Displacement, Proximity and Position sensors

Position means the determination of the object's coordinates (linear or angular) with respect to a selected reference. Displacement means moving from one position to another for a specific distance or angle. In other words, a displacement is measured when an object is referenced to its own prior position rather than to another reference.
A critical distance is measured by proximity sensors. In effect, a proximity sensor is a threshold version of a position detector.

2.Inductive Displacement Sensors

Inductive sensors are primarily based on the principles of magnetic circuits. They can be classified as self-generating or passive.

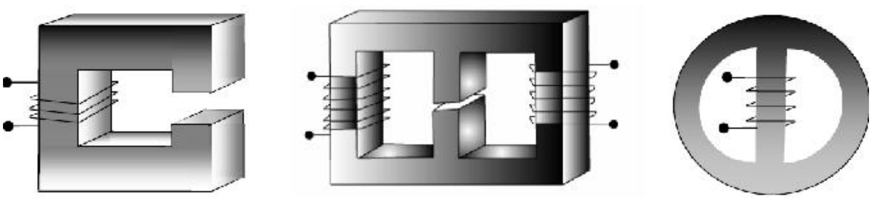
- *The self-generating types* utilize an electrical generator principle; that is, when there is a relative motion between a conductor and a magnetic field, a voltage is induced in the conductor.Or, a varying magnetic field linking a stationary conductor produces voltage in the conductor.

In instrumentation applications, the magnetic field may be varying with some frequency and the conductor may also be moving at the same time. In inductive sensors, the relative motion between field and conductor is supplied by changes in the measurand, usually by means of some mechanical motion.

- *The passive transducer* requires an external source of power. In this case, the action of the transducer is simply the modulation of the excitation signal.

2.1 Principle of Operation

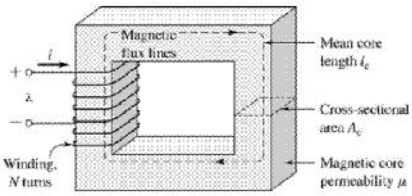
Magnetic fields are the fundamental mechanism by which energy is converted from one form to another in motors, generators and transformers. All of which have a magnetic structure of regular geometric shape called *core* and an *exciting coil* having a number of turns (= N) of conducting material are wound over the core.



The physics of the structure that describes the relationship of current on exiciting coil and generated magnetic field is given by Ampere's Law:

$$\oint H dl = I_{net}$$

where H is the magnetic field intensity produced by the *current* I_{net} and dl is a differential element of length along the path of integration. H is measured in Ampere-turns per meter.
For specifically a structure a current currying conductor is wrapped around a ferromagnetic core;



Applying Ampere's law, the total amount of magnetic field induced will be proportional to the amount of current flowing through the conductor wound with N turns around the ferromagnetic material as shown in above figure.

- Since the core is made of ferromagnetic material, it is assume that a majority of the magnetic field will be confined to the core
- The path of integration in Ampere's law is the mean path length of the core, l_c. The current passing within the path of integration I_{net} is then Ni, since the coil of wires cuts the path of integration N times while carrying the current i.

Hence Ampere's Law becomes

$$H l_c = Ni$$

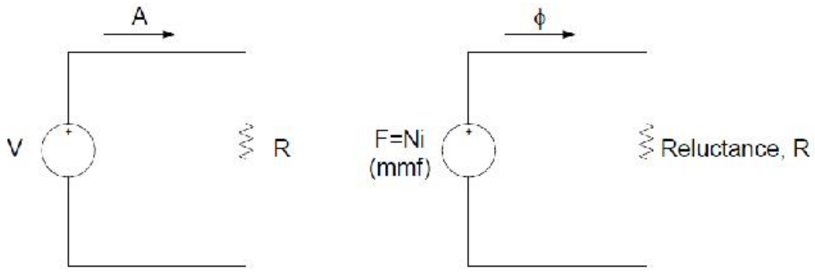
Using modified Ampere's law, magnetic flux density due to exciting coil is:

$$H = \frac{Ni}{l_c} \Rightarrow B = \mu H \Rightarrow B = \frac{\mu Ni}{l_c}$$

Rewriting above terms for magnetic flux calculation results in:

$$\phi = BA_c \Rightarrow B = \frac{\mu Ni}{l_c} \Rightarrow \phi = \frac{\mu NiA_c}{l_c}$$

