportional to the rotation rate, and since the radial velocity of the tines is sinusoidal, the force on each tine is also sinusoidal.
- Because the radial velocities of the two tines are equal and opposite, the Coriolis forces are equal and opposite, producing an oscillating torque at the base of the drive tine fork which is proportional to the input angular rate.



❖ Actuators:

- Actuators are the devices, such as fuel injectors, ignition coils, ABS modulators etc., that are operated by outputs from the ECM.
- Actuators normally rely on one of two electrical devices for their operation; they are either operated by **a solenoid or by an electric motor**.
- Solenoid-operated actuators are normally controlled in one of two ways. One is the duty cycle method, where the solenoid is switched on for a percentage of the time available, e.g. 20 or 80%.
- This means that pulses of varying width can be used to provide the desired result. The other method of solenoid control is known as pulse width modulation (PWM). Here the solenoid current is switched on and off at frequencies that change to suit operating requirements.



- Electric motors that are used in actuators may be stepper motors, or reversible permanent magnet d.c. motors.
- A stepper motor can be made to provide small movements of valves by pulsing the current supply.
- Some stepper motors rotate 7.5° per step, which means that a full rotation of the motor shaft takes 48 steps. A common form of stepper motor uses two sets of windings.
- Current in one set of windings drives the motor shaft forward and when this is switched off and current is applied to the other set of windings, the motor shaft rotates in the reverse direction.
- This means that accurate control over the position of a valve can be achieved because the control computer determines the valve position by counting the number of pulses applied to the stepper motor windings.

❖ Solenoid Valves:

- A fuel injector is (in essence) a solenoid-operated valve. The valve opens or closes to permit or block fuel flow to the engine. The valve is attached to the movable element of the solenoid and is switched by the solenoid activation.
- In a fuel injector with no current flowing, the solenoid movable element is held down against the stop, covering the aperture or nozzle.
- Fuel is thereby blocked from flowing from the pressurized fuel chamber into the aperture. When current flows through the solenoid coil, the movable element is switched upward, the aperture is exposed, and fuel (under pressure) sprays through this aperture.

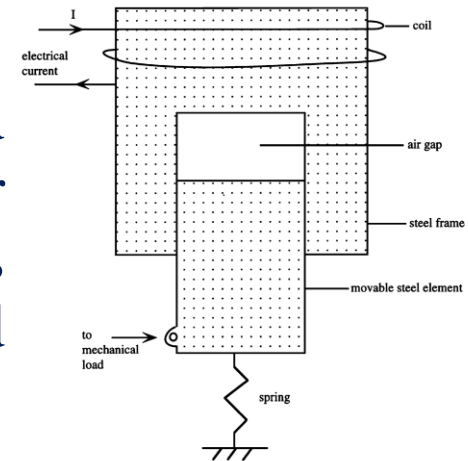
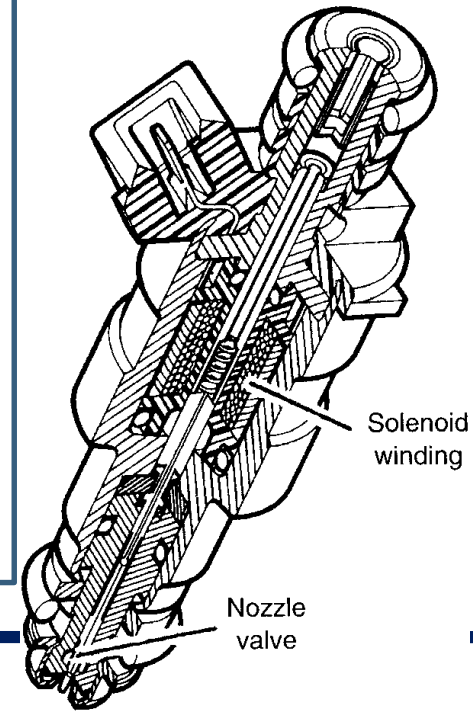


Figure A



- The fuel flow rate through the nozzle is constant for a given regulated fuel pressure and nozzle geometry; therefore, the **quantity of fuel injected into the air stream is proportional to the time the valve is open.**
- The control current that operates the fuel injector is pulsed on and off to deliver precise quantities of fuel.

