Chapter 8

Speed and Timing Sensors

The ability to measure the speed or position of a rotating shaft is necessary to the proper functioning of many types of machinery. Speed sensors, timing sensors, and encoders are used in applications as varied as automobile ignition controls, exercise equipment, and CNC machine tools. An example of a typical Hall-effect speed sensor is shown in Figure 8-1. When a toothed steel target (such as a gear) is rotated past its flat end, this device provides a train of output pulses, one for each passing target feature.

Figure 8-1: Geartooth sensor assembly (courtesy of Cherry Electrical Products).

8.1 Competitive Technologies

Speed sensing can also be performed by sensors based on technologies other than the Hall effect. Among the more commonly used alternative technologies are optical, variable reluctance (VR), and inductive proximity.

Optical sensors can be used to detect speed by having features on a rotating target either interrupt or reflect a beam of light passing from an emitter (LED or laser) to a detector (phototransistor). Optical sensors exist in a wide spectrum of forms and prices, ranging from \$0.50 opto-interruptor assemblies to high-resolution optical encoders costing hundreds or even thousands of dollars.

Variable reluctance sensors operate magnetically, and consist of a coil of wire wound around a magnet. As ferrous target features pass by the face of the sensor, they induce flux changes within the magnet, which are then converted into a voltage in the coil. VR sensors have the advantage of being very inexpensive and rugged. One application is in automotive antilock braking systems (ABS).

Inductive proximity sensors, also referred to as ECKO (eddy-current killed oscillator) sensors are frequently used as industrial automation components. These devices work by sustaining an oscillation in a high-Q LC circuit formed from a capacitor and a sensing inductor. The magnetic flux from the sensing inductor is allowed to pass to the outside of the sensor, through a detecting surface. When a conductive target is brought near the detecting surface, it absorbs energy from the magnetic field and damps the oscillation. Subsequent circuitry then reports target presence or absence based on the status of the oscillation.

While each of these alternative technologies has characteristics that suit it to particular applications, each also has its drawbacks. No single type of speed sensor, including Hall-effect devices, is the best choice for every application. Table 8-1 summarizes a few of the advantages and drawbacks of each of these technologies.

Table 8-1: Speed sensing technology comparison.

Technology	Advantages	Drawbacks
Hall effect	Hot, dirty environments No minimum speed (sometimes) Digital output	Requires ferrous targets
Optical	Fine spatial resolution Inexpensive Very fast (>100 kHz) Digital output	Susceptible to contamination Limited temp. range
VR	Inexpensive Hot, dirty environments Fast (>10 kHz)	Requires ferrous targets Minimum sensing speed Additional signal processing needed
Inductive (ECKO)	Hot, dirty environments Non-ferrous metal targets Digital outputs	Slow (<1 kHz) Low spatial resolution

8.2 Magnetic Targets

The most elementary Hall-effect speed sensor is one based on sensing the passing of a magnetized target affixed to a shaft. The magnetized target may take the form either of a number of discrete magnets, with pole faces presented to the sensor, or as a number of poles magnetized onto a single ring magnet. The decision whether to use a number of discrete magnets or a ring magnet will, as usual, be driven by functional, environmental, mechanical, and economic considerations.

If one chooses to use discrete magnets, there are two fundamental configurations available: one where each magnet presents the same pole to the sensor, and one where successive magnets present alternating poles. Figure 8-2 illustrates these two operating modes.

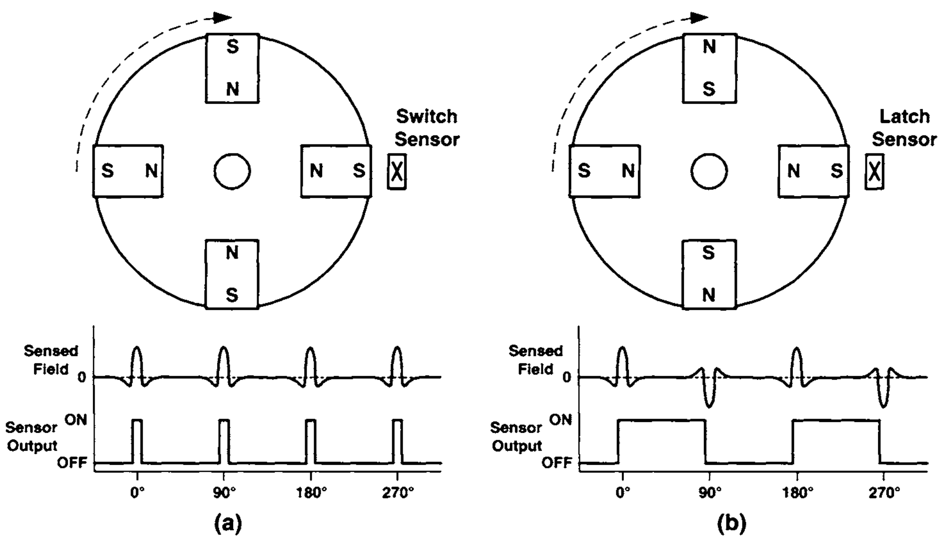


Figure 8-2: Use of Hall-effect digital switch (a) and latch (b) with discrete magnets.

When all the magnets are aligned so as to present the same pole to the sensor (Figure 8-2a), one will want to use a Hall-effect digital switch as a sensing element, with an operate point (B_{OP}) low enough to sense the field available at the operating airgap. Because this configuration is essentially identical to the slide-by mode presented in Chapter 6, the flux seen by the sensor will make a slight negative excursion as the magnet passes, assuring that a switch will be turned off. The resulting output will be a series of short pulses, each pulse corresponding to the passing of a magnet. The duty cycle of the output waveform is dependent on the following factors:

- Spatial size and separation of magnets.
- Magnet material and geometry

- Magnet-to-sensor operating airgap
- Sensor operate and release points

Because latch-type digital Hall-effect sensors can usually be obtained with lower maximum operate points than switch-type devices, it is possible to use a latch-type device to increase operating airgap. A latch, however, requires a negative field to turn it off. Mounting the magnets so that successive magnets present alternating pole faces (Figure 8-2b) meets this requirement. In exchange for higher operating airgap, however, one obtains a single output pulse for every two magnets that pass the sensor. This is because one magnet will turn the latch on, while the other magnet will turn the latch off. One additional advantage from this operating scheme is that, since one is controlling the turn-on and turn-off points by magnet position, it is possible to control the duty cycle of the output (assuming a constant shaft speed). Moreover, for the case of well-matched magnets evenly spaced around the target and symmetric latches (B_{OP} = B_{RP}), the duty cycle will remain nearly constant at 50% over a wide range of operating airgaps. One caveat with this approach is that if the latch's switchpoints are sufficiently low or the airgap is sufficiently small, the magnet's return field may inadvertently cause the latch to switch just after a magnet passes, instead of waiting for the next magnet.