The flow of magnetic flux induced in the ferromagnetic core can be made analogous to an electrical circuit hence the name magnetic circuit.The unit of magnetic flux is weber.



Electric Circuit Analogy *Magnetic Circuit Analogy*

F is denoted as *magnetomotive force* (mmf) which is similar to Electromotive force in an electrical circuit (emf). F is the prime mover or force which pushes magnetic flux around a ferromagnetic core.

$$F_{mmf} = Ni$$

The basic electromagnetic circuit structure consists of
The magnetic circuit consists of a core, made from a ferromagnetic material with a coil of n number of turns wound on it. The coil acts as a source of magnetomotive force (mmf) which drives the flux Φ through the magnetic circuit. If one assumes that the air gap is zero, the equation for the magnetic circuit can be expressed as:
The element of R in the magnetic circuit analogy is similar in concept to the electrical resistance. *Reluctance* is basically the measure of material resistance to the flow of magnetic flux

$$R_{mag} = \frac{l_c}{\mu A_c}$$

l= the total length of the flux path
μ = the permeability of the magnetic circuit material
A = the cross-sectional area of the flux path
Reluctance in this analogy obeys the rule of electrical resistance (Series and Parallel Rules). It is measured in Ampere-turns per weber.
The magnetic circuits modelled with lumped approach can be solved by using Ohm's Law in terms of the magnetic equivalents of the quantities in elcttrical formulation as follows:

$$F_{mmf} = \phi R_{mag}$$

The inductance is typified by the behavior of a coil of wire in resisting any change of electric current through the coil.

$$V = -L\frac{di}{dt}$$

Arising from Faraday's law, the inductance L may be defined in terms of the emf generated to oppose a given change in current: The unit for inductance is Henry.
The inductance is a parameter which is also related with the reluctance of the magnetic circuit:

$$V = -N\frac{d\phi}{dt} \Rightarrow \phi = \frac{F_{mmf}}{R_{mag}} = \frac{ANi\mu}{l} \Rightarrow V_{emf} = -N\frac{d}{dt}\left(\frac{ANi\mu}{l}\right) \Rightarrow V_{emf} = -\left(N^2\frac{A\mu}{l}\right)\frac{di}{dt} \Rightarrow L = N^2\frac{A\mu}{l}\ [H]$$

$$L = N^2\frac{A\mu}{l} = \frac{N^2}{R_{mag}}$$

The reluctance $\mathfrak{R}$ limits the flux in a magnetic circuit just as resistance limits the current in an electric circuit. By writing the mmf in terms of current, the magnetic flux may be expressed as:

$$\phi = \frac{ni}{R_{mag}}$$

And the he total flux linking by the entire n number of the turns of the coil is

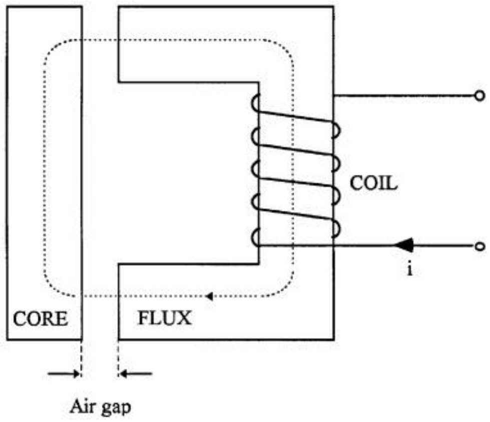
$$\Psi = n\phi = \frac{n^2 i}{R_{mag}}$$

The *self-inductance L* of the coil, which is described as the total flux (Ψ weber) per unit current for that particular coil; that is:

$$L = \frac{\Psi}{i} = \frac{n^2}{R_{mag}}$$

Now through mathematical analysis of simple magnetic circuit, it is shown that mechanical motion, magnetism and electricity effect each other through various mechanisms.

