Chapter 6

Proximity-Sensing Techniques

Sensing an object's presence or position are two of the most widespread applications in which Hall-effect sensors are used. Magnetic field sensors are well suited for this kind of application for two reasons. The first is that magnetic fields are not significantly affected by nonmagnetic materials and pass through them unhindered. The second reason is that strong magnetic fields do not occur often in nature (at least on Earth) and if a strong magnetic field is encountered, it is usually manmade. Strong magnetic "interference" sources are not very common. This rarity of accidental sources of magnetic interference makes a strong magnetic field a good indicator. While most objects one might want to detect won't produce significant magnetic fields, it is usually a simple enough matter to affix a small permanent magnet to them to provide a readily detectable field.

This chapter will describe some of the ways in which permanent magnets and Hall-effect sensors can be used to detect proximity and measure position of objects.

6.1 Head-On Sensing

When people begin working with Hall-effect sensor ICs, one of the first things they usually do is to take a permanent magnet and bring one of the poles up to the device to activate it—to "try it out." This operation mode is called *head-on* actuation, and is shown in Figure 6-1a. Head-on actuation is one of the most common methods for activating Hall sensors in binary (on-off) proximity detection applications.

In a head-on application, the sensitive axis of the sensor and the axis of magnetization are co-linear. The magnetic flux-density that the Hall-effect sensor sees as a result of being approached by a magnet pole is highly nonlinear with respect to magnet-sensor airgap. It decreases rapidly as airgap increases, as shown in Figure 6-1b. A curve like this, relating magnetic flux to physical position, is called a *flux map* or a *magnet map*. Such maps are an extremely valuable tool for developing Hall-effect-based applications, and will be used throughout this and subsequent chapters.

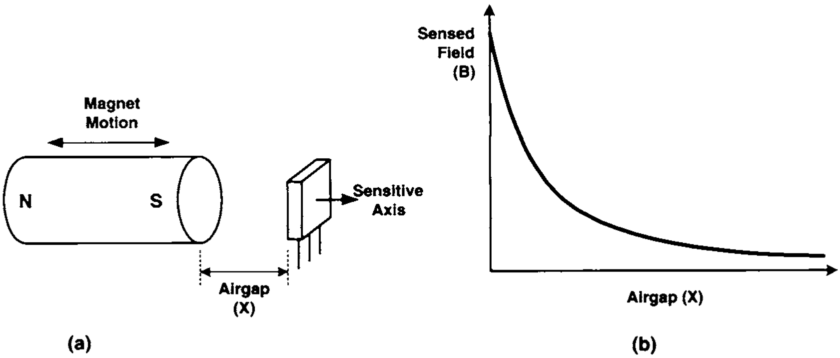


Figure 6-1: Head-on actuation mode (a) and flux density vs. airgap (b).

To get a present/absent binary output, switch-type digital Hall sensors are used in a head-on sensing system. As one approaches the magnet, the field increases as an inverse function of distance. When the field exceeds the operate point (B_{OP}) of the sensor, it will activate. As one moves away from the magnet, the sensor will deactivate when the field drops below its release point (B_{RP}). Because the magnet's field along its axis of magnetization always remains the same polarity regardless of the distance traveled along that axis, a switch-type device must be used if one wants the sensor to turn OFF. Figure 6-2 shows how mechanical operate and release points can be determined from superimposing the magnetic B_{OP} and B_{RP} points on a flux map.

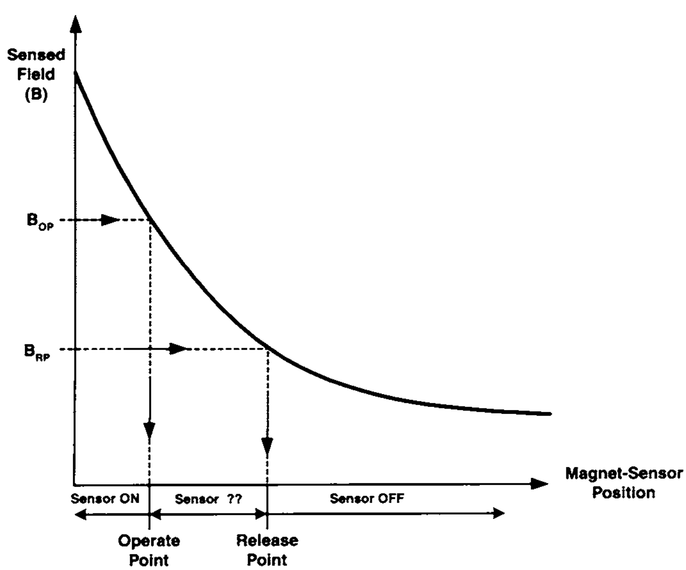


Figure 6-2: Determining mechanical operate and release point from B_{OP}, B_{RP} and a flux map.

While it is possible to get consistent mechanical operate points by using a sensor with a high B_{OP} switch point, so that it turns ON close to the face of the magnet, release points tend to be less consistent, especially for parts with large hysteresis values (B_H). This is because the gradient of field vs. distance is greater near the magnet than further away. This means that the closer you get to the magnet, the more sensitive the field measurement will be as a function of position. The nonlinear character of the magnetic field vs. distance also makes it difficult to design a magnet-sensor combination that meets an arbitrary specification for mechanical turn-on and turn-off points. For these reasons, head-on sensing is often best employed in applications where tight position-sensing tolerances are not necessary.

One can also use a linear-output sensor in an effort to measure the actual magnet-to-sensor distance. The nonlinear flux vs. airgap characteristics of head-on make it less than optimal for most linear position measurement applications. Later in this chapter we will discuss magnetic systems that are more suited for sensing linear position.

6.2 Slide-By Sensing

Another common way of using a Hall-effect sensor as a proximity detector is by sliding the pole-face of a magnet past the device, as shown in Figure 6-3a. In this scenario, the magnet's axis of magnetization and the sensitive axis of the Hall sensor are both parallel, but the magnet moves perpendicularly to the axis of magnetization. This sensing method is particularly useful when there is a significant chance that the magnet will travel past its normal end-stop position. In the case of a head-on sensing configuration, such over-travel could damage either the sensor or the magnet.

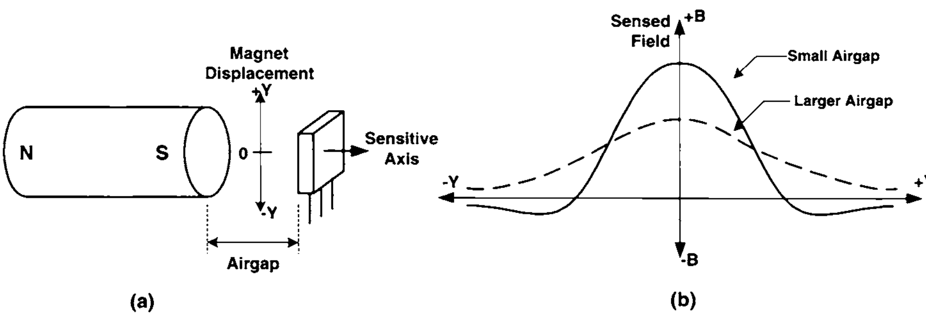


Figure 6-3: Slide-by actuation mode (a) and resultant flux vs. position (b).

Because the magnet can travel past the sensor, the slide-by configuration is only useful for indicating when the magnet is actually in front of the sensor; if one uses this configuration for an end-of-travel indicator, then a separate mechanical stop must be provided to limit the magnet movement.