While inserting a number of discrete magnets into a target can be economical for low-volume and specialty applications, ring magnets are often a better choice when manufacturing a sensor system in high volume. A ring magnet is a homogenous piece of permanent magnet material into which a number of poles have been magnetized (Figure 8-3a).

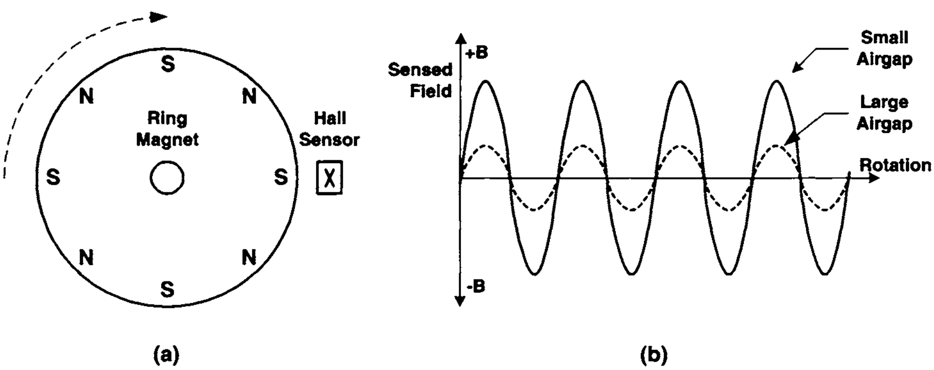


Figure 8-3: Ring magnet (a) and flux output vs. rotation (b).

One advantage of using a ring magnet is that it is possible to economically magnetize a high number of poles into one. Pole-counts ranging from 10–20 per linear inch of circumference are commonly achieved. For a 1-inch diameter magnet, this could mean 64 poles, or 32 pulses per revolution. For electronic speed-control systems high pulse-per-revolution counts are often useful for providing more accurate and consistent speed control.

Another characteristic of ring magnets, at least for ones where the poles are small relative to the operating airgap and are adjacent to each other (there are no unmagnetized regions in between the poles), the magnetic signal presented to the sensor tends to be somewhat sinusoidal as a function of rotary position. One consequence of this is that, if one uses a symmetric latch as a sensor, one will obtain a near-constant duty cycle (50%) over most of the operating airgap. A constant input duty cycle often makes the design of associated electronics simpler. There will also be a significant phase shift (½ pole width) as one moves the sensor away from the surface of the ring magnet out to maximum airgap. While this effect is inconsequential for many speed-sensing applications, it can pose a problem when one needs to reference an absolute point on the target.

One class of applications where magnet-sensing speed sensors are especially useful are those in which only a small amount of torque is available to move the target. Of all the Hall-effect-based speed-sensing methods to be presented in this chapter, magnet-based speed sensors do not put any mechanical torque load on the target, allowing it to spin freely. One case where this is essential is in turbine and paddlewheel-type flow meters, where the speed of a turbine or paddlewheel is proportional to the speed of fluid flowing through it. Discrete magnets can be embedded into the paddlewheel assembly (Figure 8-4) and sensed externally through the meter housing. In this application, the torque load and "cogging" caused by a geartooth sensor could provide unacceptable measurement errors, or even cause the paddle to stick in one position, particularly at low flow rates.

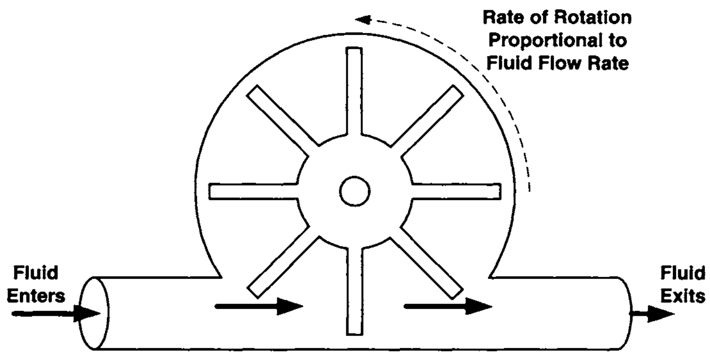


Figure 8-4: Paddlewheel type flow meter.

8.3 Vane Switches

The vane switch presented in Chapter 6 can also be used as a speed sensor. Because vane switches can provide good unit-to-unit repeatability in their mechanical actuation points, they have found widespread application as automotive ignition timing sensors. In this application, the vane sensor is used with a circular target presenting a number of steel flags that can pass through the vane switch's throat. Common target geometries include toothed wheels and notched cups, such as those shown in Figure 8-5. The actual size of targets such as those shown would be between 2 and 3 inches in diameter.

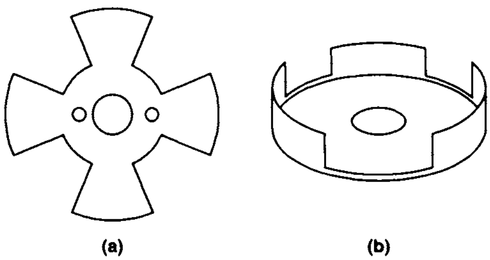


Figure 8-5: Disk (a) and cup (b) vane targets.

Although good unit-to-unit trip-point accuracy (< ±1-mm linear travel) is obtainable on the leading and trailing edges of the target, the number of vanes on a target can be limited. Because the dimensions of the vane flags and gaps between flags must be comparable to the dimensions of the vane-switch's throat, it is difficult to obtain high pulse counts from reasonably small vane interrupter targets.

What makes vane sensors attractive for speed-sensing applications in preference to ring-magnet schemes? The first advantage is that the target is a steel stamping; in high volumes these are extremely inexpensive to make. Secondly, a steel stamping is very rugged, resisting temperature, mechanical shock and many chemicals encountered inside automotive power train assemblies. Ring magnets tend to be made from either polymer-bonded or sintered materials. Bonded materials can have limited temperature range and solvent (gasoline, hot transmission fluid) compatibility issues. Sintered materials tend to be brittle and may not hold up under shock or repeated temperature-cycling conditions. Also, because a vane sensor only needs a small amount of magnetic material (which can be overmolded for environmental protection) the vane switch itself can be made at relatively low cost. The economy provided by the vane switch and its associated target is often the primary reason for using it in a given application.

