Chapter 5

Hall-based Sensing Devices

Introduction

Applying Hall effect sensors involves selecting the magnetic system and choosing the Hall sensor with the appropriate operate and release characteristics. These components must then be integrated into a system that will meet the specific application requirements. MICRO SWITCH Sensing and Control has developed a number of products that integrate the sensor and a magnetic system into a single package. Since the magnetic characteristics are pre-defined, applying these products does not involve magnetic to sensor design. Instead, applying these sensors consists of mechanical or electrical interfacing of the input.

In this chapter, vane operated position sensors, current sensors, magnetically operated solid state switches, and gear tooth sensors will be examined. For each of these products incorporating a Hall effect sensor, the principles of operation and interface requirements will be discussed. Electrical considerations as they relate to the output are the same as those presented in Chapters 2 and 4.

Vane operated position sensors

A vane operated position sensor, sometimes referred to as a vane sensor, consists of a magnet and a digital output Hall effect sensor assembled as shown in Figure 5-1. Both the magnet and the Hall effect sensor are rigidly positioned in a package made of a non-magnetic material.

The sensor has a space or gap through which a ferrous vane may pass, as illustrated in Figure 5-2. The Hall effect sensor will detect the presence (or absence) of the vane.

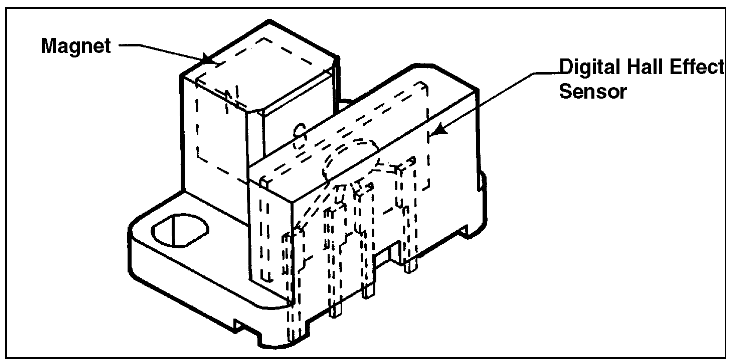

Figure 5-1 Basic vane operated position sensor

Principles of operation

Figure 5-3 shows the construction of another version of the basic vane sensor. Pole pieces have been added to direct the lines of flux by providing a low resistance path. The lines of flux, illustrated by arrows, leave the north pole of the magnet, travel through the pole piece, across the gap, and return through the sensor to the south pole. As a result, the sensor is normally ON.

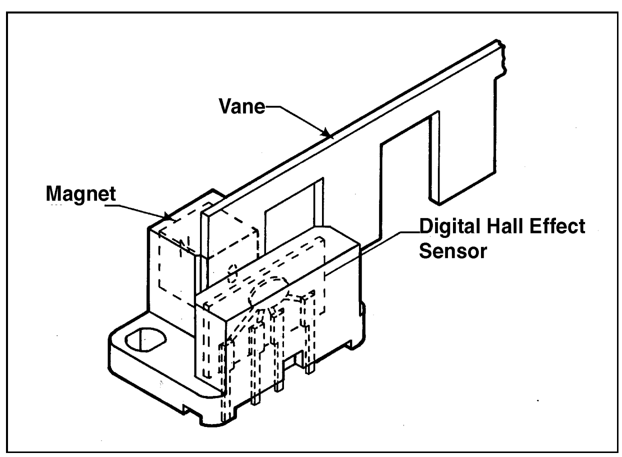

Figure 5-2 Ferrous vane in gap

The magnetic circuit (flux lines) illustrated in Figure 5-3 is altered when a vane, made of material similar to the pole pieces, is present in the gap. The vane has the effect of shunting the lines of flux away from the sensor in the manner shown by the arrows in Figure 5-4. Thus, the sensor will be turned OFF when a vane is present in the gap.

The curve in Figure 5-5 illustrates how the magnetic field sensed by the Hall effect sensing device varies as a vane is passed through the gap. Assume the sensor has the operate and release points shown. When a vane is moved from left to right, the sensor will be ON until the leading edge of the vane reaches point b. At this point (known as the left release), the sensor will be turned OFF. If this motion is continued, the sensor will remain turned OFF until the trailing edge of the vane reaches point d. At this point (known as the right operate), the sensor is turned ON again. The total left to right distance traveled by the vane with the sensor OFF, is equal to the distance between points b and d plus the vane width.

If the vane is moved from right to left, the sensor will be ON until the leading edge of the vane reaches point c (known as the right release). The sensor is then turned OFF until the trailing edge of the vane reaches point a (left operate). The total right to left distance traveled by the vane with the sensor OFF is equal to the distance between points c and a (L release to R operate), plus the vane width.

In many cases, the vane consists of several teeth. The gaps between the individual teeth are referred to as windows. Figure 5-6 shows a vane with two teeth and a single window. If this vane is passed through the gap, the distance traveled with the sensor OFF (tooth plus b to d) will be the same as for the single tooth vane shown in Figure 5-5. The total distance traveled by the vane with the sensor ON is equal to the window width minus the distance between point d and b, or between a and c, depending on direction of travel.