In situations where it can be used, the slide-by configuration provides some significant advantages over the head-on configuration. The first is that, as the magnet moves from the center ($x = 0$) position, the sensed magnetic field may eventually drop slightly negative, as shown in Figure 6-3b. This occurs because when the sensor is off center past the edge of the magnet, it will be sensing the field returning back to the rear pole. This provides a guaranteed turn-off for any kind of switch-type ($B_{RP}>0$) Hall IC. This effect will be particularly pronounced for small sensor-to-magnet airgaps. The physical displacement at which the field crosses zero is also fairly consistent with respect to small variations in the effective gap between the magnet and sensor. This means that by using a Hall switch with low B_{OP}/B_{RP} points, consistent physical operate and release points can be obtained. This also means that the width of the ON region can be controlled by the width of the magnet employed. In many cases, for a switch with sufficiently low B_{OP} and B_{RP} points, the width of the on-state region will closely match the width of the magnet pole-face, even over significant variations in magnet-to-sensor spacing. Because the negative field past the magnet edges may be small in relation to the positive field at the magnet face, a switch-type sensor will often be the best choice of sensor type because the negative field eventually tapers off to zero at some distance, and even at the magnet edge may be insufficient to provide a guaranteed turn-off for a latch-type sensor.

6.3 Magnet Null-Point Sensing

While the last sensing methods relied on detecting some finite positive field to trip a sensor, the next class of sensor-magnet configurations to be discussed rely on detecting null-points in the field around a magnet, or places where the net field in a particular axis is zero. These techniques are especially useful in situations where a high degree of switching accuracy over a small amount of total travel is needed. Using positive flux to denote the ON region and negative flux to denote the OFF region provides several advantages:

- The positions of magnetic null points tend to be stable over temperature, especially for magnetic systems consisting of a single magnet of a single material.
- Highly sensitive symmetric latch-type Hall ICs can be used. These parts, particularly auto-nulling types, can be very stable over variations in temperature and power supply conditions.
- It is possible to create very sharp transitions between negative and positive fields with the proper magnetic circuits, allowing for fine control of actuation points. The rate of this transition is referred to as the *gradient*.

Figure 6-4 shows two methods of developing a magnetic null point from a single magnet. The arrow emanating from the sensor indicates the sensitive axis. Both of these techniques are useful in slide-by type applications.

The configuration of Figure 6-4a detects the normal (perpendicular) flux emanating from one of the nonpole sides of a rectangular bar magnet. Halfway between the poles, this flux is zero, and gets stronger as one approaches either pole (this is why steel objects aren't attracted to the middle of bar magnets, but to the ends).

Figure 6-4b shows a sensor oriented to detect the flux parallel to a magnet pole face. Because the flux diverges from the pole, its pole-surface-parallel component is negative to the left of centerline, positive to the right of the pole center, and zero at the centerline.

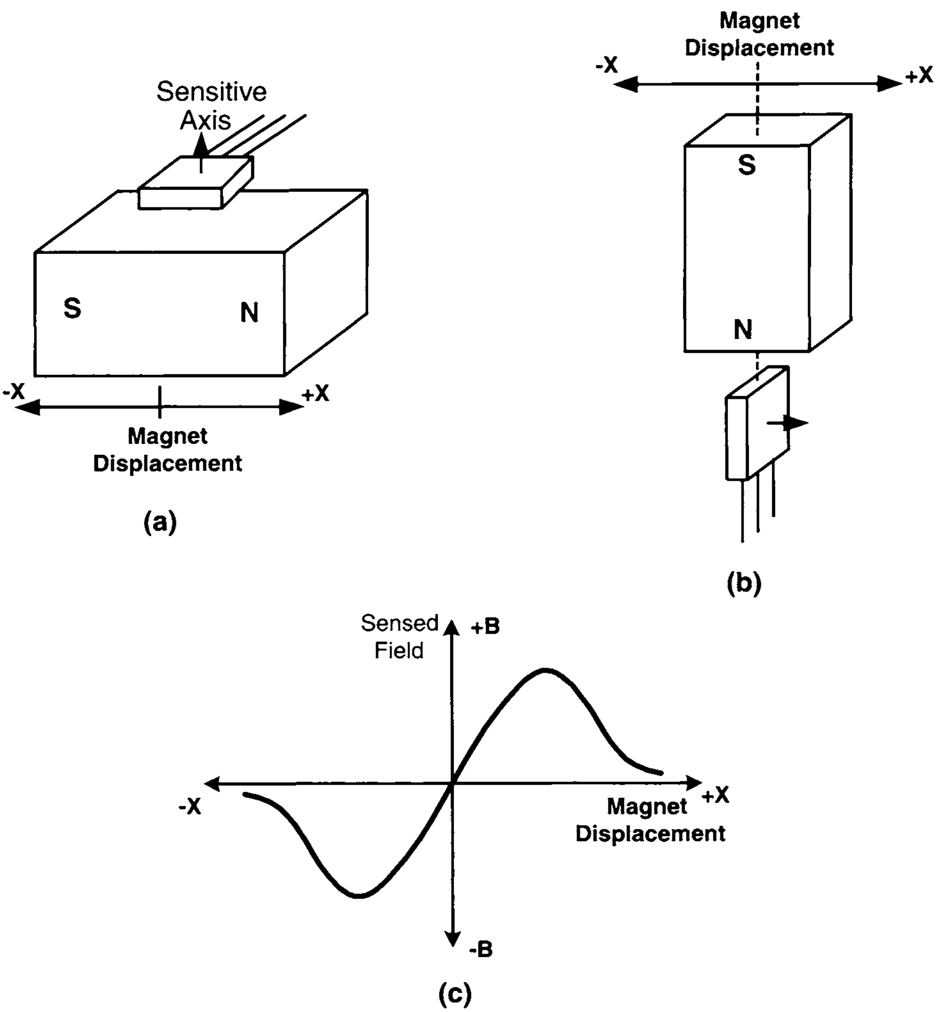


Figure 6-4: Methods of creating magnetic null-points.

Although both of these configurations will provide roughly the response shown in Figure 6-4c, there can be significant differences both in the shape and magnitude of the response, resulting from measuring the field at the pole face versus measuring the field along the length of the magnet. Because the packaging of most Hall-effect sensors allows one to position the transducer element closer to the magnet surface in the example presented in Figure 6-4a, this configuration will usually provide the highest magnetic gradients, and the sharpest switching points of the two alternatives.

In general, when using comparable magnets, the configuration of Figure 6-4a will tend to provide both a greater response and steeper gradients than the configuration of Figure 6-4b.

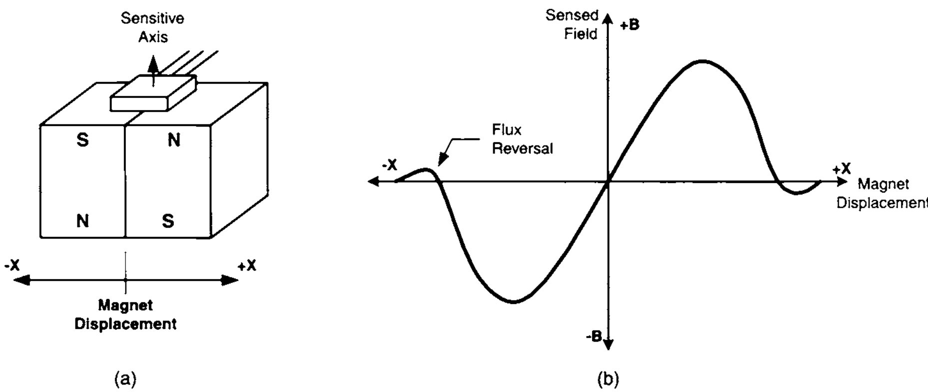


Figure 6-5: Developing high magnetic gradients with a compound magnet.