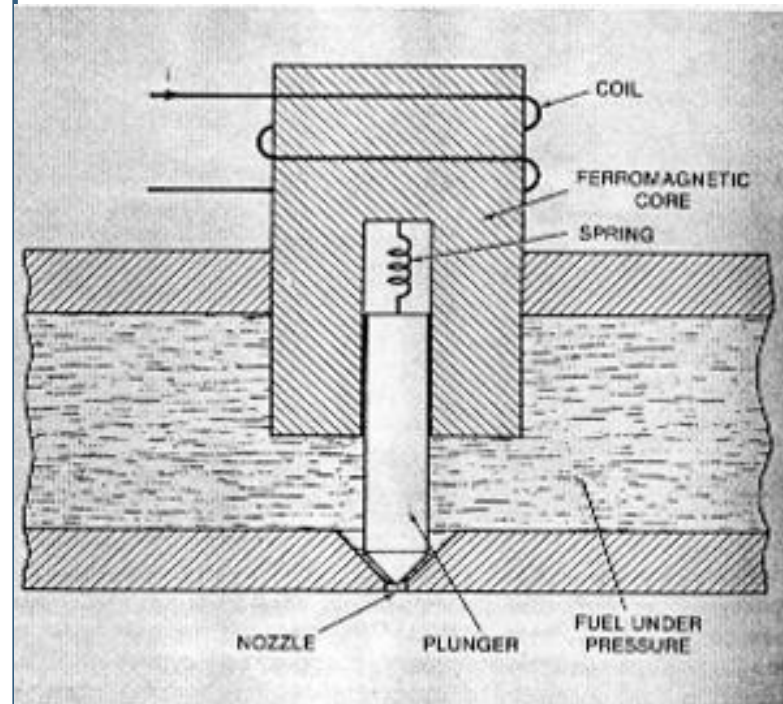


Figure B

□ Fuel Injector Signal

- Consider an idealized fuel injector as shown in Figure B, in which the injector is open when the applied voltage is on and is closed when the applied voltage is off.
- In this idealization, the control voltage operating the fuel injector is a binary pulse train (i.e., *either on or off*).
- For a pulse train signal, the ratio of on time t to the period of the pulse T (on time + off time) is called the *duty cycle*.

High air-to-fuel ratio.

Low air-to-fuel ratio.

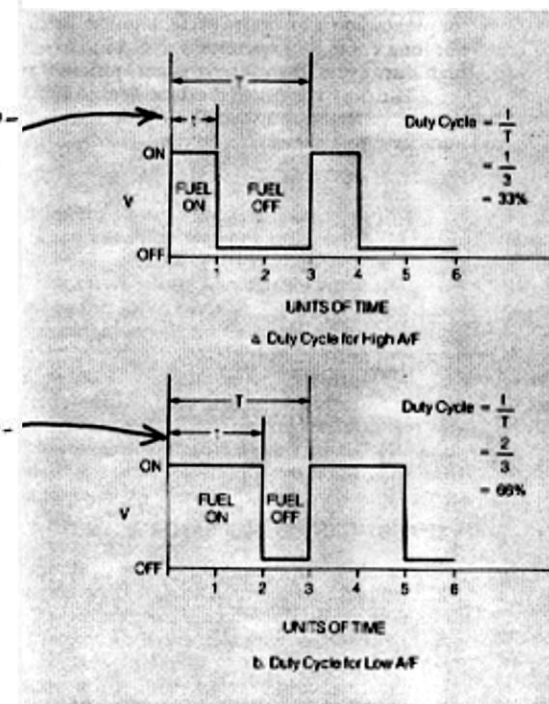


Figure C



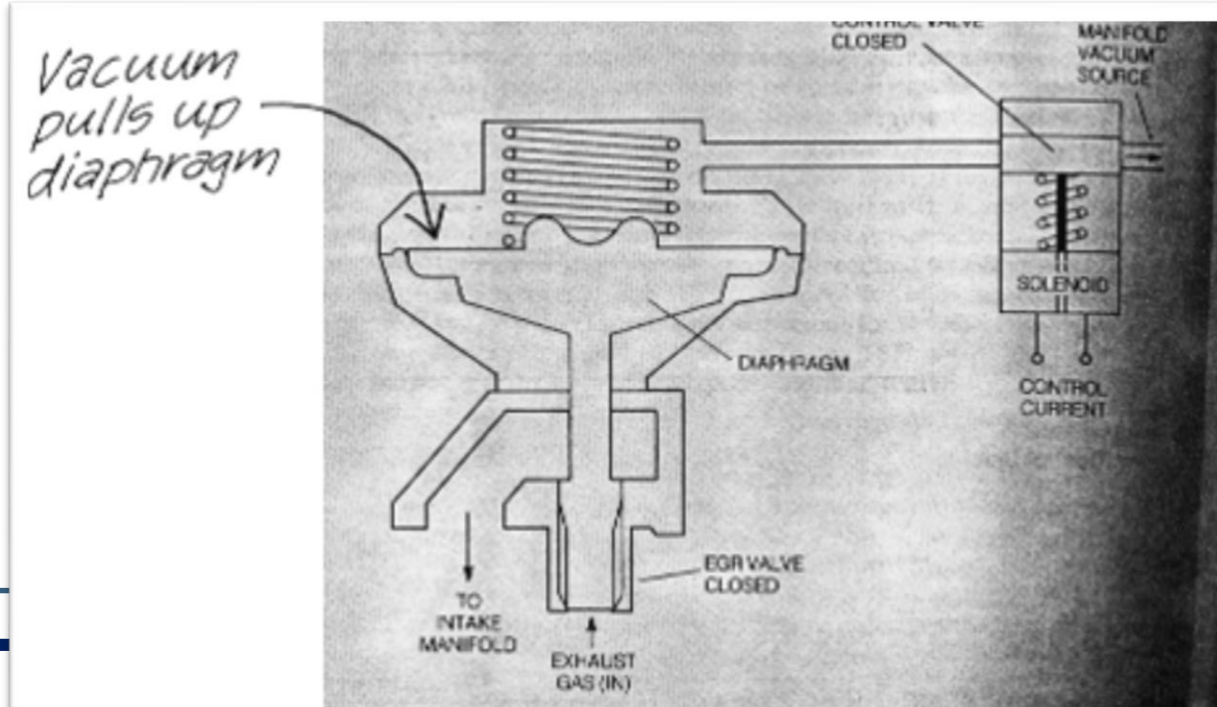
- This is shown in Figure C. The fuel injector is energized for time t to allow fuel to spray from the nozzle into the air stream going to the intake manifold. The injector is de-energized for the remainder of the period.
- Therefore, a low duty cycle, as seen in Figure C-a, is used for a high air/fuel ratio (lean mixture), and a high duty cycle (Figure C-b) is used for a low air/ fuel ratio (rich mixture).