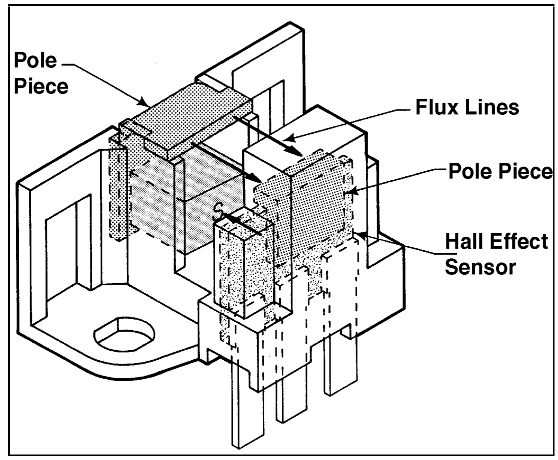

Figure 5-3 Vane operated sensor with pole pieces

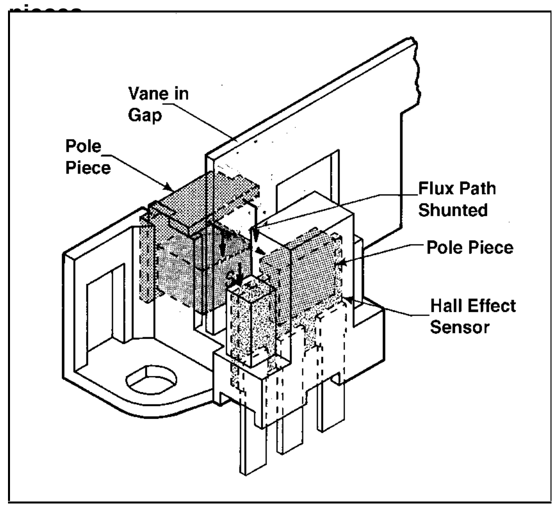

Figure 5-4 Ferrous vane in gap

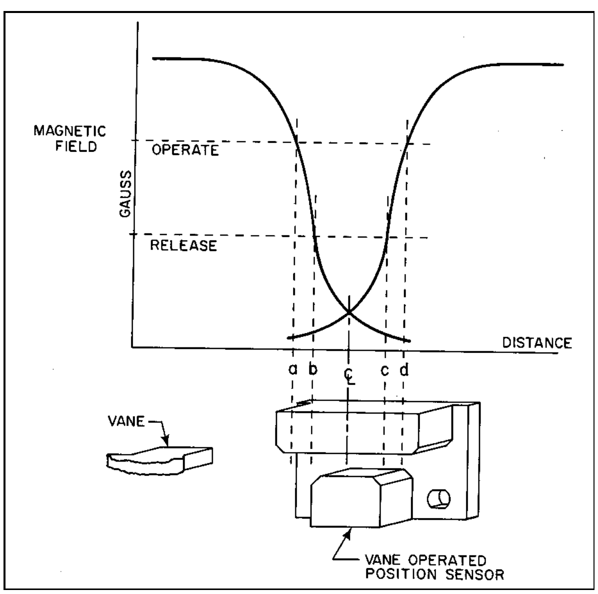

Figure 5-5 Ferrous vane passing through the gap

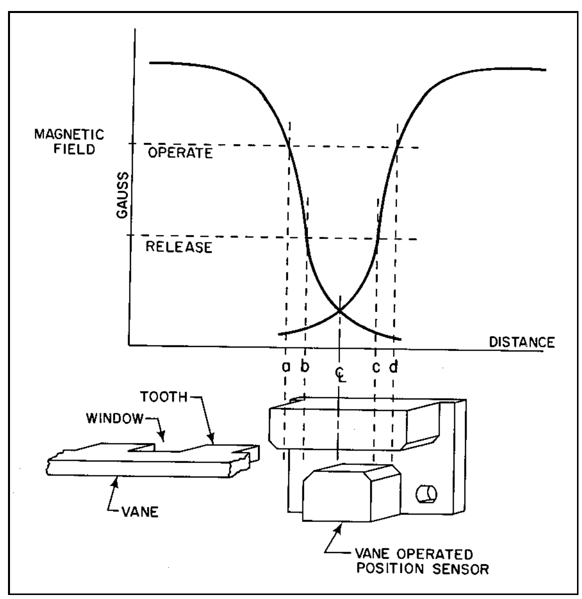

Figure 5-6 Multiple tooth vane operation

The relationships between ON and OFF travel for a multiple tooth vane are summarized in Figure 5-7.

Travel	OFF Distance	ON Distance
Left to Right	Tooth width plus (b to d)	Window width minus (d to b)
Right to Left	Tooth width plus (c to a)	Window width minus (a to c)

Figure 5-7 Relationship between ON and OFF travel

Sensor specifications

Vane operated position sensors are specified in terms of vane characteristics and mechanical characteristics. Mechanical characteristics are the left and right operate and release points previously discussed. Vane characteristics define the minimum and maximum dimensions the vane required to operate a given sensor.

Figure 5-8 illustrates how the mechanical characteristics of a vane operated position sensor are defined. The left and right operate and release characteristics are specified as the center of the round mounting hole of the sensor. As a result, dimensions a, b, c and d are specified individually as distances from this reference point.

The mechanical characteristics for a typical vane operated position sensor are shown in the table, Figure 5-9. Refer to Figure 5-8 for the definition of a, b, c and d. The first (dimensions) row in the chart lists the characteristics at room temperature (25°C) and their tolerances. The left-difference (b-a), right difference (d-c) and left-right difference (d-b or c-a) have been included because their tolerances are smaller than the differences calculated from a, b, c and d individually. The second row lists the additional tolerance increase over the temperature range of the sensor (-40° to +125°C, for instance).

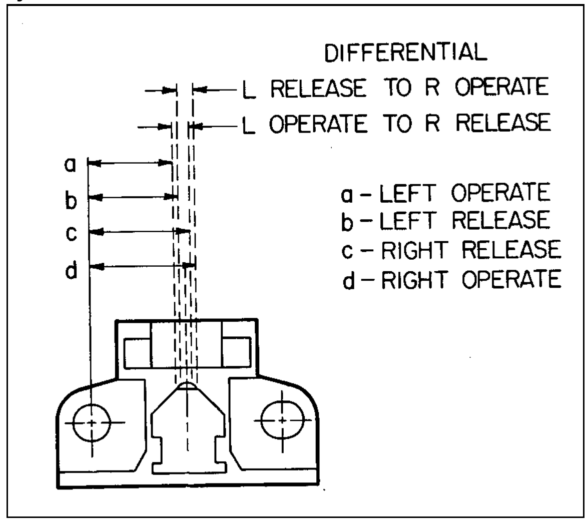

Figure 5-8 Reference points for mechanical characteristics

Temperature	Left			Right			L-R Diff.
	Operate a	Release b	Difference	Operate d	Release c	Difference	
25°C (77°F)	.390 ± .03	.410 ± .03	.020 ± .014	.510 ± .03	.490 ± .03	.020 ± .014	.100 ± .040
-40° to 125°C (-40° to 257°F)	± .040	± .040	± .010	± .040	± .040	± .010	± .070

Figure 5-9 Typical mechanical characteristics . . . Vane operated position sensor

Some typical dimensions for a multiple tooth vane are illustrated in Figure 5-10. The maximum thickness of a tooth is limited by gap width and required clearances. The amount of material necessary to shunt the magnetic field governs the minimum tooth thickness and tooth width. The minimum window width and tooth depth are specified to prevent adjacent vane material (teeth and frame) from partially shunting the magnetic field. The recommended range of tooth thickness and the corresponding minimum tooth width, window width, and tooth depth are shown in Figure 5-10.