A basic inductive sensor consists of a magnetic circuit made from a ferromagnetic core with a coil wound on it. The coil acts as a source of magnetomotive force (mmf) that drives the flux through the magnetic circuit and the air gap.

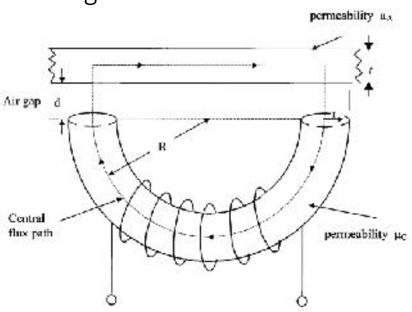


- The arrangement illustrated in Figure becomes a basic inductive sensor if the air gap is allowed to vary. In this case, the ferromagnetic core is separated into two parts by the air gap.
- The total reluctance of the circuit now is the addition of the reluctance of core and the reluctance of air gap. The relative permeability of air is close to unity, and the relative permeability of the ferromagnetic material is of the order of a few thousand, indicating that the presence of the air gap causes a large increase in circuit reluctance and a corresponding decrease in the flux.
- Hence, a small variation in the air gap causes a measurable change in inductance

2.2 Linear and Rotary Variable-Reluctance Transducer

The variable-reluctance transducers are based on change in the reluctance of a magnetic flux path. This type of transducer finds application particularly in acceleration measurements. However, they can be constructed to be suitable for sensing displacements as well as velocities.

The Single-Coil Linear Variable-Reluctance Sensor:



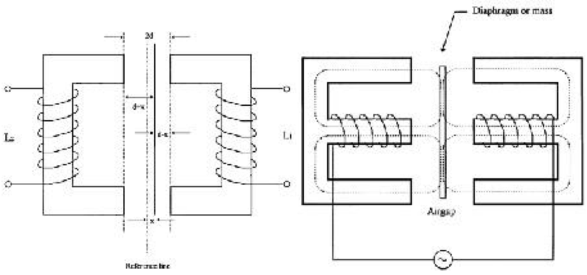
The sensor consists of three elements: a ferromagnetic core in the shape of a semicircular ring, a variable air gap, and a ferromagnetic plate. The total reluctance of the magnetic circuit is the sum of the individual reluctances: the reluctances of the core, air gap, and armature, respectively.

$$\Re_T = \Re_C + \Re_G + \Re_A$$

$$\Re_T = R/\mu_C \mu_0 r^2 + 2d/\mu_0 \pi r^2 + R/\mu_A \mu_0 rt$$

- The length of flux path in the core is taken as πR. The cross-sectional area is assumed to be uniform, with a value of πr^2.
- The total length of the flux path in air is 2d, and it is assumed that there is no fringing or bending of the flux through the air gap, such that the cross-sectional area of the flux path in air will be close to that of the cross section of the core.
- The length of an average central flux path in the armature is 2R. The calculation of the appropriate cross section area of the armature is difficult, but it may be approximated to 2rt, where t is the thickness of the armature
- all of the parameters are fixed except for the one independent variable the air gap. Hence, it can be simplified as:
  $$\Re_T = \Re_0 + kd \quad \text{where } \Re_0 = R/\mu_0 r\,[1/\mu_C r + 1/\mu_A t], \text{ and } k = 2/\mu_0 \pi r^2$$
- the inductance can be written as:
  $$L = n^2 / (\Re_0 + kd) = L_0 / (1 + \alpha d) \quad L_0 = \text{the inductance at zero air gap},\ \alpha = k/\Re_0$$
- The values of L_0 and α can be determined mathematically: they depend on the core geometry, permeability, etc., as explained above.
- It can be seen from equation that the relationship between L and α is nonlinear.