Because vanes switches can exert a significant mechanical force on a passing target flag, they will tend to strongly detent or "cog" the shaft to which the target is attached. This can be an issue for two reasons. If the target is not driven with enough force to pull the target flags smoothly through the vane switch, then the target speed can vary as it rotates, or in the worst case it can become stuck. Another more subtle issue is that the force exerted by the vane switch on the target flags will tend to mechanically "pluck" them, resulting in acoustic noise. While this may not be a problem at low speeds, it can create annoying amounts of noise when the vane rate runs into mid-range audio frequencies (500–5000 Hz) or when the vane rate hits a resonant frequency of part of the system, in which case the resulting noise can be especially loud. While acoustic noise may not be an important consideration in some applications, it can be a major drawback in applications such as a household appliance or a piece of office equipment.

8.4 Geartooth Sensing

Often, it is not desirable to add a ring magnet or vane target to a system in order to sense its speed. In many cases this is because the speed sensor is designed in as the last part of the assembly, and an additional target cannot be accommodated without significant redesign and retooling. It then becomes desirable to be able to sense speed from features that either already exist or are easy to add to a rotating member, such as gears, pinions, keyways, and holes. If the available target features are ferromagnetic and have appropriate geometries, Hall-effect speed sensors can often be used to detect them. Since ferromagnetic steels are ubiquitous in modern machinery, finding or making a suitable target is usually straightforward.

Detecting an unmagnetized steel target, however, presents a completely different set of challenges than those of detecting a magnet. When detecting an unmagnetized target, the sensor assembly must both provide a magnetic field and discriminate perturbations in that field caused by target features. A typical "geartooth sensor" will consist of a Hall-effect sensor IC placed on the face of a bias magnet, as shown in Figure 8-6a. The approach of a ferrous target (Figure 8-6b) intensifies the normal flux at the face of the magnet. Interpreting differences in flux patterns between the target present and target absent states is where the challenge of making a good geartooth sensor lies.

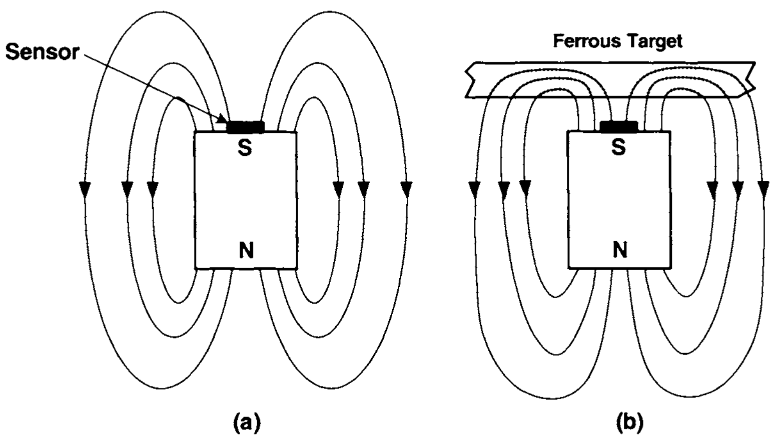


Figure 8-6: Flux around magnet (a) is altered by presence of ferrous target (b).

Because detecting presence or absence of a target can be difficult, many geartooth sensors are designed only to detect target features as they move past them. A sensor of this type may or may not register the presence of a target when the power is first turned on, after a power interruption, or when the target has not been moving for a short time. The ability to discriminate the presence of a stationary target feature is often called true proximity detection or power-on recognition. For many speed-sensing applications, lack of true proximity detection does not pose a significant problem. The lack of this feature, however, makes most types of geartooth sensors completely unsuitable for use as proximity detectors. When misused as a proximity detector, a geartooth sensor lacking true proximity detection capability can exhibit erratic and unpredictable behavior.

8.5 Geartooth Sensor Architecture

While there are literally dozens of schemes available for making Hall-effect based geartooth sensors, most of them fall into one of a few major categories. These categories are based on the features of the magnetic field being measured, and how the resulting measurements are interpreted into an output signal.

When measuring magnetic flux density in an effort to discriminate a target, one can either look for a magnitude or for a spatial gradient. While magnitude is readily measured with a single Hall-effect transducer element, spatial gradient cannot be measured directly; it must be approximated by subtracting the measurements from two independent, but closely spaced, transducer elements (Figure 8-7). Magnitude detection schemes are often called *single-point*, while gradient detection schemes are often called *differential*.

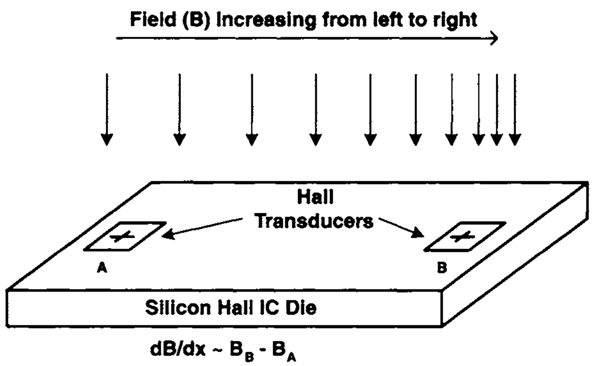


Figure 8-7: Two Hall-effect transducers on one die are used to measure flux gradient.

Both magnitude and gradient detect different characteristics of a given target. Changes in flux magnitude are useful for indicating the presence of the body of a target. One obtains the greatest magnitude response when the sensor is directly over the body of a target feature. Gradient detectors, on the other hand, respond to discontinuities in the target, such as the edges of gear teeth or the edges of holes. Each of these characteristics is useful in different applications.

The second dividing line is the method used to interpret the transducer signal. The basic idea in all schemes is to compare the transducer signal to a threshold and report presence or absence based on the results of the comparison. The distinction lies in whether the threshold is constant (a static threshold) or is allowed to vary over time (a dynamic threshold). While static thresholds offer conceptual simplicity, sensors based on the use of dynamic thresholds can offer significantly improved performance, ease of use, and applications flexibility, by allowing the sensor to adapt itself to the characteristics of the target being sensed.

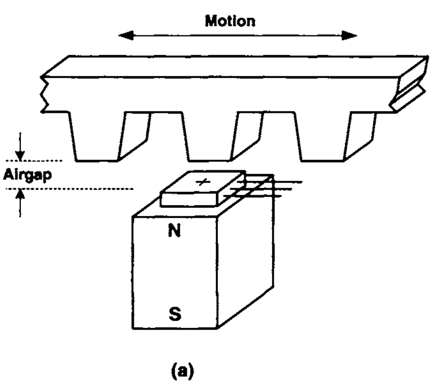
The combination of magnitude (single-point) versus gradient (differential) sensing and fixed vs. dynamic thresholds yields four possible classes of Hall-effect-based speed sensors:

- Single point/fixed threshold
- Single point/dynamic threshold
- Differential/fixed threshold
- Differential/dynamic threshold

In the following sections, we will discuss the operation and examples of each of the above types of sensors.