Thickness	Minimum Tooth	Minimum Window	Minimum Tooth Depth
0.04”	0.40”	0.40”	0.40”
0.06”	0.25”	0.40”	0.37”

Figure 5-10 Typical multiple tooth vane dimensions

The vane operated position sensor may be used with a linear vane, as shown in Figure 5-11 to sense linear position.

Vane operated position sensors may be used with a circular vane to sense rotary position. Figure 5-12 shows a circular pie cut vane with windows cut from a sector. The window and tooth widths vary from a maximum at the vanes outer circumference to a minimum at its inner circumference. Since window and tooth widths vary, care must be taken to insure that the minimum specifications (Figure 5-10) are not violated.

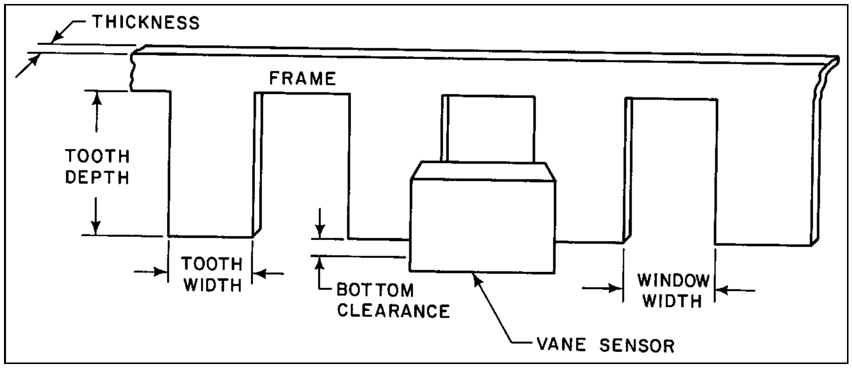

Figure 5-11 Vane operated linear position sensor

Another circular vane configuration is shown in Figure 5-13. This vane has uniform tooth and window widths, eliminating the drawbacks of a pie cut vane.

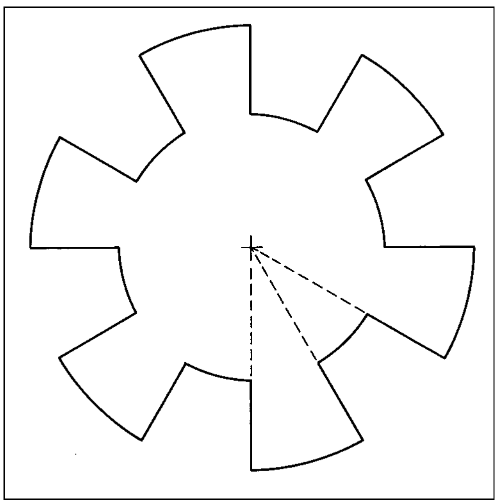

Figure 5-12 Circular vane with windows

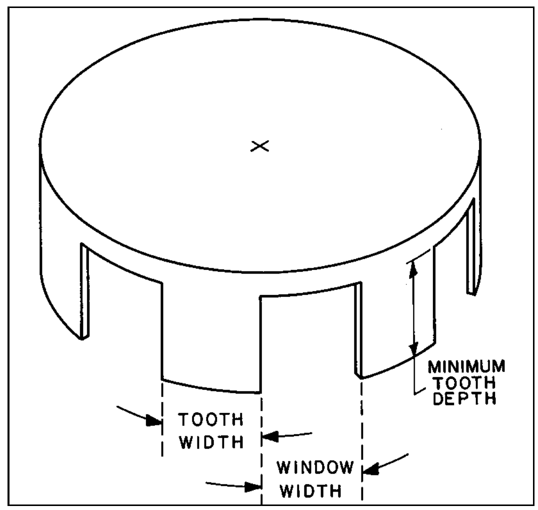

Figure 5-13 Uniform tooth and window vane

Digital current sensors

A fast-acting, automatically-resetting current sensor can be made using a digital output Hall effect sensor. The current sensor is constructed using an electromagnet and sensor assembled as illustrated in Figure 5-14. Both the electromagnet and the Hall effect sensor are rigidly mounted in a package. The current passing through the electromagnet coils generates a magnetic field which is sensed by the Hall sensor.

An overload signal could change state, from low to high or vice versa, when the current exceeded the design trip point. This signal could be used to trigger a warning alarm or to control the current directly by electronic means.

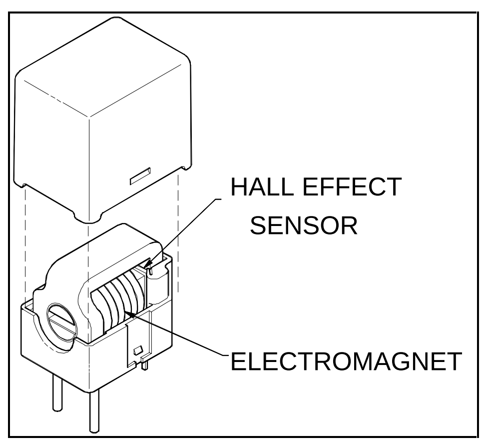

Figure 5-14 Typical digital current sensor

Principles of operation

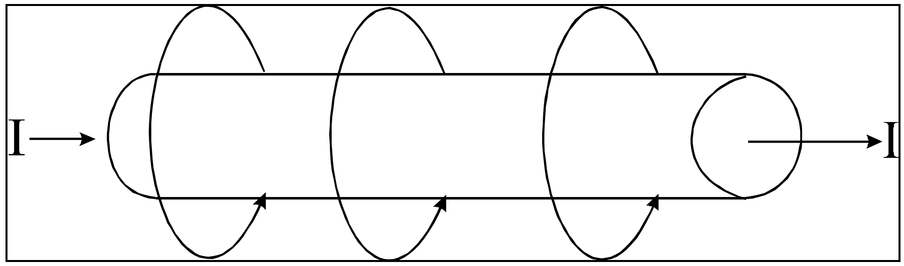

Figure 5-15 Electromagnetic field

The operation of a current sensor depends on the use of an electromagnet to generate a magnetic field. Electromagnets are based on the principle that when a current is passed through a conductor, a magnet field is generated around it. See Figure 5-15. The flux density at a point is proportional to the current flowing through the conductor. If the conductor is formed into a coil, the magnetic field from successive turns of the coil add. As a result, the magnetic field from a coil is directly proportional to the product of the number of turns in the coil and the current flowing through the coil.