To develop even sharper gradients, the system shown in Figure 6-5 may be used. By placing two magnets alongside each other in an antiparallel configuration, a very sharp transition in the flux normal to the pole-faces can be made to occur, because of the abrupt transition between the north and south poles. One disadvantage of this approach, however, is that fringing effects cause flux reversals past the pole faces, as previously discussed in the case of the slide-by configuration. If the magnetic sensor is either sufficiently sensitive, or sufficiently close to the actuator magnet pair, false actuation can occur when using a compound magnet.

In all of the above cases, it should be noted that if one uses a latch-type digital Hall-effect sensor, the output will only be valid when the sensor is actually close enough to the magnet to be positively switched either ON or OFF. Because a switch-type sensor will be OFF in the absence of magnetic field, it provides an indication that the magnet is not present. If a latch-type sensor, however, is moved far enough from the magnet so that it is no longer affected by it, it will simply maintain whatever its last state was. Similarly, if the latch-type sensor is outside the influence of the magnet when it is powered up, its state is unpredictable. If one plans on using latch-type devices in a magnetic null-point sensing configuration, provisions must be made to either ensure that the magnet does not over-travel past the sensor, or that some separate indication of over-travel conditions is provided.

One example of a system in which a null-point sensor could be useful is a linear rail positioning system. In a linear rail positioning system, a bearing block travels back and forth along polished steel rods, often propelled by either a lead screw or a drive belt. In many of these systems, it is important to know when the block has reached its end of travel, primarily so that the system has an absolute position reference (home position), and secondarily so that the system is not mechanically damaged by over-travel. An example of how a null-point sensor might be used in such a system is shown in Figure 6-6.

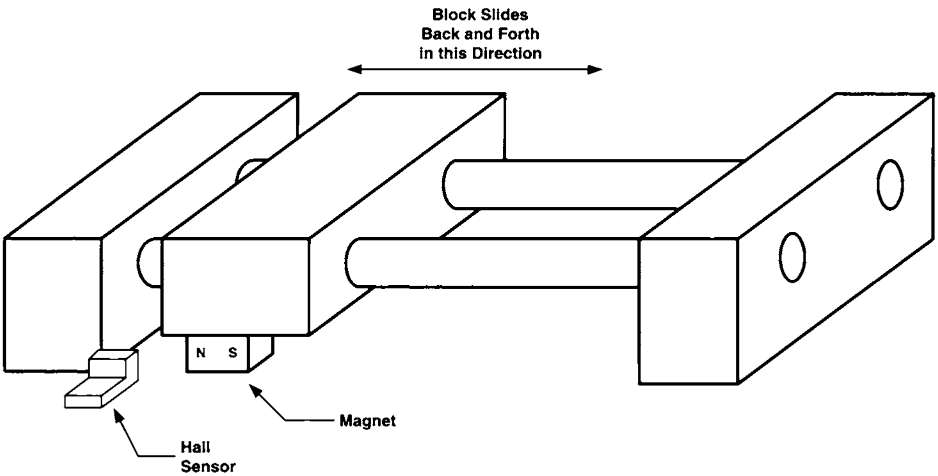


Figure 6-6: Linear rail guide system with Hall-effect home-position sensing.

Because the state of the sensor should always be HIGH when the bearing block is anywhere between its physical end-of-travel position and the home position, one needs to position the magnet and sensor so that they provide a response such as that shown in Figure 6-7.

In this system, "end-of-travel" is indicated by a ON output from the Hall-effect sensor. Because it is important to be sure when the bearing block is near the end-stop or not, a sensitive switch should be used instead of a latch. This will ensure that the "near-home" status (ON) will only be reported when the bearing block is actually near the end-stop. The home position itself is determined as where the sensor makes the OFF-ON transition. Because the magnetic hysteresis of the sensor will translate into hysteresis in the mechanical measurement, the home position will therefore be slightly different depending on the direction in which it is encountered. For this reason the

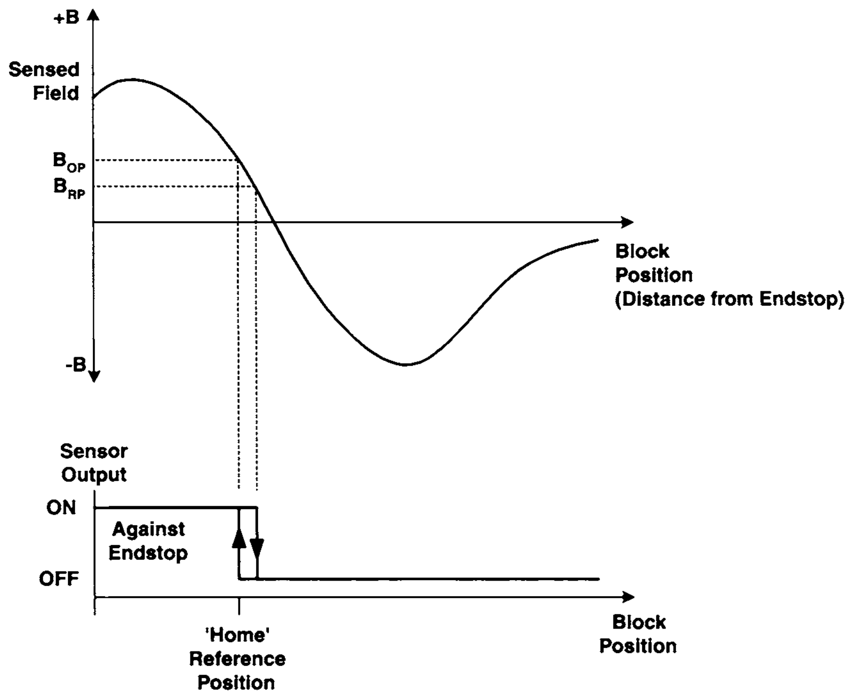


Figure 6-7: Response of Hall-effect home-position sensor.

home position must always be determined when moving in the same direction (i.e., towards the end-stop). With selection of an appropriate magnet and sensor, home position repeatability and mechanical hysteresis on the order of a few-thousandths of an inch are possible. This performance would be difficult, if not impossible, to achieve with the simpler head-on and slide-by configurations.

6.4 Float-Level Sensing

One position-sensing application that uses yet another magnetic configuration is float-level sensing. In this application, the sensor assembly is typically used to measure the level of a liquid or to determine whether that level exceeds some given low-point or high-point. Figure 6-8 shows a schematic view of a Hall-effect-based float-level sensor. A donut-shaped ring magnet is used to provide the actuating field. This magnet surrounds a shaft and is free to both move along the stem and may also be allowed to rotate. The magnet is embedded in a float assembly, which can be a hollow ball, or a piece of buoyant material such as closed-cell plastic foam. Inside the shaft are one or more Hall-effect sensors, which are used to detect the position of the magnet.

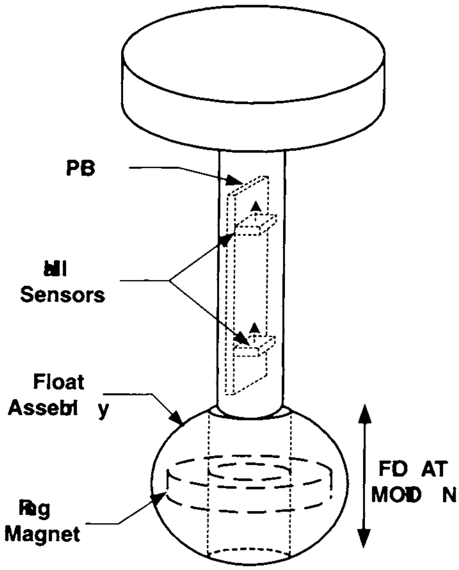
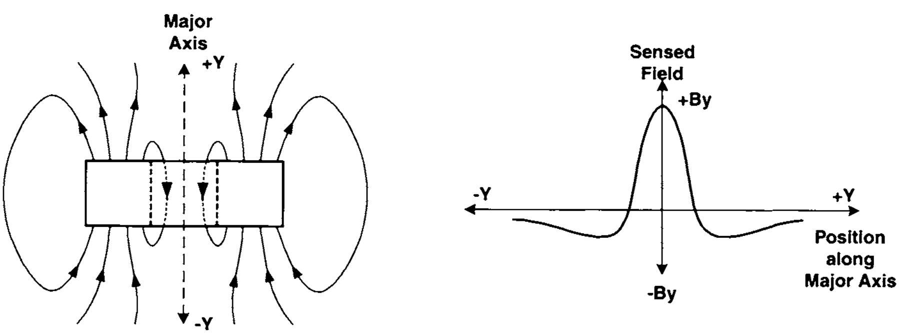


Figure 6-8: Example of liquid-level sensor using float magnet and Hall-effect sensors.