8.6 Single-Point Sensing

In a single point geartooth sensor, only one Hall transducer is used to measure the magnitude of a magnetic field. To maximize the signal from the transducer, it is common to place the Hall-effect transducer between the target being detected and the pole-face of a magnet, as shown in Figure 8-8a. Typical magnetic responses, as seen by the sensor at various sensor-to-target airgaps, are shown in Figure 8-8b.



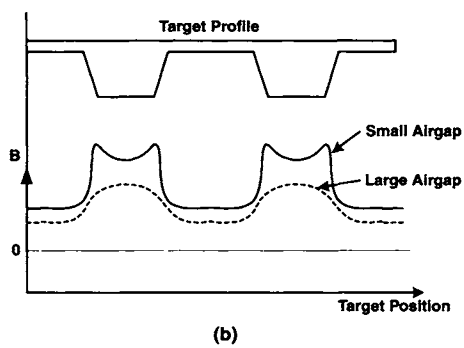


Figure 8-8: Pole face sensor (a) and response (b).

The magnetic response of this example shows several characteristics that are important to understand if intending to implement or use geartooth sensors using this magnetic configuration. The first is that the peak-to-peak signal is a function of airgap. The peak-to-peak signal allows one to distinguish target features from nonfeatures. In the case of a gear, the positive peak occurs when the sensor is over a tooth, and a negative peak occurs when the sensor is over the gear's root (valley between the teeth). The peak-to-peak signal drops rapidly, with a near inverse-exponential characteristic as a function of airgap. Because of this exponential fall-off rate, it is difficult to obtain greatly increased operating airgaps by using improved magnetic materials alone. A factor of three increase in net flux density (which might be provided by replacing an Alnico magnet with a Samarium-Cobalt magnet) will be unlikely to provide a 3× increase in operating airgap.

The second important signal feature is the baseline flux value measured when the sensor is positioned between teeth. This has two key characteristics, the first of which is its high value in relation to the peak-to-peak signal. The second characteristic of the baseline is that it tends to decrease as effective airgap increases, although by a much smaller amount than the peak-to-peak signal decreases. Targets with shallow gaps between teeth, and/or fine-pitched tooth spacing tend to have smaller differences between their baseline and peak flux densities than targets with larger tooth pitches and deeper gaps.

The high value of the baseline can pose a problem, especially for those sensors that must be able to provide true proximity detection. Remember that the sensor does not have the luxury of looking at the entire response curve shown in Figure 8-8b; it must make its target-present/absent decision based solely on its view of one or two closely spaced points on that curve. For the case of a small peak-to-peak signal variation riding on top of a much larger baseline reading, target determination can be difficult. Finally, a high magnetic baseline places addition requirements on the dynamic range of any signal-processing circuitry following the transducer. Subsequent circuitry must be able to accept high incoming signals without saturating, while still maintaining enough sensitivity to detect small changes in those signals.

A third characteristic of the magnetic response of the sensor is overshoot. This effect usually occurs at small effective airgaps (e.g., < 0.04"), and is caused by flux concentration at the corners of a target profile. This effect occurs because a corner or other sharp transition at the edge of a target feature can act as a better flux concentrator over a small region than the body of the target feature. Overshoot can be a problem because it often manifests itself by causing a geartooth sensor to output multiple pulses for each target feature.

Square-cut gear teeth, and other target features with sharp transitions, are especially prone to contribute to overshoot effects. Whether or not overshoot constitutes a problem depends on two factors. The first is whether the sensor is even sensitive to overshoot; some types, such as fixed-threshold single point, may not be if the trip points are adjusted to levels appropriate for the working airgap. The second factor is airgap.

Overshoot effects decrease rapidly with increased airgap, so even if the particular sensor doesn't work well in the presence of overshoot, specifying a minimum working airgap for a given target may solve the problem. Finally, adding chamfers or radii to target features can often eliminate overshoot in the magnetic signal.

8.7 Single-Point/Fixed-Threshold Schemes

One can make a useful geartooth sensor by simply comparing the signal resulting from the fixed-point configuration shown above against a set of thresholds. All that is needed is to select appropriate levels for B_{OP} and B_{RP} thresholds, as shown in Figure 8-9. Because of variation in the magnetic baseline as measured over the operating airgap, it may not be possible to select a single set of thresholds that allows for operation over more than a small range of airgap. Operating the sensor closer than some minimum airgap will result in its output being stuck "on," while attempted operation beyond a maximum airgap will result in a permanent "off" condition. In addition, as one approaches either airgap extreme, output duty cycle can vary significantly, and the output waveform may not necessarily be a good representation of the target profile.

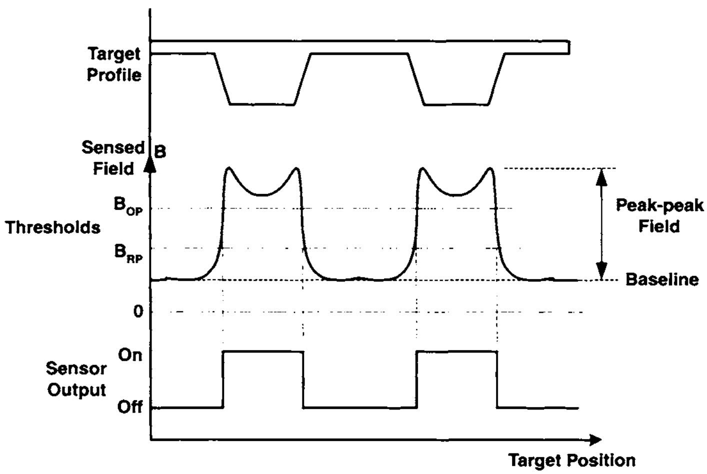


Figure 8-9: Thresholding a signal from a single-point sensor to obtain an output signal.

While conceptually simple, in practice this fixed-threshold scheme runs into serious difficulties. The biggest problems result from the high levels of baseline signal in relation to peak-to-peak signal. Flux variation in the sensor assembly's magnet, resulting from normal materials variation, will almost always require trimming the B_{OP} and B_{RP} points of each sensor produced. But even this will not eliminate baseline variation problems; temperature coefficients in the magnet material and the sensor can also cause baseline shifts over temperature that can't be easily trimmed out. Finally, it is difficult to obtain sensors that can be used at useful baseline levels. Most digital Hall-effect switches have B_{OP} points of less than 500 gauss, while most modern linear devices are limited to a sensing range of about ±1000 gauss before they saturate. The field strength at the face of an Alnico magnet can be 1000–1500 gauss, while that of a rare earth magnet can be in the range of 2500–5000 gauss. While one can shim the sensor off the face of the magnet to reduce the field to easily measured levels, this technique will also reduce the resulting sensor's maximum working airgap. Since few, if any, integrated switches or linear sensors operate at these high field levels, one may have to use discrete transducer elements and signal processing circuitry, which can result in increased system cost.