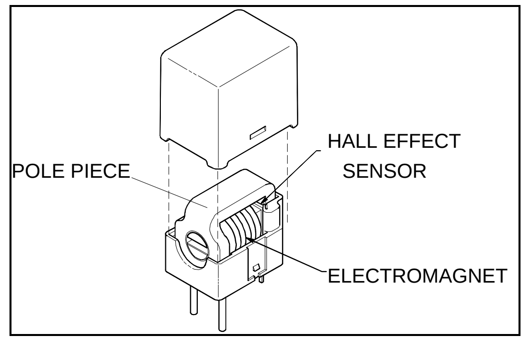

Figure 5-16 Current sensor with pole pieces

Conductors, coiled conductors or either of these in combination with pole pieces (magnetically soft materials) can be used as an electromagnet. Pole pieces are used in a current sensor, such as the one shown in Figure 5-16, to concentrate the magnetic field in a gap where a Hall effect sensor is positioned. The magnetic field in the gap is proportional to the current flowing through the coil.

For a digital output Hall effect sensor with operate and release points as indicated in Figure 5-17, the current sensor will turn ON when current I_2 is reached and OFF when the current drops to I_1. Ideally the current sensor will turn ON at the moment I_2 is reached. However, if the current level is changing rapidly, eddy currents (current induced by the time rate of change of flux density) will be induced in the pole pieces. In turn, these currents produce a magnetic field that opposes the input current, thus reducing the net flux density seen by the Hall effect sensor. The result is an apparent delay between the time I_2 is reached and the output turns ON.

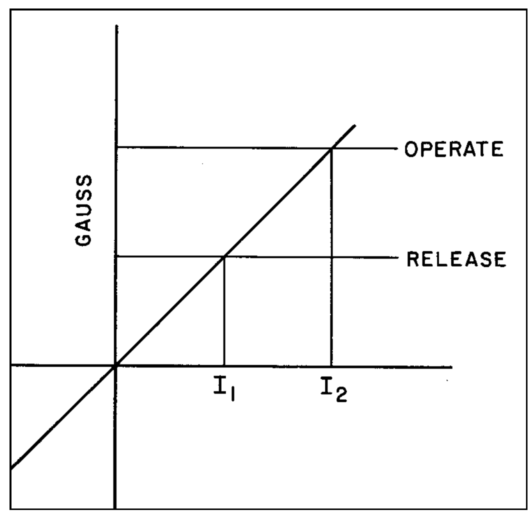

Figure 5-17 Current sensor transfer function

The same principles of operation apply when using a linear Hall effect sensor. Refer to Chapter 6 where design concepts for linear sensors are discussed.

Sensor specifications

Typical operational characteristics of a digital output current sensors are shown in Figure 5-18. The direct current (DC) operate and release characteristics of a digital output current sensor are specified in terms of an operate current (within a tolerance), and a minimum release current. Where a digital output current sensor is used to indicate a low current condition, the normal current will be greater than the operate level. Maximum continuous DC current specifies the largest continuous current that may be used in this type of application. Maximum coil resistance is used to calculate the voltage drop (insertion loss) across the coil and the power dissipated by the coil. Temperature stability is used to calculate the shift in operate and release characteristics of the sensor as a function of temperature.

Figure 5-18 Typical digital output current sensor specifications

DC Current				
Operate	**Min. Rel.**	**Max. Cont.**	**Max. Coil Resistance**	**Temperature Stability**
5 ± .25	3.8 A	25°C/20 A	5 mΩ	± .008 A/°C

Linear current sensors

A current sensor with an analog output can be made using a linear Hall effect sensor. The current sensor is constructed using a ferrite or silicon steel core and a Hall effect IC as shown in Figure 5-19. Both the core and the IC are accurately mounted in a plastic housing. The current passing through the conductor being measured generates a magnetic field. The core captures and concentrates the flux on the Hall effect IC. The linear response and isolation from the sensed current makes linear current sensors ideal for motor control feedback circuits.

The voltage output of the Hall effect IC is proportional to the current in the conductor. The linear signal accurately duplicates the waveform of the current being sensed.

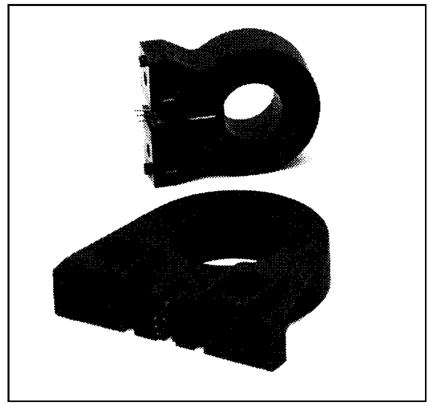

Figure 5-19 Typical linear current sensor

Principles of operation

Linear current sensors monitor the gauss level of the magnetic field created by a current flow, not the actual current flow. The current being measured is passed through a flux-collecting core that concentrates the magnetic field on the Hall effect sensor. The waveform of the sensor voltage output will trace AC or DC waveforms of the measured current. The through-hole design electrically isolates the sensor and ensures that it will not be damaged by over-current or high voltage transients. It also eliminates any DC insertion loss.

The Hall effect sensor is a ratiometric device. The output voltage of the sensor will be half of the supply voltage (V_{CC}) when the current in the conductor being measured is zero. The output voltage range is 25% of the supply voltage up to 75% of the supply voltage ($0.25\ V_{CC} < V_{out} < 0.75\ V_{CC}$). When the current is flowing in the positive direction, the output voltage will increase from the null ($V_{CC}/2$) towards 0.75 V_{CC}. See Figure 5-20 for an example of a linear current sensor output. When current is flowing in the opposite direction, the voltage output decreases from the null towards 0.25 V_{CC}. Since the sensor is ratiometric, sensitivity is also a functions of V_{CC}.