In this magnetic configuration, the ring magnet is magnetized parallel to its major axis (through the donut-hole). If the inner diameter of the ring magnet is of comparable dimension to its height, there will be a significant field inside the inner diameter, with a polarity opposite to that in which the ring magnet is magnetized. The sensors in the stem are oriented so that they detect the field aligned along the direction of the stem. Figure 6-9 shows a cross section of the field surrounding a ring magnet, and also a graph of the field along the major axis.



(a) (b)

Figure 6-9: Cross section and graph of flux-density along major axis of axially magnetized ring magnet.

When designing a float-level sensor, there are a few points worth keeping in mind. First, if one is trying to make a minimum or maximum level switch, one must put a mechanical end-stop at the appropriate points to make sure that the float doesn't travel past the sensor. If one is trying to determine actual level, as opposed to merely making a less-than/greater-than type of measurement, one must use multiple sensors spaced along the length of the stem. In this case it is important to make sure that the sensors are spaced closely enough together so that the magnet actuates at least one of them at all times; otherwise you will have measurement "dead-spots." Finally, because the field inside the ring magnet's inner diameter does not present any steep gradients, it can be difficult to make a float sensor with highly accurate trip points (unit-to-unit) when using this magnetic configuration. Low trip-point accuracy can be worsened by the use of floats that fit loosely on the stem and are allowed to tip into an off-axis orientation. Despite potential issues of low trip-point accuracy, this configuration provides a simple and robust solution to the problem of measuring liquid level.

6.5 Linear Position Sensing

In addition to being useful as binary presence/absence detectors, Hall-effect sensors can be used to measure continuous displacement. To perform this measurement requires two items: a linear-output Hall transducer, and a magnetic circuit that provides a magnetic field that varies monotonically as a function of displacement over some specified range of motion. While a linear magnetic response is not essential, as "correction" can be applied later, either electronically or in software, a linear response does make the system easier to work with. If the magnetic response versus displacement is sufficiently linear, no correction may be needed in many applications.

Simple continuous position sensors can be implemented by taking any of the proximity-sensing schemes described above and replacing the digital sensor with a linear output device. While such implementations may be useful for particular applications, they suffer because the output will be significantly nonlinear with respect to position. Another problem encountered will be sensitivity to mechanical tolerance between the magnet and the sensor.

Fortunately, there are several magnetic configurations that can provide near-linear flux density as a function of mechanical displacement over distances comparable to the size of the magnets employed. One such scheme employs two magnets held a fixed distance apart by a nonmagnetic yoke with similar poles facing, as shown in Figure 6-10. The flux density in the X direction between the two magnets varies from negative minimum at one pole face, reaches zero halfway between the poles, and increases to a positive maximum at the pole face of the other magnet. Near the halfway point, the slope is nearly constant, resulting in a region with an approximately linear transfer function. One feature of this arrangement is that it is possible to select magnets that will provide a linearly varying field over most of the distance between them. If the dimensions of the pole faces are large compared to the pole separation, the field as seen by the Hall-effect sensor will also be relatively insensitive to translations in sensor position in directions other than the X axis.

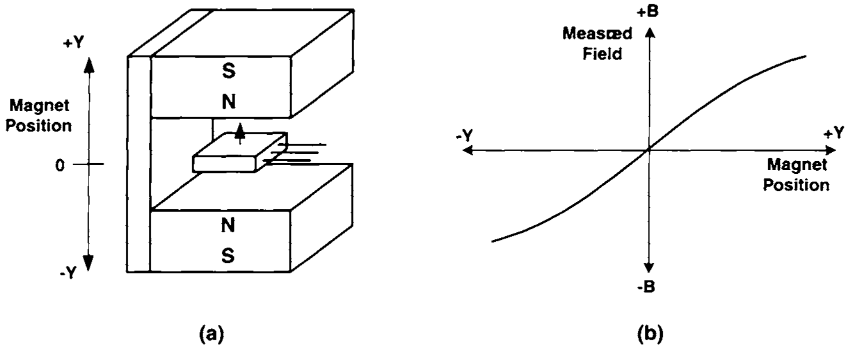


Figure 6-10: Magnets arranged to give linear varying field in gap.

Although this arrangement provides a magnetic flux density proportional to displacement, with a zero-flux null point in the middle, it doesn't allow for the possibility of over-travel. When one cannot guarantee that the magnets won't stop moving before they hit the sensor, the magnet configuration of Figure 6-11 can provide an alternative solution.

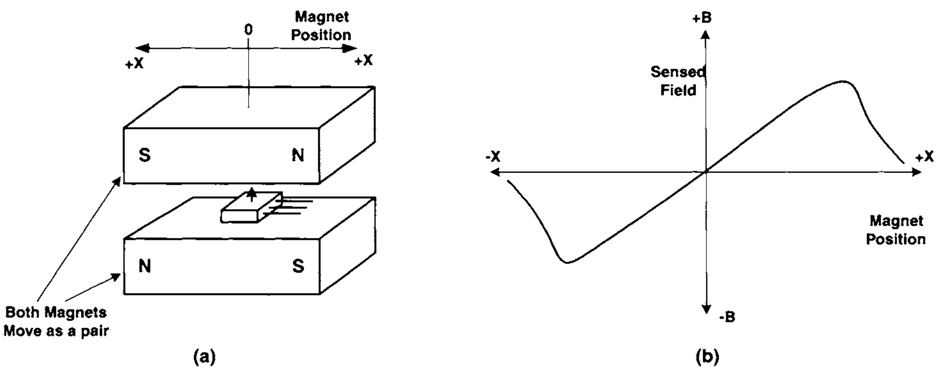


Figure 6-11: Another linear flux density vs. position scheme.

The advantage of this latter arrangement is that the sensor won't crash into the magnets under an over-travel condition. With the appropriate selection of magnet materials and geometries, it also provides a linear flux variation in response to motion. The primary drawback is that, as the sensor moves out of the gap in the direction of travel, the measured flux begins to drop, which can cause false position readings. For this reason, one still needs to consider the effects of over-travel, but from a system performance standpoint.

When considering the use of one of the above schemes, there are several issues to keep in mind. The first is that the length-of-stroke over which measurements can be made will be comparable to the size of the magnets. Unless one wants to use very large magnets, one will be limited to small ranges of mechanical measurement.

The second issue is in choice of magnet materials. While rare-earth magnet materials such as NdFeB or SmCo are often a logical choice for actuators in a binary (On/Off) proximity detection system because of their high field strength, they may not be as efficacious in a linear position-sensing system. This is because many linear sensor ICs are designed to operate over the range of ±1000 gauss or less; the 3000–5000 gauss obtainable from a rare-earth actuator can saturate the sensor, shortening the effective measurement range to a small fraction of the total mechanical travel. In cases where linearity over a wide travel range is required, the use of Alnico or ceramic magnets should also be considered, as their flux output in many configurations is comparable to the sensing range of many linear Hall-effect sensors.