Because a high baseline field can make the design of an effective fixed-threshold sensor difficult, several schemes have been developed to remove baseline signal though clever magnetic design. Because the offset cancellations are performed magnetically within a single magnet, or multiple magnets of the same material, these techniques provide good temperature stability.

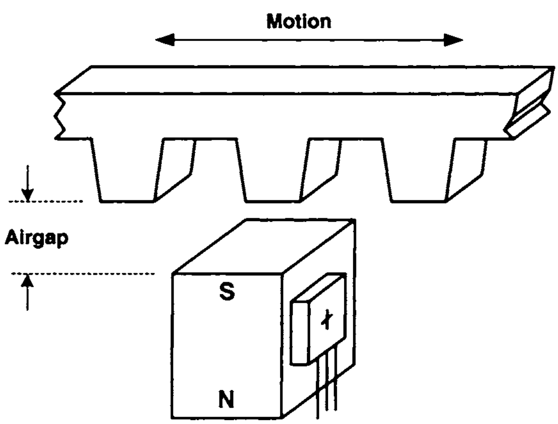


Figure 8-10: Lateral-field speed sensor.

One scheme [Wolfe90] relies on detecting the flux emanating from the side of the magnet. When no target is present, there is normally a null-point of zero net flux located halfway between the poles of the magnet (Figure 8-10). When a target approaches one of the magnet's poles, it causes a redistribution of flux in and around the magnet, and subsequently causes the null-point to move away from the magnet's center and closer to that pole. The sensor then experiences a nonzero flux, which can cause it to turn on.

Transducer placement is critical to the proper operation of this type of sensor, and is also application dependent. For optimum performance, sensors must be adjusted to match the target with which they are intended to operate.

Because the perturbation caused by an approaching target is spatially "filtered" through the bulk of the magnet, we would not expect as high a peak-to-peak response to small targets (as compared to the size of the magnet) as we would get where the sensor is placed between the magnet pole and the target. In many cases, however, this characteristic can be useful as it results in reduced sensitivity to sharp corners and surface roughness.

A second baseline offset removal scheme [VIG98] uses a compound magnet in the form of a "sandwich," as shown in Figure 8-11. In this arrangement, the normal flux from the inner magnet layer cancels the flux from the outer layers in the vicinity of the Hall-effect transducer, effectively creating a null point near the face of the compound magnet. An approaching ferrous target, however, causes a flux perturbation of a magnitude near what one would expect from a single magnet of comparable size and composition. Because the transducer element is at the "pole-face" of the compound magnet, in close proximity to the target, this architecture should yield good sensitivity to small target features. A commercial example of this type of sensor is the Allegro ATS535 geartooth sensor module. This device consists of a programmable switch over-molded into an assembly with a compound magnet. To implement a sensor using this assembly, one must present a target (often rotating) to the sensor assembly, and then electronically adjust the B_{OP} of the Hall effect IC so that it correctly senses the presence and absence of target features.

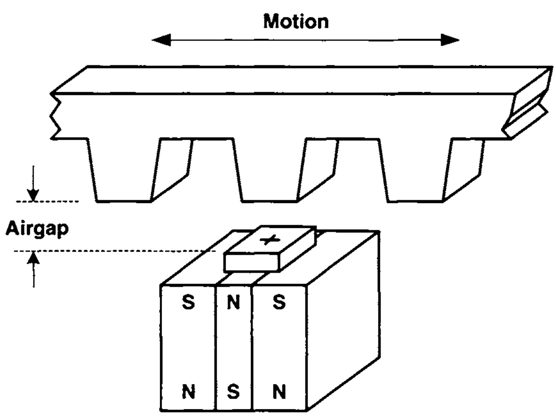


Figure 8-11: Speed sensor using magnetic "sandwich" to develop a null point.

8.8 Single-Point/Dynamic-Threshold Schemes

Because baseline flux variation makes it almost a necessity to adjust B_{OP}/B_{RP} points on individual sensors, single-point/fixed-threshold sensing schemes can be difficult to implement and use effectively. If the sensor were vested with the ability to adjust its operating thresholds to accommodate both target, magnet, and sensor variations, it would result in a more flexible and easy-to-use device.

The first, and oldest, dynamic threshold detection scheme is often called either DC blocking or AC coupling. A block diagram of this type of sensor is shown in Figure 8-12.

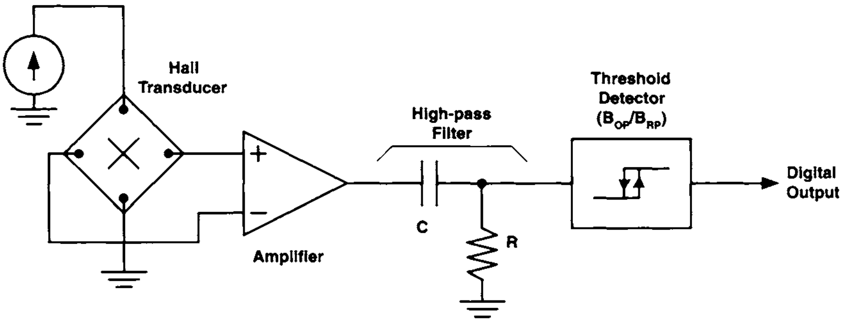


Figure 8-12: AC-coupled geartooth sensor.

The above circuit blocks any DC bias signal from getting through to the threshold detector. The resulting signal, as seen by the threshold detector, has an average over time of zero. The operate and release thresholds, therefore, are often set symmetrically about zero. Because the DC average is removed from the input signal, the sensor behaves as if it were adjusting its operate and release points to accommodate that average. Figure 8-13 shows idealized versions of some of the waveforms inside an AC-coupled sensor. The input signal is first level-shifted so that it is symmetric about a "zero" point. This signal is then compared to B_{OP} and B_{RP} levels that are commonly set to be symmetric about zero. This results in an output waveform that is independent of the baseline flux measured by the transducer.