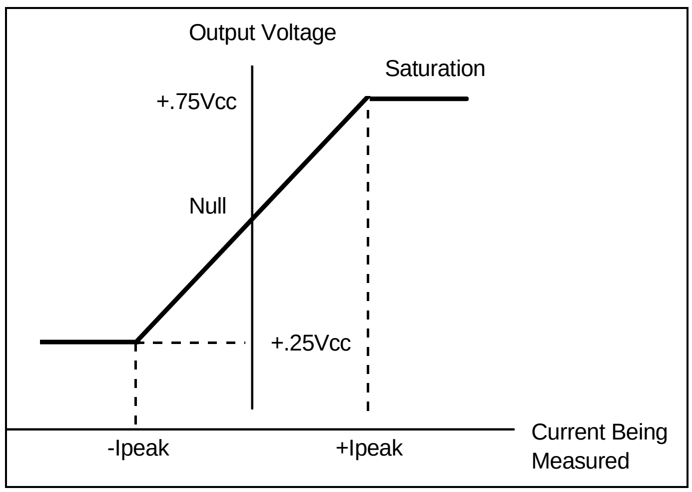

Figure 5-20 Linear current sensor ideal output

Current sensors are best used towards the maximum end of the sensed range. This will help with noise. To increase the current measured to a level near the maximum, the number of times the wire is passed through the core can be increased. For example, a 50 amp peak sensor could be used to measure a 10 amp peak conductor by looping the wire through the sensor aperture five times. Count the number of turns as the number of wire cross-sections in the core hole. The position of the wire in the core is not a major contributor to measurement error. The sensitivity of the sensor also increases as the number of times the conductor is passed through the hole.

As with Hall effect sensors, current sensors are subject to drift because of temperature changes. Linear current sensors can have their null offset voltage and the sensitivity change with temperature. Sensors with ±0.02 to ±0.05 percent per degree C offset shift are common. The change in voltage offset from temperature shift can be calculated as:

$$\Delta Voffset = \pm 0.0002 * \Delta Temp * Voffset \ @ \ 25C \qquad \textbf{(5-1)}$$

Values of the sensitivity shift are ±0.03 %/C typically. The change in sensitivity can be calculated in the same way as the null shift.

The flux collector is typically a ferrite or silicon-steel core. Core material is selected on the basis of saturation and remanance. At some point, a core material will not collect additional flux and is defined to be saturated. When this happens, the sensor will no longer supply an increasing voltage output to increasing conductor field strength. Remanance is the residual flux that is present in the core after the excitation of the current sensor. The remanance will create a shift in the null offset voltage. The air gap in the core also has an effect on the saturation point. By varying the width of the gap, the level of current that produces the amount of gauss necessary to saturate the sensor is varied.

Typical sensor characteristics are provided in Figure 5-21

Supply Voltage (Vdc)	Supply Current (mA max)	Offset Voltage (Volts 2%)	Offset Shift (%/ c)	Response Time (μsec)
6 to 12	20	Vcc/2	± 0.02	3

Figure 5-21 Typical linear output current sensor characteristics

Closed Loop Current Sensors

Another application of Hall effect technology in current sensing is the closed loop current sensor. Closed loop sensors amplify the output of the Hall effect sensor to drive a current through a wire coil wrapped around the core. The magnetic flux created by the coil is exactly opposite of the magnetic field in the core generated by the conductor being measured (primary current). The net effect is that the total magnetic flux in the core is driven to zero, so these types of sensors are also called null balance current sensors. The secondary current in the coil is an exact image of the current being measured reduced by the number of turns in the coil. Passing the secondary current through a load resistor gives a voltage output.

The closed loop current sensor has some very desirable characteristics. The feedback system responds very fast, typically less than one microsecond. Frequency response bandwidth is typically 100 kHz. Closed sensors are very accurate with linearity better than 0.1%. All of these specifications exceed what is possible with open loop linear sensing. However, the higher cost, larger size, and increased supply current consumption of the closed loop sensors must be balanced with the application's requirements for accuracy and response.

Principles of Operation

The closed loop sensor has several more components in addition to the core and Hall effect sensor used in the open loop linear sensor. The feedback electronics including an operational amplifier and the coil are the significant additions. Figure 5-22 shows the construction of a typical closed loop sensor.

The primary current being measured (Ip) creates a magnetic flux in the core just as in the open loop linear sensor. The core is made up of thin pieces of steel stacked together to give high frequency response. The Hall effect sensor in the core gap measures the amount of flux in the core. As with the open loop sensor, the voltage output of the Hall effect sensor is proportional to the current Ip. The output of the Hall sensor is amplified in the compensation electronics. The current output of the compensation electronics (Is) creates a second magnetic field in the coil. The magnitude of this secondary field is the product of current Is times the number of turns in the coil (Ns). The magnetic flux from the secondary coil cancels out the flux from the primary to zero. The feedback system of the current sensor is shown in Figure 5-23.