❖ EGR Valve Actuator:

- The exhaust gas recirculation (EGR) is utilized to reduce NOx emissions. The amount of EGR is regulated by the engine controller.
- When the correct amount of EGR has been determined by the controller based on measurements from the various engine control sensors, the controller sends an electrical signal to the EGR actuator.
- Typically, this actuator is a variable-position valve that regulates the EGR as a function of intake manifold pressure and exhaust gas pressure. Although there are many EGR configurations, only one representative example will be discussed to explain the basic operation of this type of actuator.
- The example EGR actuator is shown schematically in Figure. This actuator is a vacuum-operated diaphragm valve with a spring that holds the valve closed if no vacuum is applied.

- The vacuum that operates the diaphragm is supplied by the intake manifold and is controlled by a solenoid-operated valve. This solenoid valve is controlled by the output of the control system.
- This solenoid operates essentially the same as that explained in the discussion on fuel injectors. Whenever the solenoid is energized (i.e., by current supplied by the control system flowing through the coil), the EGR valve is opened by the applied vacuum.





- The amount of valve opening is determined by the average pressure on the vacuum side of the diaphragm.
- This pressure is regulated by pulsing the solenoid with a variable-duty-cycle electrical control current.
- The duty cycle of this pulsing current controls the average pressure in the chamber that affects the diaphragm deflection, thereby regulating the amount of EGR.

❖ Petrol engine idle speed control

- Idle speed control is an important element of the control strategy for any engine management system. The control strategy for engine idling must take account of factors such as engine coolant temperature, engine load, power assisted steering, alternator load, etc.
- Many systems are fitted with an idle speed control valve that provides a supply of air that by-passes the throttle valve, whilst other systems may make use of the electronic throttle control.
- Two types of valve are used to provide a computer controlled idle air supply. One makes use of a **stepper motor**, as shown in Fig. 6.12, and the other uses a **solenoid operated valve** as shown in Fig. 6.15.