While it is possible to base an effective geartooth sensor on an AC-coupled architecture, the scheme has a number of limitations. The first is that the target has to be moving at a certain minimum speed in order to actuate the sensor. Because the low-frequency response of the first-order RC filters typically used in this type of sensor rolls off gradually, one does not see a sharp minimum speed below which the sensor ceases to function. A more graceful degradation occurs, with the effective maximum airgap declining with target speed. Additionally, sharp features in the target introduce harmonics into the input signal. A square-wave signal with a frequency of 1 Hz also contains significant energy at 3 Hz and 5 Hz. These harmonics can also cause the sensor to switch. Because the harmonic content of the input signal is dependent on the airgap and geartooth geometry, the shape of the gear target also has a significant effect on lower operating frequency.

Another disadvantage of a simple AC-coupled scheme is that, in order to get a large effective airgap, one must set the operate and release points to a low value. While this results in a sensor that provides satisfactory performance at moderate to wide airgaps, overshoot effects can result in spurious output pulses when the target is too close to the sensor.

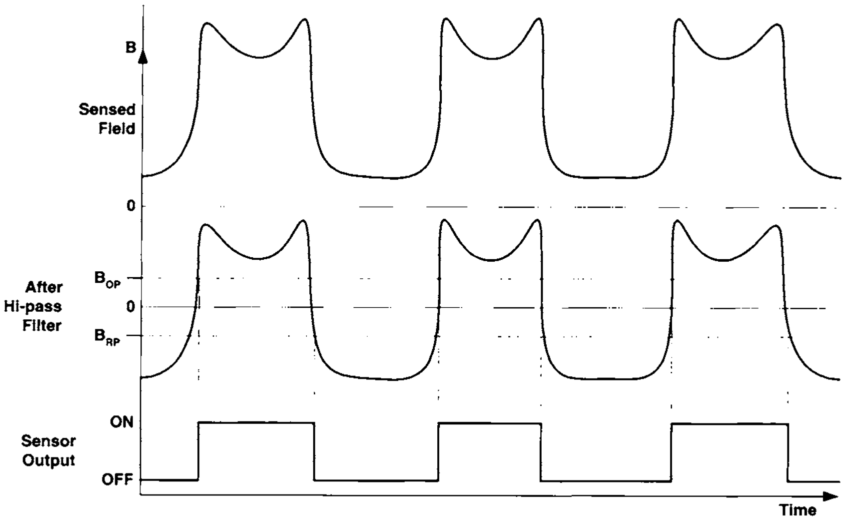


Figure 8-13: Waveforms in AC-coupled geartooth sensor.

Finally, an AC-coupled sensor will have a long "wake-up" time when it is first powered on. When power is first applied, several RC time constants will usually be required for the DC-blocking filter to stabilize. During this period the output of the sensor may be erroneous. For a "typical" AC-coupled geartooth sensor, with a low-frequency corner of approximately 5 Hz, this wake-up time can amount to as much as a few hundred milliseconds. For applications requiring instant wake-up on power-up, such as automobile ignition systems, this can be a serious drawback.

Another dynamic threshold detection scheme is related to AC coupling, but uses the capacitor to temporarily store the peak value of the signal [VIG95]. The peak value is then used to determine the values of the operate and release points. By deriving the B_{OP} and B_{RP} points from the peak flux, the sensor can adjust itself to the characteristics of both the magnet used to bias it, and the target being sensed. A block diagram of this technique is shown in Figure 8-14.

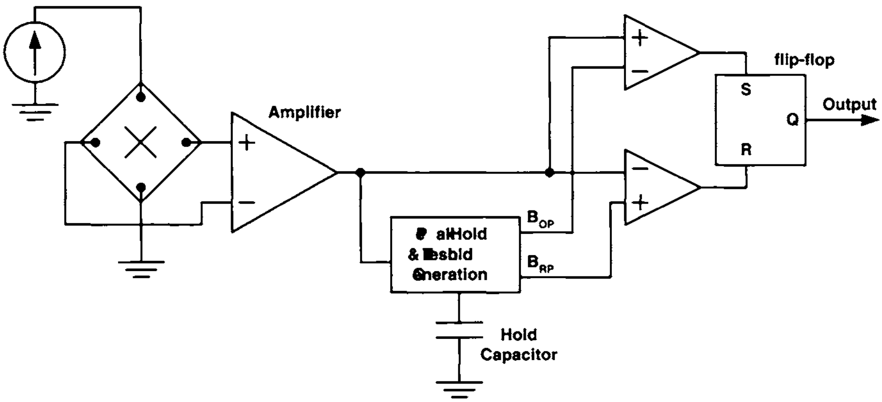


Figure 8-14: Peak-hold geartooth sensor.

This technique has a number of advantages over the AC-coupled detection scheme. The first is that a peak-detecting circuit will respond very quickly when establishing a peak value and hold that value for a substantial amount of time. This means that wake-up response can be very fast, with the circuit stabilizing as soon as a signal peak is encountered. Since the decay rate of a peak-hold circuit can be made long compared to the peak capture time, it is also possible to sense targets moving at very low speeds, at least compared to AC-coupling schemes. Finally, by scaling the values of the operate and release points to the magnitude of the peak incoming signal, this type of signal-processing system yields much better timing performance than the simple AC-coupled scheme.

It is also possible to perform signal-processing operations in the digital domain and, as integrated circuit processes yield higher component densities, this will become an increasingly attractive option. When one digitizes the transducer signal, it becomes possible to perform some very sophisticated processing to derive an output signal. The general block diagram of this type of signal-processing system is shown in Figure 8-15.

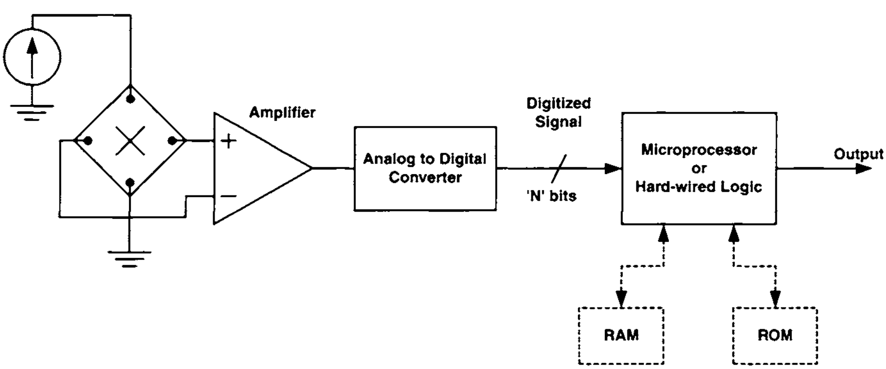


Figure 8-15: Geartooth sensor based on digital signal processing.