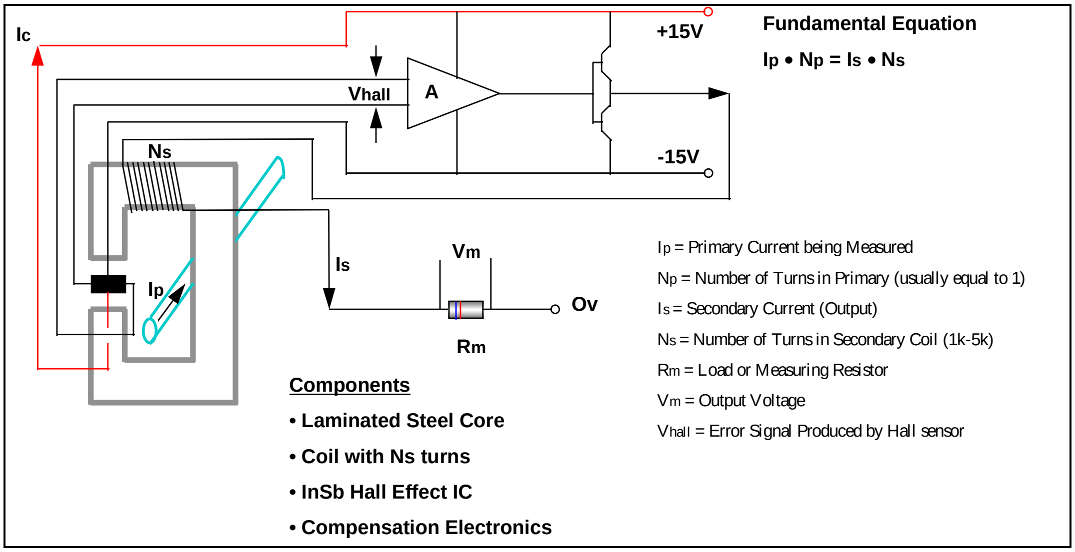

Figure 5-22 Closed loop current sensor construction

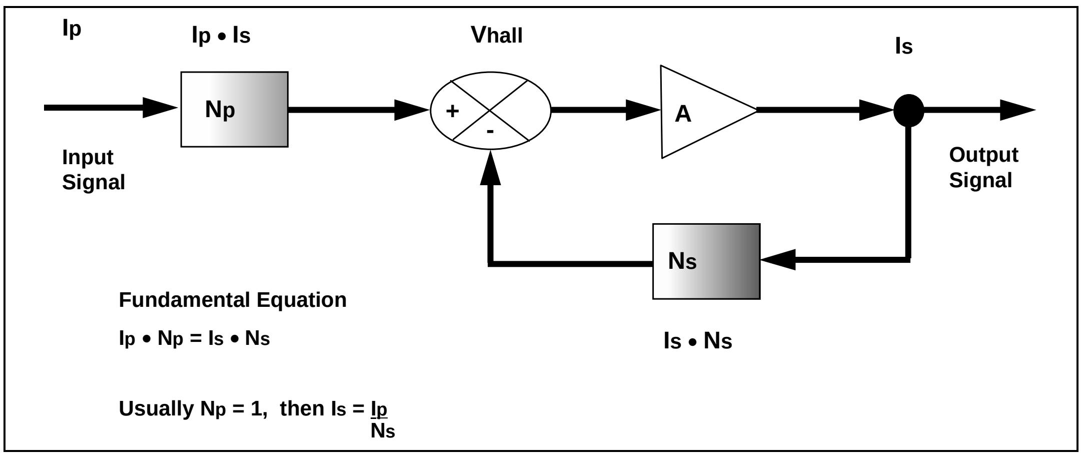

Figure 5-23 Block diagram showing feedback system

The output of the closed loop current sensor is the secondary current Is. When the current is passed through a measuring or load resistor, the output becomes a voltage that is proportional to the primary current being measured. DC, AC, and impulse currents can be accurately measured and waveforms duplicated. The selection of the load or measuring resistor has a major impact on the maximum current that can be sensed. The maximum measuring range of Is is determined by the supply voltage available and the selection of the measuring resistor according to the following equation:

$$Is = \frac{Vsupply - Vce}{Rm + Rs}$$

where:

Vsupply = the supply voltage available (in Volts)
Vce = the saturation voltage of sensor output transistors (typ. 3.5V max.)
Rm = the measuring or load resistor value (Ω)
Rs = the resistance of the internal secondary coil Ns (Ω)

The maximum current that can be sensed will increase with the selection of a lower load resistance. See Figure 5-24 for an example output range of a 300 amp nominal closed loop current sensor.

The output current is not exactly zero when the primary current Ip is zero. There is a small offset current from the operational amplifier and Hall effect sensor. This current is typically less than ±0.2 mA. Accidental distortion of the offset can occur if the magnetic circuit is magnetized by a high DC current when the sensor is not powered up. This value is usually limited to 0.5 mA. Finally, there will be a drift in offset current with temperature changes. The drift is caused by the operational amplifier and the Hall sensor changing values of temperature. The offset error is typically limited to ±0.35 mA.

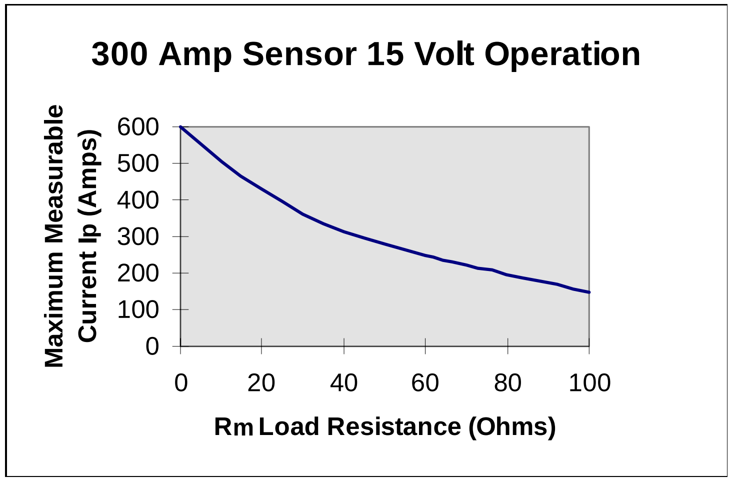

Figure 5-24 300 Amp sensor output range

Mechanically operated solid state switches

The mechanically (plunger) operated solid state switch is a marriage of mechanical switch mounting convenience and solid state reliability. These switches consist of a magnet attached to a plunger assembly and a Hall effect sensor mounted rigidly in a package as shown in Figure 5-25. From an external viewpoint, the solid state switch has characteristics similar to a traditional mechanical snap-action switch. High reliability, contactless operation, and microprocessor compatible outputs are the primary distinguishing features.

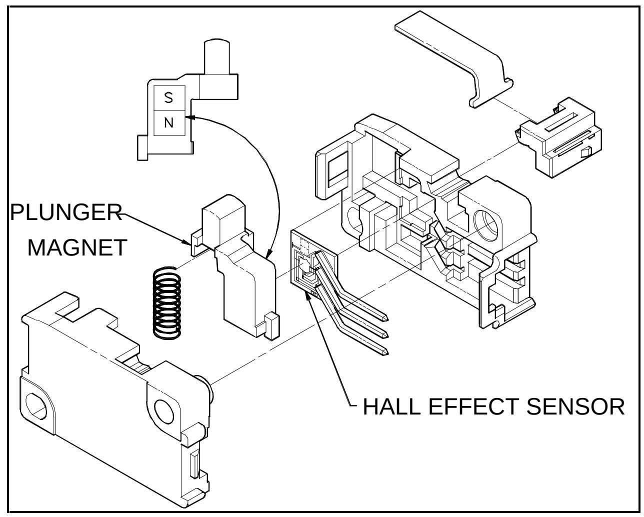

Figure 5-25 Typical solid state switch (normally OFF)

Principles of operation

The solid state switch shown in Figure 5-25 employs a magnet pair to actuate a digital output Hall effect sensor. These magnets are mounted in the bipolar slide-by mode, to provide precision operate and release characteristics.