While we have described the magnetics required to obtain linearity, we have ignored issues such as offset and span. Offset errors will result from assembly tolerances and from inhomogeneities in the magnets. Span errors will result from variations in magnetization, as well as from tolerancing errors. As long as the resulting system (magnetics+sensor) is linear, however, offset and span can often be accounted for and trimmed out downstream from the sensor in subsequent signal processing.

6.6 Rotary Position Sensing

Sometimes one needs to know the angular as opposed to the linear position of an object. While it is possible to create mechanical linkages that convert a rotary motion into a linear displacement, there are also ways to measure rotary motion directly. Figure 6-12 shows one of the simplest methods, which is to rotate a uniform field around a Hall-effect sensor.

If the Hall-effect sensor is placed at the center of rotation, it will always be exposed to the same field, but from a different direction. Because a Hall-effect sensor only is responsive to field components in a single axis, this results in a response that is of the form $V_O = k \sin \theta$. While not linear, this function is monotonic over a range of ±90° of rotation. This means that it is possible to determine the angle from the sensor's reading over this range through application of the $\sin^{-1}$ function. For practical sensors, the necessary conversions can often be implemented as look-up tables in a microcontroller.

Gain and offset adjustment are critical operations that must be performed on the transducer signal before it is passed through a $\sin^{-1}$ correction (Figure 6-13). Offset needs to be adjusted when the assembly is in the 0° position. The net flux at this point, as seen by the sensor, should be very close to zero, assuming no asymmetries in the magnets or their locations. The dominant source of offset error at 0° will often be the transducer. When the magnets are moved to 90° (or the sensor assembly's maximum functional span) gain adjustment can then be performed. The gain errors will be a combination of flux variation in the magnet (degree of magnetization) and the transducer gain.

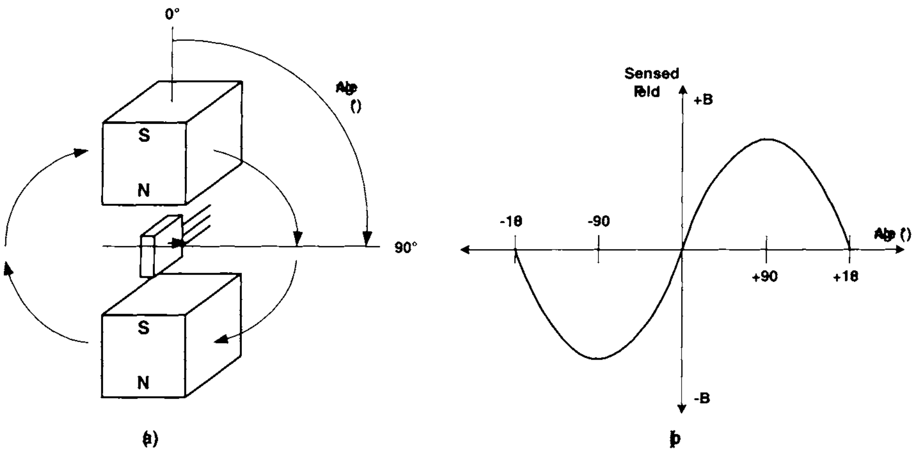


Figure 6-12: Rotary position sensor and response.

Figure 6-13: Signal correction for rotary sensor.

If a smaller angular sensing range is required, it may be possible to ignore the nonlinearity of the sinusoidal response. Response over the range of ±30° or less often is sufficiently close to linear to be useful in many applications without requiring any $\sin^{-1}$ correction. In this case it is also desirable to use higher levels of flux in the magnetic circuit so as to increase sensitivity.

The addition of a circular flux concentrator (Figure 6-14) can be a useful improvement to a rotary position sensor's magnetic circuit. By routing the flux through a closed magnetic circuit, the concentrator greatly reduces the flux that can escape into the outside environment and possibly interfere with any other magnetic devices. Through the same shunting mechanism, the concentrator may also reduce the measurement errors caused by external magnetic fields. Finally, by shortening the overall path the field must take though the magnetic circuit, a concentrator can allow for the use of less magnet material, or lower grades of magnet material, reducing overall system cost.

What if angular measurements are needed over more than ±90° of rotary travel? One solution is to use two Hall sensors, placed at right angles to each other, as shown in Figure 6-15. In this configuration one obtains outputs that are proportional to sin θ and cos θ functions. By looking at the relative polarity and magnitude of the two output signals, angle can be determined over the entire 360° range.

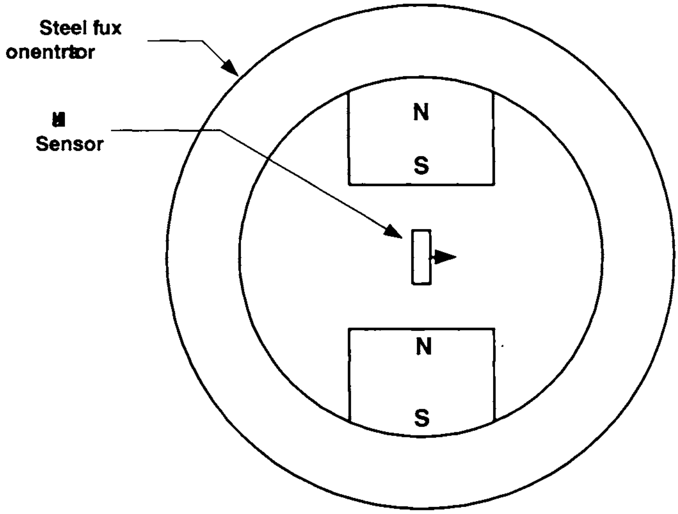


Figure 6-14: Circular flux concentrator.

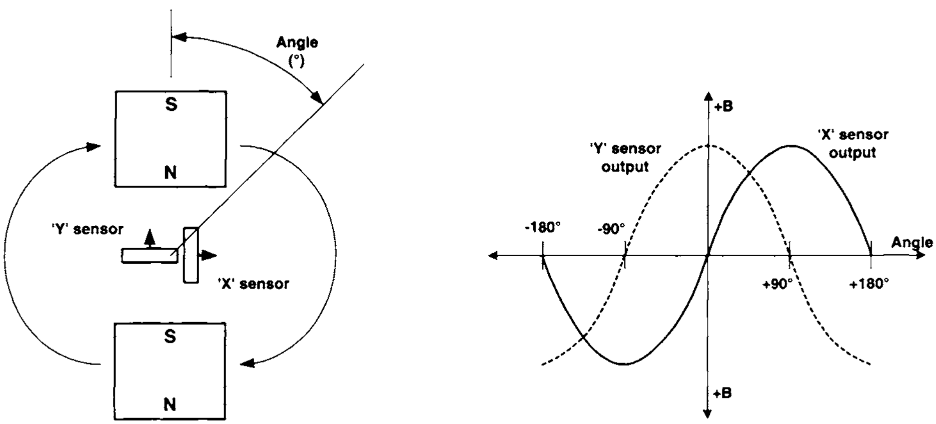


Figure 6-15: Sensor for 360° (±180°) operating range.

While one can resolve angle by processing the outputs of each sensor separately, with $\sin^{-1}$ and $\cos^{-1}$ correction, and determining the quadrant of operation by considering the signs of the individual outputs, there is a better way to perform this function. The angle (θ) can also be derived by considering the function:

$$\theta = \tan^{-1}\left(\frac{B_Y}{B_X}\right)$$ **(Equation 6-1)**

Deriving angle as a function of the ratios of the two sensor outputs provides several advantages. The first is that one need only match the gains of the two transducers. As long as the magnetic circuit provides the transducers with enough flux to make accurate measurements without driving them into saturation, the exact amount of flux provided by the magnet becomes less important. For the same reason, the temperature coefficient of the magnets also becomes insignificant. Finally, if one can match the two transducer's temperature coefficients of sensitivity, transducer temperature coefficients also become much less significant. Note, however, that transducer offset error is still a consideration and needs to be minimized.