The use of DSP offers the potential of choosing from a great number of processing techniques. One example is found in the Melexis 90217 geartooth sensor. The amplified analog transducer signal is first converted into a digital form through an A/D converter. Digital logic then looks for the minimums and maximums in that signal. When a maximum is passed, and the signal declines by the hysteresis amount, the output of the sensor is turned ON. When the minimum is found and the signal increases by the hysteresis amount, the output will switch OFF. Because bits in a digital storage register are used to store temporary reference values, as opposed to representing these values as charge on an analog capacitor, this type of sensor can detect targets moving at arbitrarily low speeds.

8.9 Differential Geartooth Sensors

By placing two Hall-effect transducers close to each other on the same IC, it is possible to obtain an accurate approximation of the spatial gradient of magnetic flux density [Avery85]. On most commercially available differential geartooth sensor ICs, the Hall transducers are spaced about 2 mm apart. By subtracting the signals from the individual transducers, it is possible to derive an approximation to the gradient in the region near the sensor. When such a sensor is placed on the pole-face of a magnet, as shown in Figure 8-16a, a signal such as that shown in Figure 8-16b may be obtained in response to a passing gear.

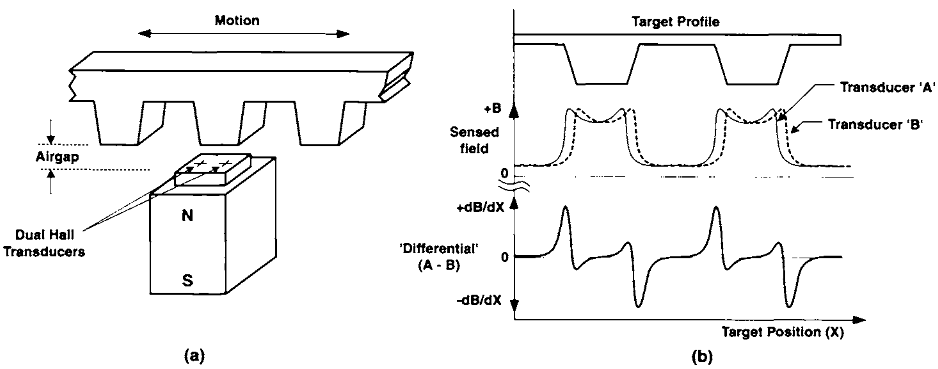


Figure 8-16: Positioning of differential transducer (a) and signal resulting from passing gear (b).

The first thing to note is that this sensor only provides a response to edges of target features. Flat features, be they gear teeth or the spaces in between, do not elicit any response. In the case shown above, a tooth to the right of the sensor results in a positive signal, while a tooth to the left of the sensor results in a negative signal. At all other times the signal is zero.

The edge-detecting behavior of a differential sensor offers a number of advantages over single-point sensing schemes. The primary advantage of an "ideal" differential signal is that, because one is looking for positive and negative signal events against a zero-level background, it is easy to identify target edges. Differential sensing should also make it easier to build a sensor whose performance is less susceptible to sensor, target, and airgap variations than that of a single-point sensor. While AC-coupling or other variable-threshold techniques can be used to detect edges by the signal's change in time, a DC-coupled differential sensor can detect an edge even when the target is standing still.

Another potential advantage of a differential geartooth sensor is that of more accurate timing response. Because one is looking at the spatial flux gradient caused by the edge of a target feature, it is easier to locate the edge accurately with differential sensing methods than with single-point ones.

Despite their potential advantages, differential sensing schemes also have their share of quirks. Two of these are orientation sensitivity and phase-reversal.

To sense an edge, a differential sensor must be oriented so that the sensor IC is straddling that edge, with one of the Hall-effect transducer elements in proximity to the geartooth, and the other in proximity to the space between teeth. If the sensor is rotated 90°, however, so that both transducers "see" the tooth or both transducers "see" the gap, then it will not detect a gradient. While 90° of sensor rotation represents the worst case (no signal out), performance will degrade as the sensor is rotated from its optimal working position to the point where it ceases to detect the target.

If one rotates the sensor 180° from normal working position, the sensor will still output a signal; the polarity, however, will also flip. If leading edges were represented by positive output signals and trailing edges by negative output signals when the sensor was correctly oriented, the leading edges will be represented by negative signals and the trailing edges by positive signals if the sensor is rotated 180°. While this effect may not be an issue in speed-sensing applications, where all one cares about is the total number of pulses, it can cause problems in systems that are specifically looking for particular edge transitions. One example of an application in which mounting a differential sensor backwards could cause havoc is the timing sensor for an automotive ignition system. Reversing the polarity of the output train prevents the engine controller from accurately identifying critical timing angles, and consequently from running the engine properly.

Another counter-intuitive behavior unique to differential sensors is polarity inversion resulting from the direction in which the target is rotating. With a differential sensor, if you rotate the target backwards, the phase of the output signal inverts, in a manner similar to that described above. There are situations, however, in which this effect can be put to good use. If you make a target that results in an output signal with a duty cycle that is not 50% (output is HIGH 50% of the time), you can determine the target's direction of rotation. For example, if the target is cut so that the duty cycle in the forward direction is 75%, you will see a 25% duty cycle when the target is rotated backwards.

If differential geartooth sensors exhibit all of the strange behaviors described above, why do people use them? The reason is that, when applied properly, they offer good timing accuracy and generally high performance. And, as is the case with single-point sensors, there are numerous signal-processing strategies that can be used to optimize performance for a given set of applications.

8.10 Differential Fixed-Threshold

The simplest signal-processing method for differential geartooth sensors is to set a fixed threshold. Because it is necessary to look for both positive and negative signal peaks, however, a pair of thresholds is required. Ideally, these thresholds will be set symmetrically about zero, such that $B_{OP} > 0$, $B_{RP} < 0$, and $B_{RP} = -B_{OP}$. By remembering the polarity of the last "edge event" the output of the threshold detector will track the target profile. The block diagram in Figure 8-17 shows the major functions and signal flow of a differential fixed-threshold speed sensor.