Despite this nonlinearity, these types of single coil sensors find applications in some areas, such as force measurements and telemetry.
The coil usually forms one of the components of an LC oscillator, for which the output frequency varies with the applied force. Hence, the coil modulates the frequency of the local oscillator.
The Variable-Differential Reluctance Sensor
The problem of the nonlinearity can be overcome by modifying the single coil system into a variable differential reluctance sensor (also known as push-pull sensor). This sensor consists of an armature moving between two identical cores, and separated by a fixed distance of 2d.



- Commercially available variable differential sensor has a iron corewhich is located halfway between the two E-shaped frames.
- The flux generated by primary coils depends on the reluctance of the magnetic path, the main reluctance being the air gap.
- Any motion of the core increases the air gap on one side and decreases it on the other side, thus causing reluctance to change, in accordance
  $$L_1 = L_{01} / [1 + \alpha(d - x)]$$
  $$L_2 = L_{02} / [1 + \alpha(d + x)]$$
- And thereby inducing more voltage on one of the coils than on the other.
- Motion in the other direction reverses the action with a 180° phase shift occurring at null.
- The output voltage can be modified, depending on the requirements in signal processing, by means of rectification, demodulation, or filtering.

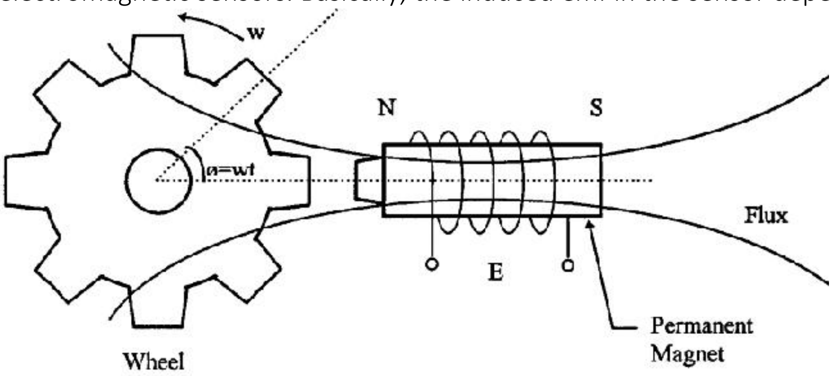
Although the inductance equations are still nonlinear, the sensor can be incorporated into an ac deflection bridge to give a linear output for small movements.

- These sensors respond to both static and dynamic measurements.
- They have continuous resolution and high outputs,
- but they may give erratic performance in response to external magnetic fields.
- The resistance of the coil must be carefully considered when designing oscillator circuits
- The hysteresis errors of these transducers are almost entirely limited to the mechanical components.

Variable reluctance transducers have small ranges and are used in specialized applications such as pressure transducers. Magnetic forces imposed on the armature are quite large and this severely limits their application. However, the armature can be constructed as a diaphragm; hence, suitable for pressure measurements.

Variable-Reluctance Tachogenerators

The sensors are based on Faraday's law of electromagnetic induction; therefore, they may also be referred to as electromagnetic sensors. Basically, the induced emf in the sensor depends on the linear or angular velocity of the motion.



The variable-reluctance tachogenerator consists of a ferromagnetic, toothed wheel attached to a rotatingshaft,
and a coil wound ontoa permanent magnet,extended by a soft iron pole piece.