The price to be paid, however, is significantly more complex logic required to resolve the angle from the individual sensor measurements. Because Eqn. 6-1 provides a unique angle only over the span of ±90° ($B_X > 0$), a number of variations must be used to resolve angles in other quadrants. Additionally, because the ratio B_Y/B_X becomes very large as one approaches either +90° or –90°, it is better to take the $\tan^{-1}$ of the reciprocal and add an offset when $|B_Y| > |B_X|$. To accurately interpret the raw B_X and B_Y measurements requires three tests:

1) Is $B_X > 0$?
2) Is $B_Y > 0$?
3) Is $|B_y| > |B_x|$?

Based on these three criteria, one can then select an appropriate formula for resolving the angle (as measured clockwise from the positive *Y* as shown in Figure 6-15) from Table 6-1.

Table 6-1: Formulae for resolving 360° resolution.

Range (°)	$\|Bx\| > \|By\|$	Bx > 0	By > 0	Formula for θ (°)
0–45	No	Yes	Yes	$\theta = \tan^{-1}(B_x/B_y)$
45–90	Yes	Yes	Yes	$\theta = 90° - \tan^{-1}(B_y/B_x)$
90–135	Yes	Yes	No	$\theta = 90° - \tan^{-1}(B_y/B_x)$
135–180	No	Yes	No	$\theta = 180° + \tan^{-1}(B_x/B_y)$
180–225	No	No	No	$\theta = 180° + \tan^{-1}(B_x/B_y)$
225–270	Yes	No	No	$\theta = 270° - \tan^{-1}(B_y/B_x)$
270–315	Yes	No	Yes	$\theta = 270° - \tan^{-1}(B_y/B_x)$
315–260	No	No	Yes	$\theta = 360° + \tan^{-1}(B_x/B_y)$

6.7 Vane Switches

Sometimes it is undesirable to affix a magnet to a moving member to sense position. Another proximity sensor that can be made with Hall-effect sensors is the vane switch. This type of sensor detects the presence or absence of a ferrous flag (the vane). In its simplest form, a vane switch consists of a Hall-effect switch and a magnet in close proximity. When the flag is not present, the Hall sensor detects the magnet's field and remains ON (Figure 6-16a). When the flag passes between the magnets and the Hall switch, it interrupts the field and the switch turns OFF (Figure 6-16b). Note that the flag doesn't block the magnetic field; it merely provides a shorter path back to the far pole of the magnet, and by doing so shields the sensor from the magnet's field.

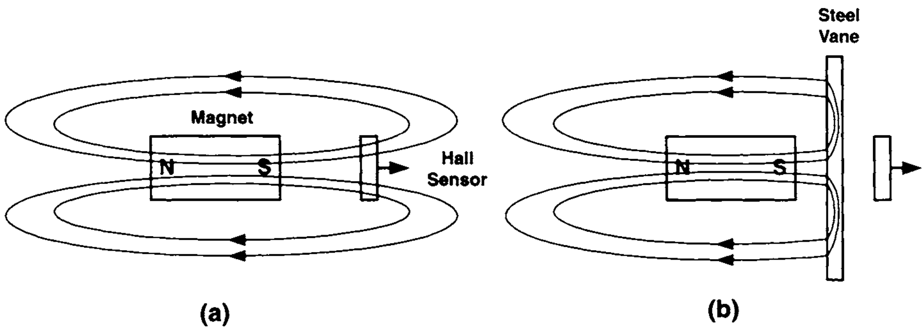


Figure 6-16: Vane switch operation. Vane absent (a) and vane present (b).

Figure 6-17 shows the general characteristics of how the magnetic flux density as seen by the sensor varies in response to the vane entering the gap between the magnet and sensor. When the vane is clear of the gap, the sensor detects a maximal amount of on-state flux. As the vane begins to enter the gap, the flux begins to drop off rapidly. Both the point at which the drop-off begins and the rate of drop-off are dependent on a combination of the magnetic design of the vane switch and on the geometry and composition of the vane flag. For practical vane switches, flux decay may begin to occur when the vane is still a significant distance from the vane switch's centerline.

When the vane has completely entered the gap, the sensor will still see a small amount of leakage flux. This is field that has passed through the vane to the sensor, as opposed to having been shunted back to the magnet. Finally, to make matters even more complex, the position of the vane within the gap will also influence the behavior.

In order to develop an effective vane switch, one must consider the following factors:

- On-state field
- Leakage field
- Mechanical start and end points of flux density roll-off
- Rate of flux density roll-off (slope)
- Matching the magnetic design to available Hall-effect devices

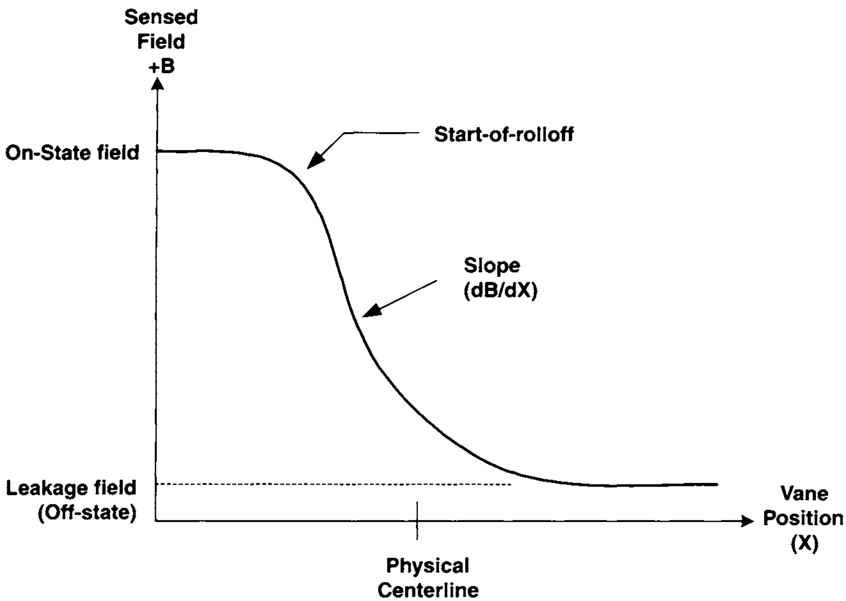


Figure 6-17: Vane switch flux map and key characteristics.

On-state flux field is important because if there isn't enough flux to activate the Hall-effect switch with no vane in the gap, the vane switch will never indicate vane absence. On-state flux density therefore needs to be greater than the sensor's maximum B_{OP} under worst-case conditions. Additionally, if B_{OP} is only slightly less than the on-state flux density, the vane switch assembly may not switch ON until the vane is a significant distance away from the assembly's centerline, possibly remaining OFF even when the vane is mechanically out of the assembly.

Leakage field presents the opposite problem. If the vane and magnetics allow too much leakage flux to reach the sensor, the Hall-effect switch may never turn OFF, resulting in a failure to indicate vane presence. The leakage flux should therefore be less than the sensor's minimum B_{RP} under worst-case conditions. In many cases this issue can also be addressed by appropriate design of the vane. Vane flags that are too small (do not shield sensor), too thin, or made of materials that saturate easily can result in excessive levels of leakage flux. For this last reason, a piece of inexpensive cold-rolled steel will often make a better vane interrupter than an expensive piece of mu-metal or permalloy (specialty high-permeability magnetic alloys), because these alloys tend to saturate more easily than common steels.

Start, end and rate of roll-off are extremely complex factors to determine a priori in a design, but should be characterized, either through finite element simulation, or measurement of prototype assemblies, in order to get some idea of how sensitive the design will be to variations in both the magnetics and the characteristics of the Hall-effect sensor.