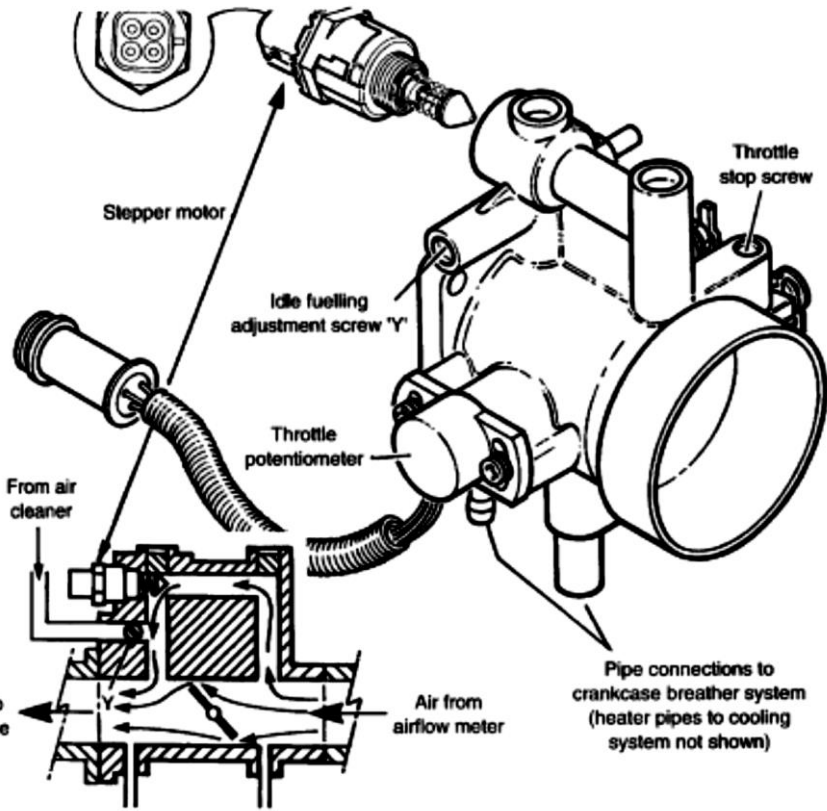


Fig. 6.12 A stepper motor operated air valve

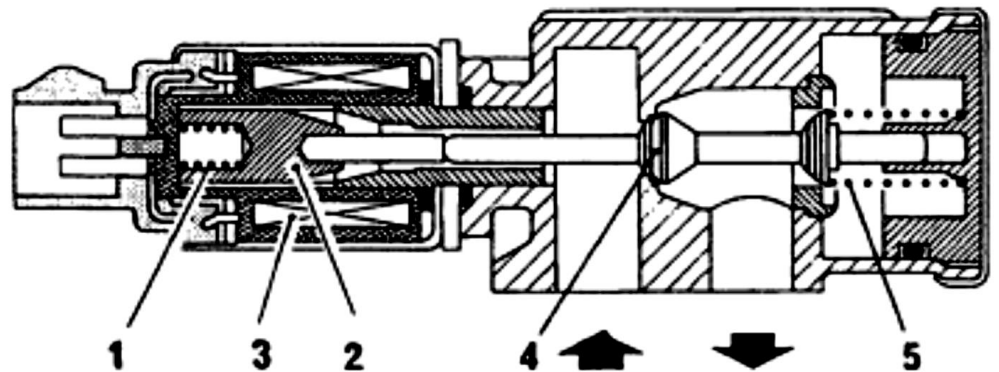
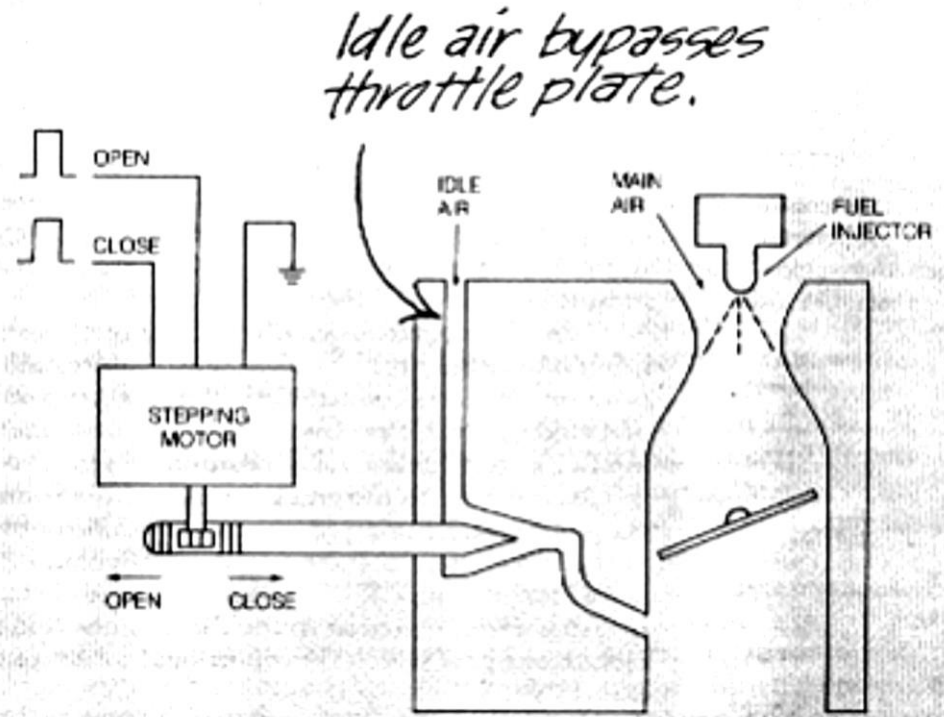


Fig. 6.15 A solenoid operated idle speed control valve



❖ STEPPER MOTOR-OPERATED VALVE

- Figure 6.12 shows a simplified arrangement of the extra air (air by-pass) valve that is built into the throttle body of some petrol injection systems.
- The ECU pulses the transistor bases, in the correct sequence, so that the stepper motor moves the air valve to provide the correct air supply, for any given condition.
- In addition, other sensor signals will enable the ECU to provide the correct amount of fuel to ensure that the engine continues to run smoothly. Figure 6.13 shows the stepper motor with the air valve attached.
- The multiple pin connection is typical of the type of connection that is used to electrically connect the stepper motor to the ECU. The stepper motor can normally be checked by operating it with the diagnostic tool connected to the serial communication port of the ECM.

- An oscilloscope can also be used to check the pulses that are sent to the motor from the ECM. Figure 6.14 gives an impression of the type of result that is to be expected from the PMS 100 oscilloscope when used to test a stepper motor.