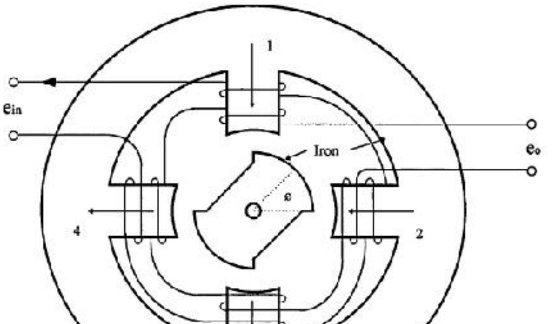
The wheel moves in close proximity to the pole piece, causing the flux linked by the coil to change, thus inducing an emf in the coil. The reluctance of the circuit depends on the width of the air gap between the rotating wheel and the pole piece. When the tooth is close to the pole piece, the reluctance is minimum and it increases as the tooth moves away from the pole. When the wheel rotates with a velocity ω, the induced emf is given by:

$$E = bm\omega \sin m\omega t$$

b = the amplitude of the flux variation
m = the number of teeth

Microsyn (giving output signals as low as 0.01°)

A microsyn is a variable reluctance transducer that consists of a ferromagnetic rotor and a stator carrying four coils. The stator coils are connected such that at the null position, the voltages induced in coils 1 and 3 are balanced by voltages induced in coils 2 and 4.

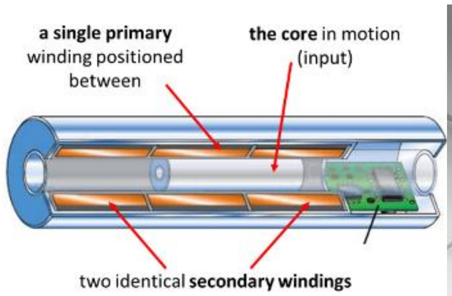


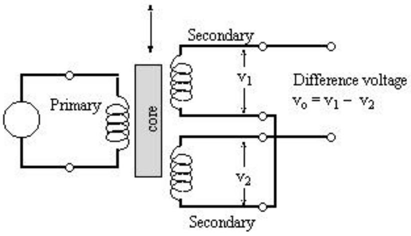
The motion of the rotor in one direction increases the reluctance of two opposite coils while decreasing the reluctance in others, resulting in a net output voltage e_0.The movement in the opposite direction reverses this effect with a 180° phase shift.

By the use of microsyns, very small motions can be detected, giving output signals as low as 0.01° of changes in angles.

The linear variable-differential transformer

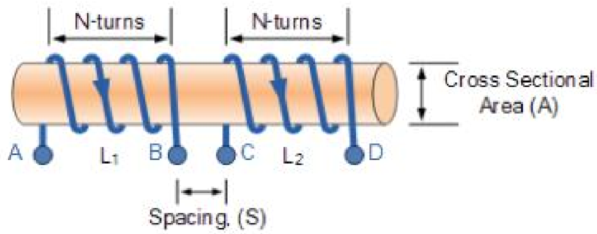
The linear variable-differential transformer, LVDT, is a passive inductive transducer. It consists of a single primary winding positioned between two identical secondary windings wound on a tubular ferromagnetic former. The moving element of an LVDT is a separate tubular armature of magnetically permeable material. This is called the core, which is free to move axially within the coil's hollow bore, and mechanically coupled to the object whose position is being measured.





- The primary winding is energized by a high-frequency 50 Hz to 20 kHz ac voltage.
- The two secondary windings are made identical by having an equal number of turns and similar geometry. They are connected in series opposition so that the induced output voltages oppose each other
- As the core inside the former moves, the magnetic paths between primary and secondaries change, thus giving secondary outputs proportional to the movement.
- the differential voltage between two secondary coils are measured:

Operating Principle:
Mutual Inductance: When two coils are placed close to each other, a changing flux in one coil will cause an induced voltage in the second coil. The coils are said to have mutual inductance M, which can either add or subtract from the total inductance depending on if the fields are aiding or opposing. Mutual Inductance is the basic operating principle of any electrical component that interacts with another magnetic field.