Because adjustable-threshold (B_{OP} and/or B_{RP} are user-selectable) Hall-effect switches are, at the time of writing this book, considerably less common and more expensive than fixed-threshold devices, most economically practical vane switch designs will employ fixed-threshold devices. This means that you, as the designer, have a somewhat limited number of choices to select a Hall-effect switch from. Consequently, the magnetics must be designed to accommodate the characteristics of available Hall switches, which can make the design process quite challenging. This is especially true when one must develop a vane switch to operate and release at arbitrary points when operated with a specific target.

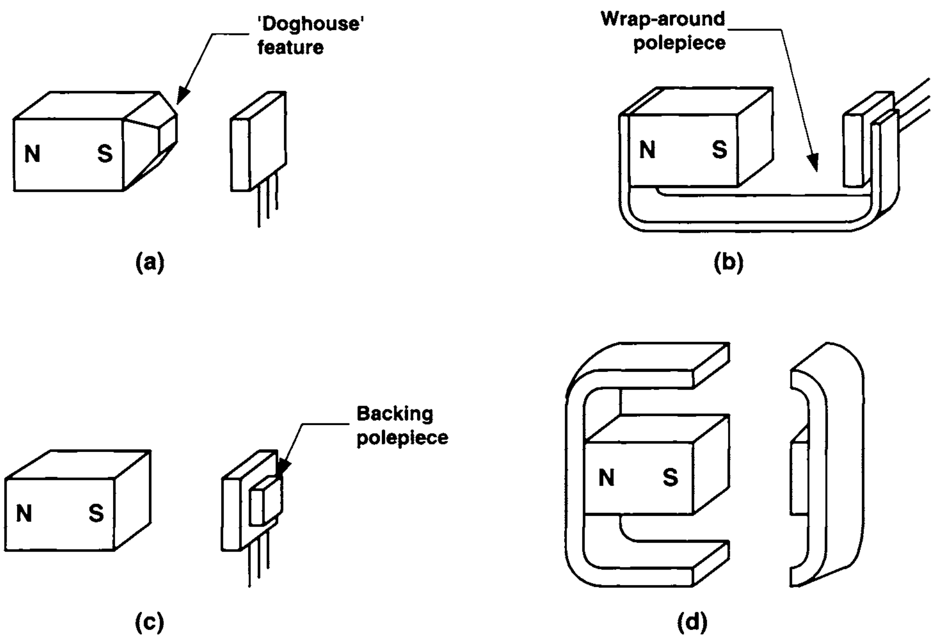


Figure 6-18: Vane switch magnetic architectures.

There are many magnetic structures that can be used to implement vane switches. Each of these structures will change both the amount of field present in the gap, and the rate at which it changes in response to an entering vane. The main goals of using complex magnetic structures in a vane sensor assembly are to reduce the cost (by allowing for the use of smaller magnets) and controlling the vane sensor's trip-points. Because of the complexity of magnetic interactions, and of designing a vane switch and vane combination for a particular application, we can't provide any specific design formulas, or even general rules for application. What follows is a general description, however, of a few potentially useful magnetic structures and what they do:

1) ***Doghouse magnet*** (Figure 6-18a). Forming the magnet into a flattened point will tend to concentrate the flux at that point. This technique is more effective with Alnico-type magnets than with rare-earth magnets, because of the lower permeability of rare-earth magnets. Using a piece of soft steel to form the doghouse tip results in even still more flux effective concentration, at least until the flux density increases to the point where it saturates the steel.
2) ***Wrap-around polepiece*** (Figure 6-18b). Wrapping a soft steel polepiece around from the back of the magnet to the back of the sensor reduces the total effective path that the magnet's flux has to travel. This intensifies the field seen by the sensor, allowing for the use of smaller magnets. It also provides the side benefits of reducing the stray fields produced by the vane assembly, and may in some cases make the vane less susceptible to influence from external stray fields.
3) ***Sensor-backing polepiece*** (Figure 6-18c). Backing the sensor with a piece of high-permeability material will intensify the field it sees, allowing for the use of a smaller magnet and providing better control over trip-points. Unlike the wrap-around polepiece, however, a sensor-backing polepiece will tend to make the vane assembly more susceptible to interference from outside fields.
4) ***E-core polepiece*** (Figure 6-18d). This represents a compromise between the wrap-around and the sensor-backing polepieces. The author used this architecture once in a design for a wide-throat vane sensor where manufacturing constraints would not allow for a wrap-around polepiece design.

It is also possible to combine various aspects of these structures to meet a given set of requirements. The development of a cost-effective vane interrupter is a nontrivial task that requires both a good knowledge of magnetics as well as a willingness to experiment.

Because Hall-effect vane switches are largely unaffected by contamination, external light, and can operate well at temperature extremes, they are often used in harsh environments as more-rugged alternatives to optical interrupters. One big difference between using an optical interrupter and using a Hall-effect vane switch is the mechanical force exerted on the vane by the magnets. The vane switch's magnet will tend to pull the vane into the airgap. For applications where significant amounts of torque are available to move the vane, such as a lead-screw end-of-travel limit switch, the sensor's mechanical drag may not be an issue. For other applications, such as a printer paper-path sensor, where the vane must be moved by a piece of paper, a vane switch may be completely unsuitable.

A commercial example of a vane-switch designed specifically to replace optical-interrupters in high-contamination environments is shown in Figure 6-19. Because it was intended as a direct replacement, both cost and housing geometry were the major design constraints. This required using a very simple magnet-sensor system, consisting of a small rare-earth magnet and a commodity bipolar switch. The result is a unit that can be used to replace optical interrupters in numerous applications by merely changing the pad-patterns of the printed circuit board into which it is to be soldered, and making sure a ferrous vane is used as a target.

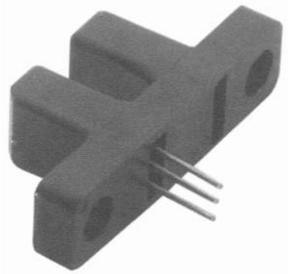


Figure 6-19: Example of packaged Hall-effect vane switch assembly (courtesy of Cherry Electrical Products).

6.8 Some Thoughts on Designing Proximity Sensors

One common design trap that people fall into when developing sensor assemblies around off-the-shelf Hall-effect ICs is the deceptive simplicity of getting a prototype to work. Many designs can be tweaked so that small numbers of articles will function adequately. The problem that often then occurs is high fallout when that design is transferred to production and must function in the face of random variation in both the sensor ICs and associated magnetics. The solution to this problem is a careful consideration of the effects of component variation and tolerance.

There are three major sources of variation in a typical Hall-effect-based position sensor:

1) The magnetic parameters of the sensor IC
2) The characteristics of the magnetic materials
3) Mechanical tolerance

Hall-effect sensor IC manufacturers usually publish minimum and maximum limits for their devices' key parameters, often specified over their operating temperature ranges. These minimum and maximum datasheet limits are extremely important as design guidelines, as product may fall *anywhere* within these limits. Because of the batch nature of IC fabrication processes, devices from the same wafer or same processing lot will tend to have similar characteristics, with a statistical distribution much tighter than might be inferred from the datasheet limits. Devices from a different lot, however, while still falling within published specifications, may have a significantly different statistical distribution. Figure 6-20 illustrates this kind of lot-to-lot variation.