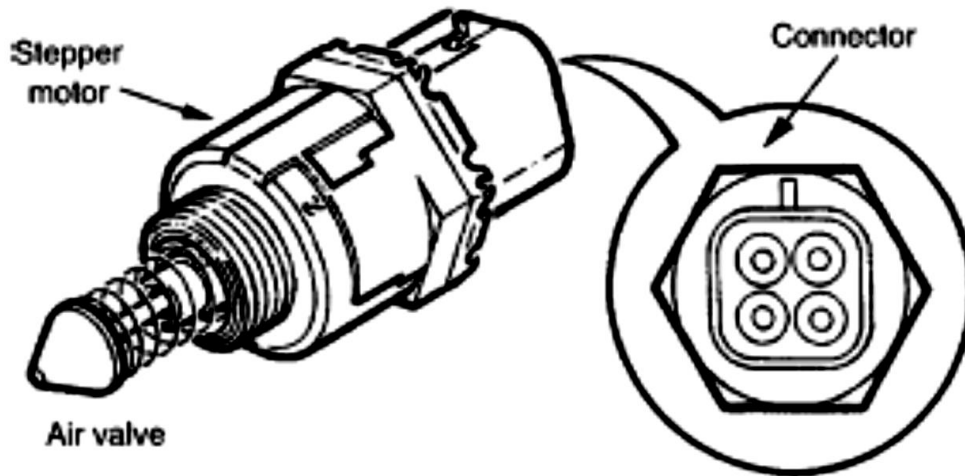
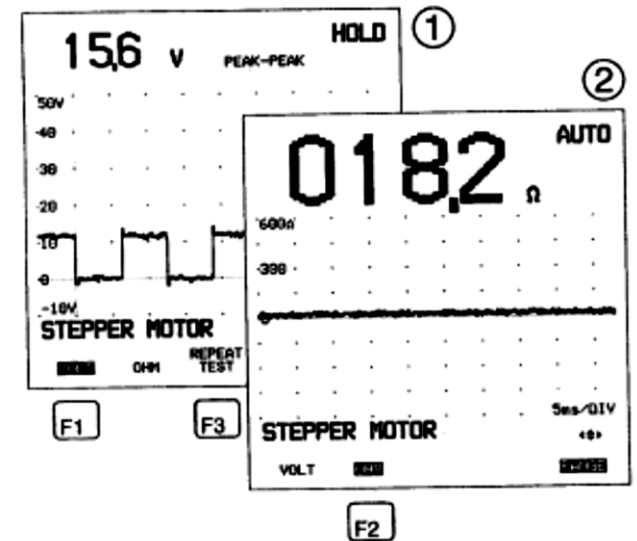
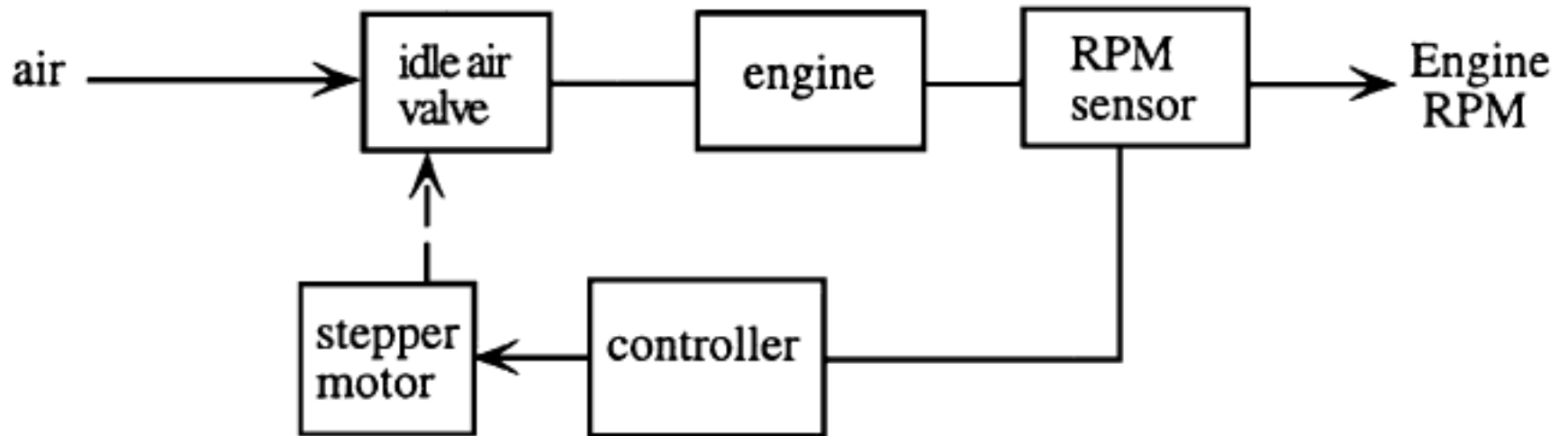


Fig. 6.13 The stepper motor and extra air valve (Lucas)



- PEAK-PEAK** Indicates the difference in voltage between the lowest and the highest value of the displayed waveform.
- This screen displays the measured resistance in ohms (Ω).

Fig. 6.14 Voltage trace from a stepper motor test



❖ *SOLENOID-OPERATED VALVE*

- This type of valve regulates the amount of air that by-passes the throttle valve through the medium of a solenoid-operated valve of the type shown in Fig. 6.15.
- In the rest position shown, the valve (4) is closed by the spring (5) and the armature of the solenoid (2) is pushed back inside the solenoid coil (3). When operating, the energized solenoid opens the valve (4) and admits air to the induction system. The quantity of air admitted is controlled by duty cycle pulses that are sent from the ECM.