Magnetically Coupled Coils

Mutual inductance is the ability of one inductor to induce a voltage across a neighboring inductor. It can be greatly increased by positioning them on a common soft iron core or by increasing the number of turns of either coil as would be found in a transformer
Assuming a perfect flux linkage between the two coils the mutual inductance that exists between them can be given as

$$M_{12} = N_2 \frac{\Psi_1}{i_2} = \frac{\mu_0 \mu_r N_1 N_2 A}{l} [\text{Henry}]$$

Fort the cases in which we have known indcutances of coupled coils then the mutual inductance terms can be defined as:

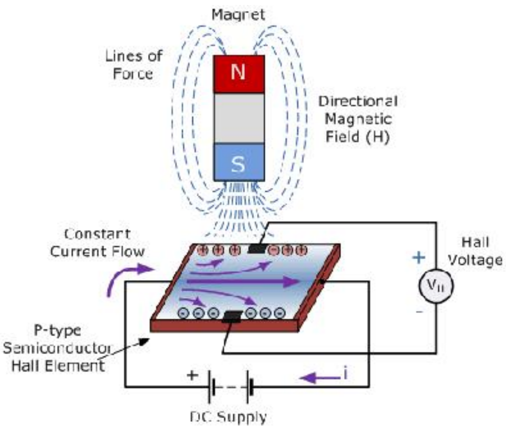
$$M_{12} = M_{21} = \sqrt{L_1 L_2} [\text{Henry}]$$

<u>Coupling Factor Between Coils (k):</u> The amount of inductive coupling that exists between the two coils is expressed as a fractional number between 0 and 1, where 0 indicates zero or no inductive coupling, and 1 indicating full or maximum inductive coupling. Then the equation above which assumes a perfect coupling can be modified to take into account this coefficient of coupling, k and is given as:

$$M_{12} = k\sqrt{L_1 L_2} [\text{Henry}]$$

When the coefficient of coupling, k is equal to 1, (unity) such that all the lines of flux of one coil cuts all of the turns of the second coil, that is the two coils are tightly coupled together, the resulting mutual inductance will be equal to the geometric mean of the two individual inductances of the coils.
The operation principle of LVDT is closely related to this coupling factor as the flux linkages are directly modified via motion of the core
The core causes the magnetic field generated by the primary winding to be coupled to the secondaries. When the core is centered perfectly between both secondaries and the primary, as shown, the voltage induced in each secondary is equal in amplitude and 180 deg out of phase. Thus the LVDT output (for the series-opposed connection shown in this case) is zero because the voltages cancel each other.
Eddy-Current Linear Displacement Sensors
Eddy-current sensors use high-frequency magnetic fields to sense the distance to a metal target. Sensing begins by passing alternating current through the sensing coil. This creates an alternating magnetic field around the coil.
When this alternating magnetic field interacts with the conductive target, it induces a current in the target material called an eddy current.
This eddy current produces its own magnetic field which oppose the sensing coil's field. As the eddy currents in the target oppose the sensing field, the impedance of the sensing coil will change. The amount of impedance change is dependent on the distance between the target and the sensing coil in the probe.
Current flow in the sensing coil, which is impedance dependent, is processed to create the output voltage which is an indication of the position of the target relative to the probe

Magnetic sensors for displacement sensing
Magnetoresistive and integrated Hall sensors measure the strength of magnetic field components. With different ways, this can directly affect their successful use in a position sensing application.
Hall Effect Sensor Principals
Hall Effect Sensors consist basically of a thin piece of rectangular p-type semiconductor material such as gallium arsenide (GaAs), indium antimonide (InSb) or indium arsenide (InAs) passing a continuous current through itself.
When the device is placed within a magnetic field, the magnetic flux lines exert a force on the semiconductor material which deflects the charge carriers, electrons and holes, to either side of the semiconductor slab. This movement of charge carriers is a result of the magnetic force they experience passing through the semiconductor material.
As these electrons and holes move side wards a potential difference is produced between the two sides of the semiconductor material by the build-up of these charge carriers.This generates an output voltage called the Hall Voltage, V_H.