For the magnet pair shown in Figure 5-25, the north pole is normally opposite the sensor maintaining the switch in a normally OFF state. When a plunger is depressed, the south pole is brought into proximity to the sensor, turning it ON. This type of switch is referred to as normally OFF.

A normally ON switch will result from reversing the magnet pair. The south pole is normally opposite the digital output Hall effect sensor, maintaining the switch is a normally ON state. When the plunger is depressed, the north pole is brought near the sensor, turning it OFF.

Switch specifications

The operating characteristics of a typical mechanically operated solid state switch are shown in Figure 5-26. These characteristics are defined below.

Pre-travel	The distance the switch plunger moves from the free position to the operating point
Operating point	The position of the plunger, relative to a fixed point on the switch, where the sensor will change state
Over-travel	The distance the plunger may be driven past the operating point
Differential travel	The distance between the switch's operating point and release point
Operating force	The mechanical force necessary to depress the plunger

Pre-travel (max.)	**Operating Point**	**Over-travel (min.)**	**Differential Travel (max.)**	**Operating Force (ounces)**
2,16 mm .085 in.	14,73 mm .580 in.	1,02 mm .040 in.	0,30 mm 012 in.	.35 +.18 (-.14)

Figure 5-26 Typical solid state switch operating characteristics

Detailed information on the use of precision switches can be found in MICRO SWITCH General Technical Bulletin No. 14, Applying Precision Switches, by J. P. Lockwood.

Gear Tooth Sensors

A gear tooth sensor is a magnetically biased Hall effect integrated circuit to accurately sense movement of ferrous metal targets. An example of an assembled gear tooth sensor is shown in Figure 5-27.

The IC, with discrete capacitors and bias magnet, is sealed in a probe type, non-magnetic package for physical protection and cost effective installation. See Figure 5-28 for typical construction of a gear tooth sensor and wiring diagram.

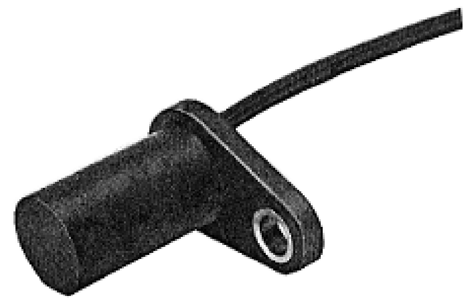

Figure 5-27 Gear tooth Hall effect sensor

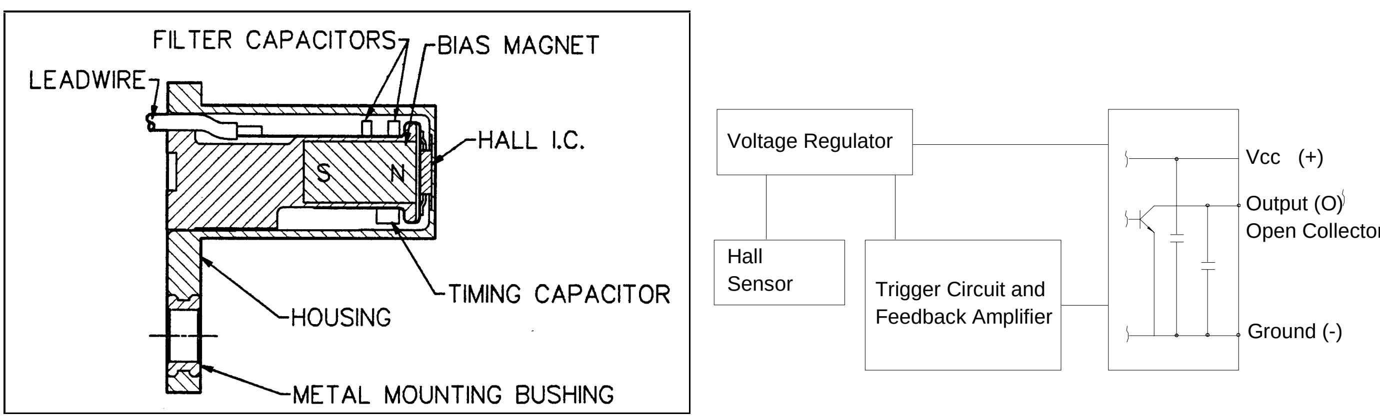

Figure 5-28 Gear tooth sensor construction and wiring diagram

Principles of Operation

As a gear tooth passes by the sensor face, it concentrates the magnetic flux from the bias magnet. The sensor detects the change in flux level and translates it into a change in the sensor output. The current sinking (normally high) digital output switches between the supply voltage and saturation voltage of the output transistor. See Figure 5-29 for sensor output.

A thin film laser-trimmed resistor network in the preamplifier/trigger circuit is used to set and control the Hall element offset voltage and operate point. The sensor output is an open collector switching transistor, which requires a pull-up resistor.

A feedback circuit is integrated into the silicon IC and is used to reduce the effects of temperature and other variables. It uses a discrete capacitor to store a reference voltage that is directly proportional to the no-tooth magnetic field strength. This design requires that one target space must be moved past the sensor on power up to establish the reference voltage. The trigger circuit uses this voltage to establish the reference level for the operate point.