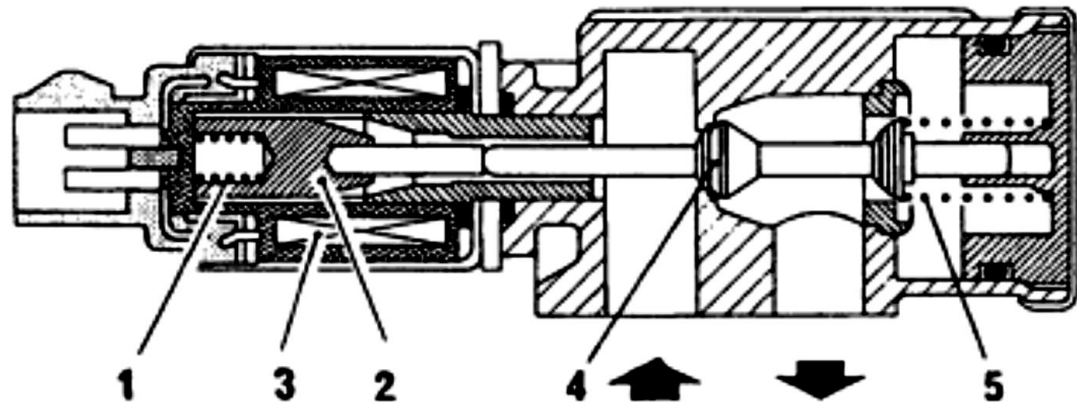


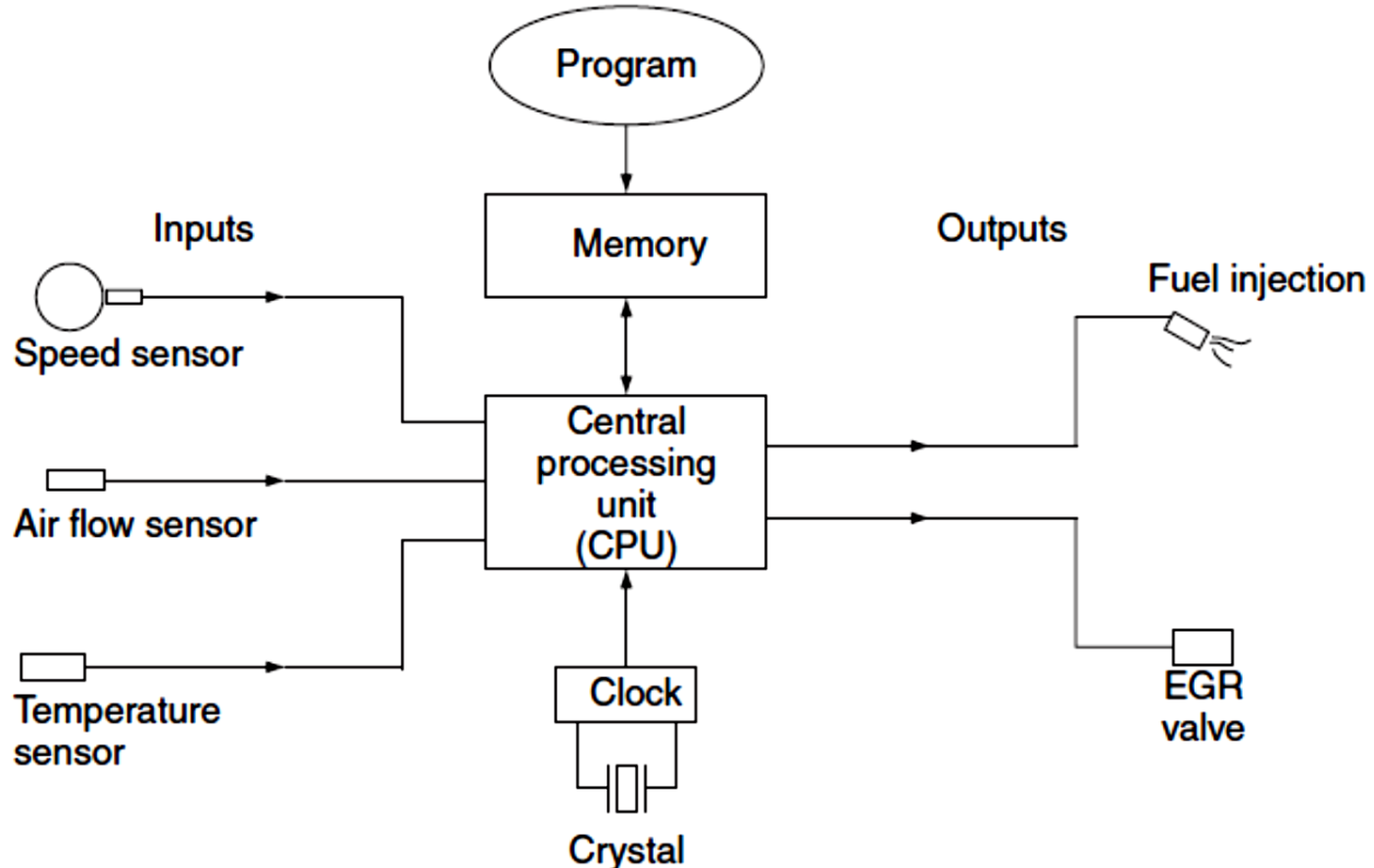
Fig. 6.15 A solenoid operated idle speed control valve