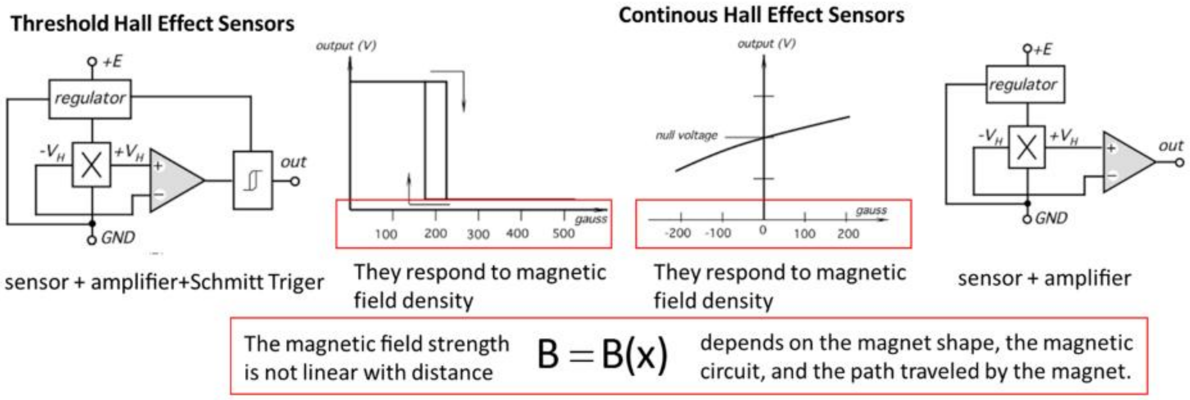
Generally, Hall Effect sensors and switches are designed to be in the "OFF", (open circuit condition) when there is no magnetic field present. They only turn "ON", (closed circuit condition) when subjected to a magnetic field of sufficient strength and polarity. There are two types of Hall sensors: continous and threshold

<u>A continous hall effect</u> sensor usually incorporates an amplifier for the easier interface with the peripheral circuits. In comparison with a basic sensor, they operate over a broader voltage range and are more stable in a noisy environment. These sensors are not quite linear with respect to magnetic field density and, therefore, the precision measurements require a calibration.

Designing a position detector with a Hall sensor, an overall analysis should be performed. First, the field strength of the magnet should be investigated. The strength will be the greatest at the pole face and will decrease with increasing distance from the magnet. The field may be measured by a gaussmeter or a calibrated Hall sensor.

There are three possible paths of motion for detecting a magnetic field, and below are common sensing configurations using a single magnet: Broadside Detection and Sideways (Fly by) Detection and shaft rotation detection.
Broadside Detection requires that the magnetic field is perpendicular to the hall effect sensing device and that for detection, it approaches the sensor straight on towards the active face. A sort of "head-on" approach.
This head-on approach generates an output signal, VH which in the linear devices represents the strength of the magnetic field, the magnetic flux density, as a function of distance away from the hall effect sensor. The nearer and therefore the stronger the magnetic field, the greater the output voltage

The second sensing configuration is "sideways detection". This requires moving the magnet across the face of the Hall effect element in a sideways motion. Sideways or slide-by detection is useful for detecting the presence of a magnetic field as it moves across the face of the Hall element within a fixed air gap distance for example, counting rotational magnets or the speed of rotation of motors.



In addition to the amplifier, the threshold-type sensor contains a Schmitt trigger detector with a built-in hysteresis. The output signal is a function of a magnetic field density.. The signal is a two-level one and has clearly pronounced hysteresis with respect to the magnetic field. When the applied magnetic flux density exceeds a certain threshold, the trigger provides a clean transient from the OFF to the ON position
For the threshold-type Hall sensor, the longest distance at which the sensor's output goes from ON (high) to OFF (low) is called a release point. It can be used to determine the critical distance where the sensor is useful.