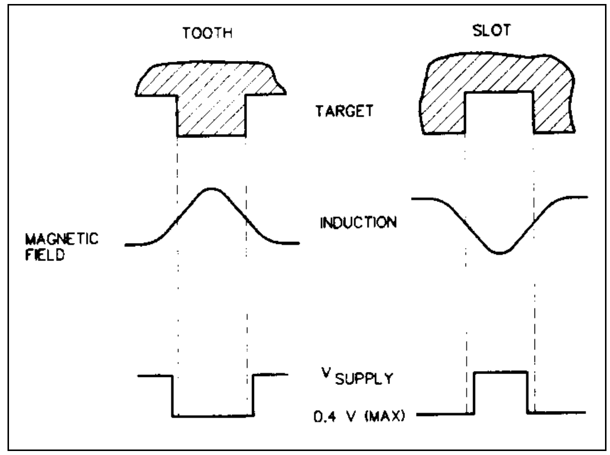

Figure 5-29 Sensor output (with pull-up resistor added to output circuit)

When the magnetic field sensed by the Hall element changes by a pre-defined amount, the signal from the Hall element to the trigger circuit exceeds the trigger point and the output transistor switches ON (low). The trigger circuit switches the transistor output OFF (high) when the Hall signal is reduced to less than 75% of the operate gauss.

Target Design

The optimum sensor performance is dependent on the following variables to be considered in combination:

- Target material, geometry, and speed
- Sensor/target air gap
- Ambient temperature
- Magnetic material in close proximity to the sensor and target

Figures 5-30, 5-31, and 5-32 show some of the typical tradeoffs involved with these variables. The operate point is defined as the distance from the leading edge of a tooth to the mechanical center of the sensor where the output changes from a high to a low voltage state. It is expressed in angular degrees.

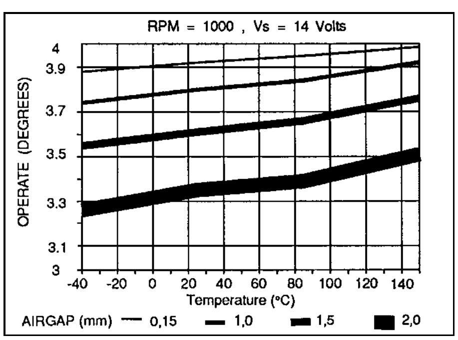

Figure 5-30 Operate Point vs. Temperature

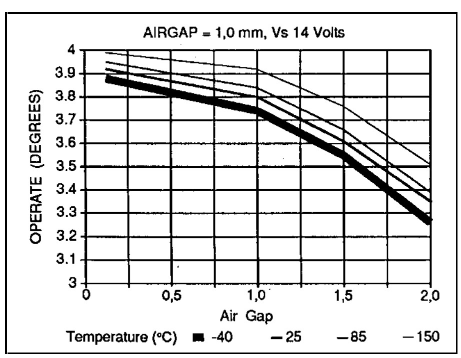

Figure 5-31 Operate Point vs. Air Gap

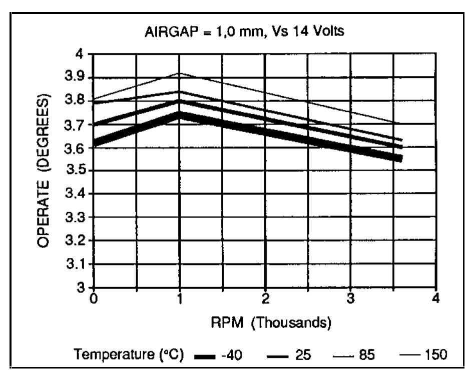

Figure 5-32 Operate Point vs. Target Speed

The following information will help in the design of a new target toothed wheel or to evaluate an existing target. The target should be made from a good magnetic material with less than 25 gauss residual magnetization. Cold rolled steels (1010-1018) are ideal. Other soft magnetic materials such as 430 stainless steel or sintered powdered metals may be used with a change in operating characteristics of less than 5%.

It is important to maximize the amount of magnetic flux available to the sensor; this will optimize the sensor's performance. See Figure 5-33 for target geometry. Increasing the tooth spacing width and the tooth height up to a certain point will maximize sensor performance. Increasing these dimensions beyond that will have little effect on the sensor.

A signature pulse can be used to indicate specific angular positions. There are two ways to provide a signature pulse: wide tooth and wide slot. Wide tooth is the simplest method. It is achieved by filling in the space between two or more teeth to make one large tooth. The advantage of this method is the spacing between the remaining teeth is uniform, insuring optimum performance.

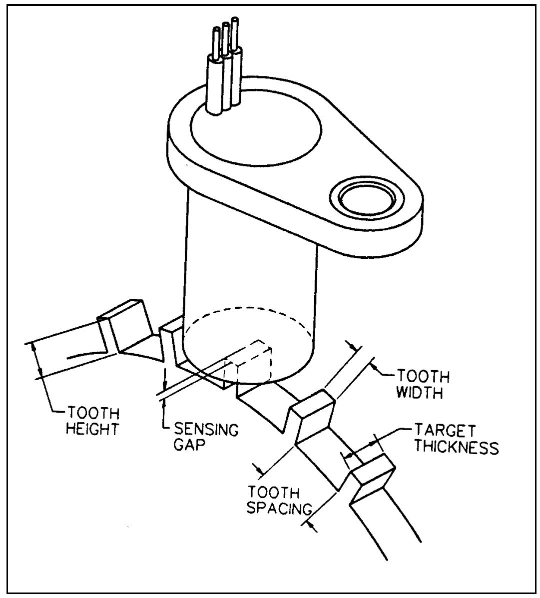

Figure 5-33 Target Geometry

The second method, wide slot, also achieves excellent results. A requirement for good target performance is that the magnetic level of the spaces between the teeth of the target be approximately the same. This can easily be done by decreasing the depth of the signature space to give it magnetic characteristics that are similar to those of the normal spaces. When this is done, the target performance will be the same as if the target had uniform spacing widths.

Target speed is the most critical detecting both the leading and trailing edge of a tooth. Gear tooth sensors can provide consistent indication of one or both edges. To achieve the highest accuracy and stability in such applications as speed sensing and counting, detection of the leading edge (operate point) is the most accurate.

At very low speeds, the output can change state due to time out (output goes high) prior to the trailing edge of the target passing the sensor. The time out is because of capacitive coupling of the feedback circuit on the IC and can vary with target geometry, air gap, and target speed. The output affects only the trailing edge (release point).

Summary

In this chapter, the principles and specifications of Hall effect based sensors have been examined. In conjunction with the information presented in Chapter 4, the techniques necessary to apply sensors have been established. The next chapter brings together the information in this and previous chapters and demonstrates how it is applied.