❖ Electronic Control Unit (ECU)

- Figure shows the general form of a computer that consists of the following parts:
 - a central processing unit (CPU)
 - input and output devices (I/O)
 - memory
 - a program
 - a clock for timing purposes.
- Data processing is one of the main functions that computers perform. Data, in computer terms, is **the representation of facts or ideas in a special way that allows it to be used by the computer.**
- In the case of digital computers this usually means binary data where numbers and letters are represented by codes made up from 0s and 1s. The input and output interfaces enable the computer to read inputs and to make the required outputs.

- Processing is the **manipulation and movement of data** and this is controlled by the clock. Memory is required to hold the main operating program and to hold data temporarily while it is being worked on.





❖ **COMPUTER MEMORY**

- Read only memory (ROM) is where the operating program for the computer is placed. It consists of an electronic circuit which gives certain outputs for predetermined input values. ROMs have large storage capacity.
- Read and write, or random access memory (RAM), is where data is held temporarily while it is being worked on by the processing unit. Placing data in memory is referred to as 'writing' and the process of using this data is called 'reading'.

❖ **THE CLOCK**

- The clock is an electronic circuit that utilizes the piezoelectric effect of a quartz crystal to produce accurately timed electrical pulses that are used to control the actions of the computer.
- Clock speeds are measured in the number of electrical pulses generated in one second. One pulse per second is 1 Hertz and most computer clocks operate in millions of pulses per second. One million pulses per second is 1 megahertz (1 MHz).



❖ A practical automotive ECU

- Figure 2.2 shows a computer controlled transmission system. At the heart of the system is an electronic module.
- This particular module is a self-contained computer which is also known as a microcontroller. Microcontrollers are available in many sizes, e.g. 4, 8, 16 and 32 bit, which refers to the length of the binary code words that they work on. In this system it is an 8-bit microcontroller.
- Figure 2.3 shows some of the internal details of the computer and the following description gives an insight into the way that it operates.

❖ *The microcomputer*

- This is an 8-bit microcontroller. In computer language a bit is a 0 or a 1. The 0 normally represents zero, or low voltage, and the 1 normally represents a higher voltage, probably 1.8 V.

- The microcontroller integrated circuit (chip) has a ROM capacity of 2048 bytes (there are 8 bits to one byte) and a RAM that holds 64 bytes.

- The microcontroller also has an on-chip capacity to convert four analogue inputs into 8-bit digital codes.