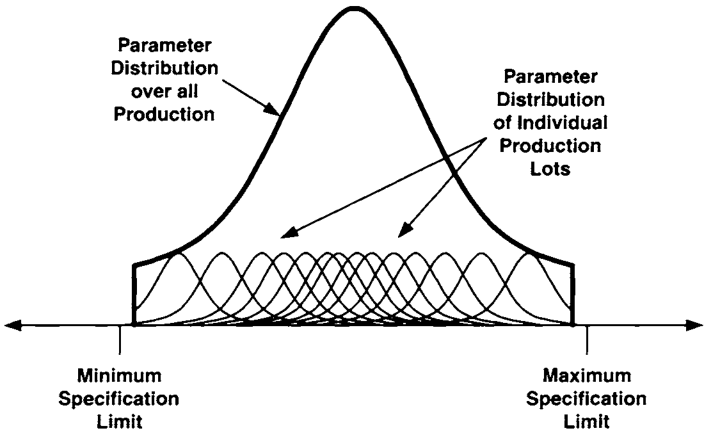


Figure 6-20: Hypothetical lot-to-lot variation in Hall-effect IC parameters.

Because of potential lot-to-lot variation, it is risky to evaluate a design solely on the basis of having a number of functional prototypes, especially if one does not know the individual characteristics of the sensor ICs used. To help ameliorate this problem, some sensor IC manufacturers can provide small quantities of characterized devices as an aid to the designer.

A similar problem arises with the magnetic components used in a design. Both permanent magnets and soft magnetic components are made in batch processes, and are subject to both variations across devices from a single batch, as well as potentially larger batch-to-batch variation. Depending on how aggressive your purchasing department is about cost reduction, you may also have to contend with variations in "identical" materials sourced from multiple manufacturers.

One serious drawback to magnetic material variation is that the majority of datasheets for magnetic materials do not provide clearly defined (if any!) upper and lower limits for many important parameters or how they vary over temperature. The more reputable manufacturers, however, will often be willing to provide some guidance in how you should account for tolerancing key parameters if you get in touch with their applications engineering departments.

Mechanical tolerance may also be a significant source of performance variation in your sensor designs. At a minimum, you must understand how the tolerances of the various components combine or "stack up," and their performance effects, to make intelligent decisions about which tolerances need to be tightened up, and even whether the sensor has a chance of being viable in production.

While accounting for the effects of all tolerances in a sensor design can be a complex undertaking, it is possible to get a first-order estimate of some of these effects. To start with, if one knows the function describing magnetic flux vs. airgap and has the worst-case (min/max) operate and release points (B_{OP} and B_{RP}) for the sensor to be used, one can predict the range of physical switchpoints for that particular sensor-magnet combination. Figure 6-21 shows how this can be done. The first step is to place the minimum and maximum operate and release points (B_{OP} and B_{RP}) on the B axis of the flux density vs. airgap curve. Lines are then extended to the curve and dropped down to the "position" axis. The worst-case physical operate points and physical release points (P_{OPMAX}, P_{OPMIN}, P_{RPMAX}, P_{RPMIN}) can then be read off the airgap axis. Note some of the different physical regions defined by this graph. Toward the ends are regions where the sensor's behavior is well-defined (Must be on/Must be off), while in the middle there are regions where the device could be in an indeterminate (either on or off) state. Minimum and maximum B_{OP} and B_{RP} values should be selected based on the sensor assembly's intended operating temperature range.

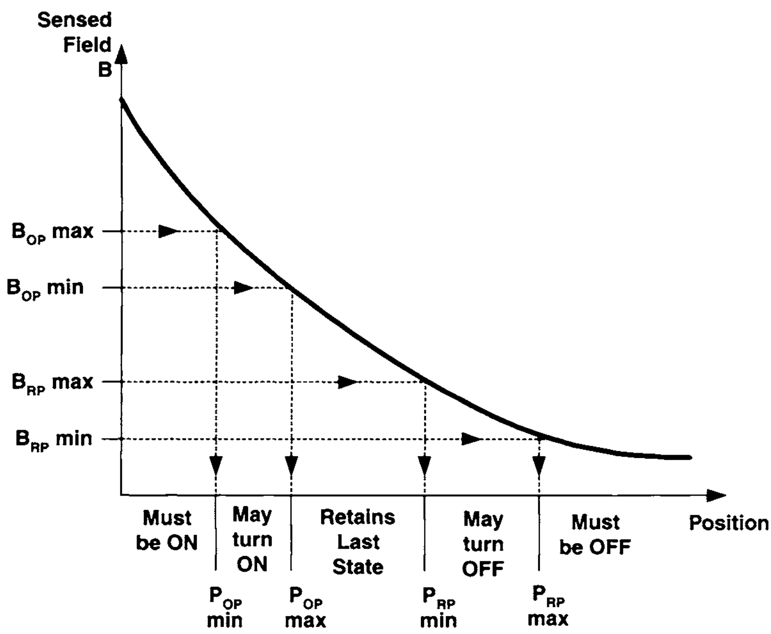


Figure 6-21: Relating B_{OP} and B_{RP} to physical operate and release points.

Once one has obtained minimum and maximum physical operate and release points, the system can also be described by a hysteresis curve relating the ON and OFF states to physical position, as shown in Figure 6-22. Again, there are several physical operating regions represented by this graph, with both well-defined and indeterminate sensor output states.

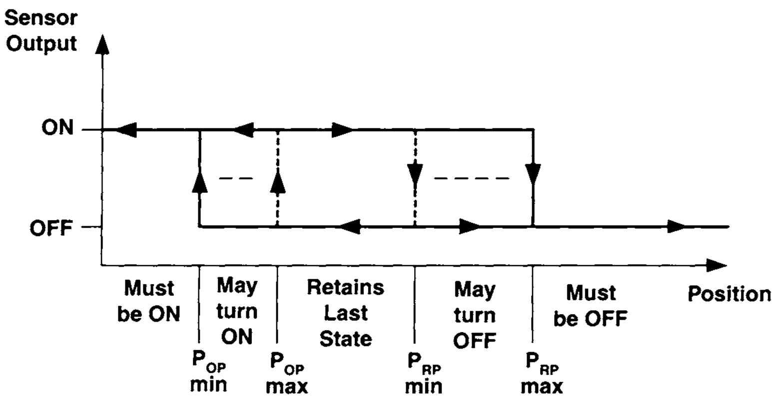


Figure 6-22: Hysteresis curve relating ON and OFF states to physical position.

If one has access to magnetic modeling software (described in Chapter 10), and can obtain minimum/maximum magnetic material models from their suppliers, it may also be possible to repeat the above exercise using a variety of magnetic flux vs. position curves. By varying magnetic material parameters and geometry in modeling software, it is possible to estimate the effects of both magnetic material and dimensional variation on the magnetic behavior of one's sensor system.

While the above method isn't a magic-bullet solution, and does not deliver magnet and IC specs based on a set of physical switchpoints, it can be useful when applied in an iterative manner, and used to move from an initial guess of magnet and IC towards a final, workable design.

Even though it is more work than simply taking the "build-it-and-see" approach, there are several tangible benefits to measuring or simulating magnet flux-vs.-airgap characteristics and iteratively performing the above exercise. The first is that you can obtain some idea of how robust your design is with respect to potential manufacturing variation. Because of the high degrees of variation in some Hall-effect devices and magnetic materials, it is quite possible to inadvertently come up with a marginal design for which the first few prototypes will work satisfactorily, but which will later experience a high percentage of fallout in production.

A secondary reason for performing an analysis such as that outlined above is that it allows you to optimize your sensor assembly. Possible optimization objectives include size, performance, and cost. By quickly allowing you to see the effect of using a particular Hall IC with a particular magnet, it is possible to look at the performance limits of many alternatives, with minimal physical experimentation. This information can be used for selection of the most appropriate combinations of magnetics and Hall-effect IC for the application.

None of the above, of course, is a substitute for actually building a usefully large sample of devices, measuring their performance, and ultimately testing them in the end-application before committing the design to production. The general approach outlined above can merely provide a little bit of understanding into how a given design works. This in turn makes it easier to get to a point where you have a design that meets your cost and performance goals.