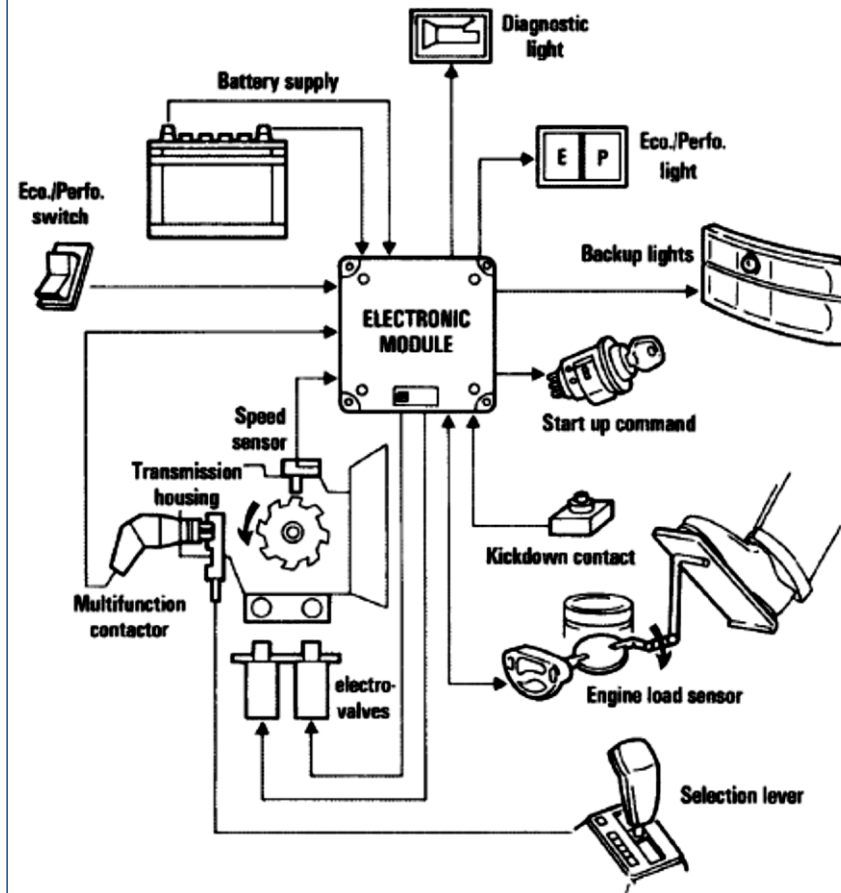


Fig. 2.2 A computer controlled transmission system

❖ *The power supply*

- The power supply is a circuit that takes its supply from the vehicle battery then provides a regulated d.c. supply of 5 V to the microcontroller, and this is its working voltage.
- The power supply also includes protection against over voltage and low voltage.
- The low voltage protection is required if battery voltage is low and it often takes the form of a capacitor.

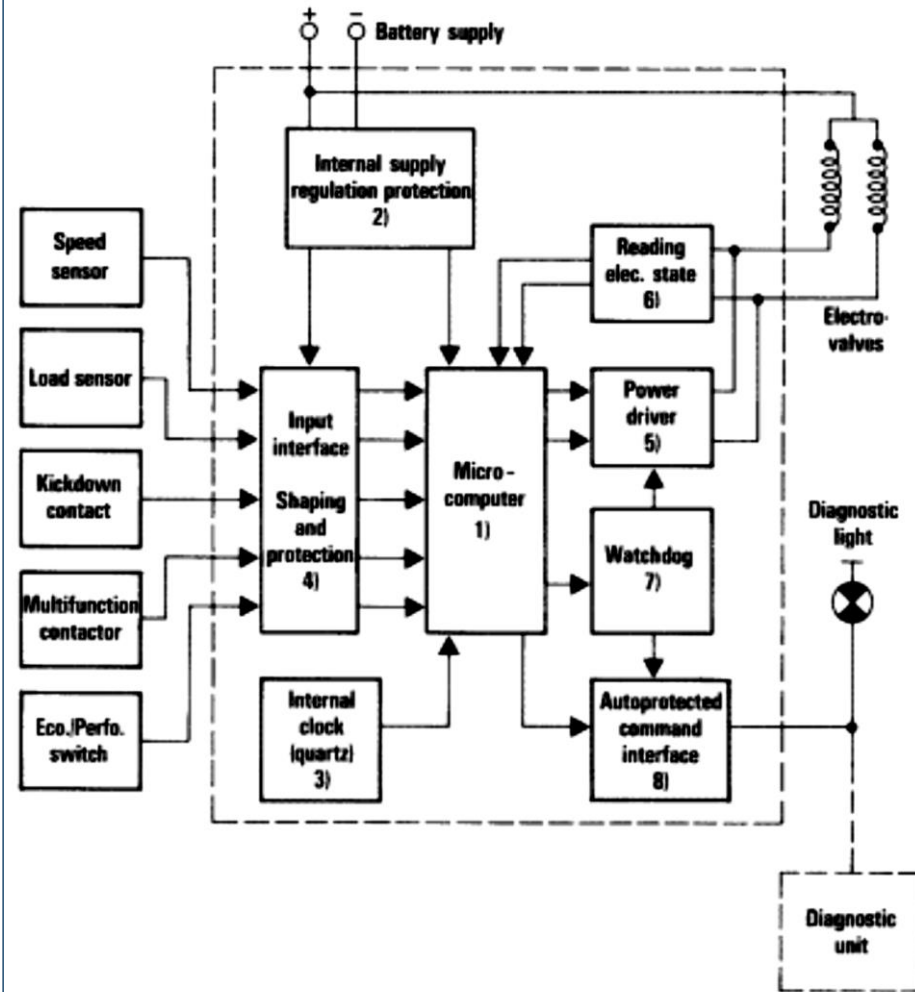


Fig. 2.3 Internal details of the computer



❖ *The clock circuit*

- In this particular application the clock operates at 4 MHz. The clock controls the actions of the computer, such as counting sensor pulses to determine speed and timing the output pulses to the electro-valves so that gear changes take place smoothly and at the required time.

❖ *The input interface*

- The input interface contains the electronic circuits that provide the electrical power for the sensors and switches that are connected to it. Some of these inputs are in an electrical form (analogue) that cannot be read directly into the computer and these inputs must be converted into computer (digital) form at the interface.



❖ *The output (power) interface*

- The power driver consists of power transistors that are switched electronically to operate electro-valves that operate the gear change hydraulics.

❖ *Feedback*

- At (6) on the diagram the inscription reads ‘ Reading electrical state’. This means that the computer is being made aware of the positions (on or off) of the electro-valves.

❖ *The watchdog*

- The watchdog circuit is a timer circuit that prevents the computer from going into an endless loop that can sometimes happen if false readings occur.

❖ *The diagnostic interface*

- The diagnostic interface is a circuit that causes a warning lamp to be illuminated in case of a system malfunction. It can also be used to connect to the diagnostic kit.