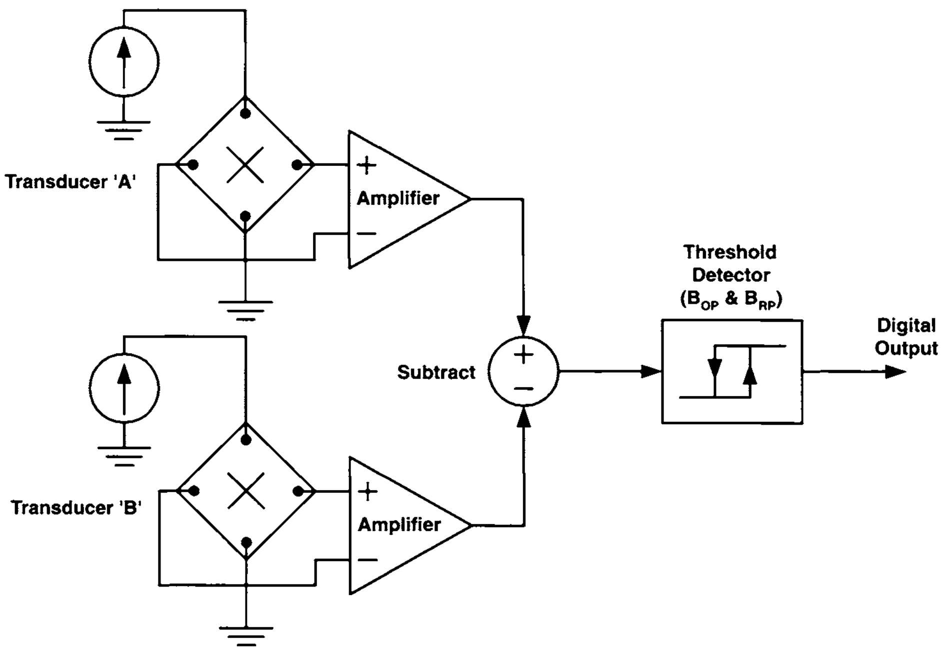


Figure 8-17: Fixed-threshold signal processing method for differential sensor.

While this method can be made to work, there are numerous issues to be addressed to ensure a successful implementation. The first, and most important, is that of offset error. The signal seen by the threshold detectors can have a constant error signal added. If this error signal is large enough compared to the threshold levels, the sensor may sporadically or completely malfunction. Some sources of offset error are:

- Electrical offsets in the transducers and front-end instrumentation amplifiers
- Nonuniformity in the magnetic field provided by the bias magnet
- Tilting of the sensor in relation to the target.

While these offsets can be minimized through appropriate design techniques, both at the IC and assembly level, they pose a limit to how low the thresholds can be set, and consequently limit the maximum working airgap of the assembly. For these reasons, while fixed-threshold differential sensors can be used as the basis of practical sensor assemblies, they are not usually the best choice for most applications.

8.11 Differential Variable-Threshold

As was the case with single-point geartooth sensors, it is also possible to use variable-threshold signal-processing schemes with differential geartooth sensors. Two of the ways in which thresholds can be adjusted are by shifting them (to reduce the effects of offset) and by widening or narrowing them (to adapt to changes in signal magnitude).

Shifting the thresholds or shifting the sensed signal can be used to reduce the effects of offset. A signal-processing scheme that performs this function will allow the geartooth sensor to cope with variations in the transducers, magnets, and alignment of the sensor assembly. One of the simplest circuits used to perform this level-shifting operation is the AC coupler that was presented for use with single-point geartooth sensors. A detailed description of this type of sensor can be found in [RAMS91]. A representative device of this type is the Allegro UGN3059.

While shifting the input signal so as to remove offset solves many problems and results in a sensor with greatly increased performance and ease-of-use over that of a fixed-threshold device, it is not a panacea. First of all, the AC-coupling scheme places a lower limit on detectable target speed, just as it did in the case of a single-ended AC-coupled sensor. Additionally, a single set of symmetric thresholds doesn't provide optimal performance under all operating conditions. If the thresholds are set high, then the sensor's maximum working airgap is limited. If one wants to increase the maximum airgap by setting the thresholds very low, false triggering from target corner effects and surface roughness can occur.

One solution is to adjust the switching thresholds based on the magnitude of the incoming signal, as was shown in the case of the single-point sensor. If the magnitude of the incoming signal is large, then the thresholds can be set high. If the signal magnitude is low, then the thresholds also become low. The signal magnitude may be determined either by taking its absolute value and averaging, or by detecting its peak value and holding that. By adjusting the thresholds to match the signal, a wide working airgap range can be achieved. An additional benefit of this approach is that it will also tend to increase accuracy in the degree to which the sensor's signal output tracks the features of the target, a useful feature for timing-sensitive applications. An example of a commercially available sensor that uses this type of signal-processing technique is the Allegro ATS610LSB geartooth sensor module.

Another way to achieve this effect is to keep the thresholds constant, but to provide a variable-gain amplifier whose gain is inversely proportional to the average signal magnitude. This type of compensation method is referred to as automatic gain control, or AGC. An example of a commercially available speed sensor that works in this manner is the Allegro ATS612 module.

8.12 Comparison of Hall-Effect Speed Sensing Methods

Because of the wide range of applications in which geartooth sensors are used, there is no single solution that works well everywhere. Table 8-2 summarizes a few of the advantages and drawbacks of the various geartooth sensing schemes described above. Examples of sensor ICs employing each of these techniques are also provided.

Table 8-2: Comparison of various geartooth sensing techniques.

Technique	Advantages	Drawbacks	Representative Devices
Single-Ended Fixed-Threshold	Power-on recognition True zero-speed sensing Orientation insensitive	Limited operating airgap range Needs to be adjusted to target and magnetics, often on a unit-unit basis Fair edge timing accuracy	A3250 (Allegro) Also many switches and latches with appropriate magnetics
Single-Ended Variable Threshold	Near-zero speed sensing Orientation insensitive Easy to Use	No power-up recognition Minimum sensing speed (in some cases)	ATS632 (Allegro) MLX90217 (Melexis)
Differential Fixed Threshold	Zero-speed sensing Good edge timing accuracy	Limited airgap range Some nonintuitive behavior	UGN3056 (Allegro) HAL300 (Micronas)
Differential Variable Threshold	Good edge timing accuracy Wide effective airgap range Easy to use	Minimum sensing speed (in some cases) Some nonintuitive behavior	UGS3059 (Allegro) ATS610 (Allegro) TLE4921-3U (Infineon)

8.13 Speed and Direction Sensing

One previously mentioned feature of differential speed sensors is that, with an appropriate target, they can also be used to determine the direction of rotation. If one knows the direction in which a target is rotating, it is possible to track the angular position of the target. Accurately measuring the angular position of a shaft is a very useful thing to be able to do, and is the basis for many types of precision positioning equipment.

The most common way of determining rotational direction is to use two separate sensors, sensing the same target at slightly different points, as shown in Figure 8-18a. To make for simple and reliable target detection, the target in this case is a ring magnet, and the sensors are digital Hall-effect latches. By spacing the sensors half a pole spacing apart, two output signals are obtained which are 90° out of phase with each other, with the leading edge of one coming either before or after the leading edge of the other. The direction of target rotation determines which signal will lead, and which one will lag. In the case of the waveforms shown in Figure 8-18b, clockwise rotation causes the A channel to lead while counterclockwise rotation causes the B channel to lead. This quality in a pair of signals is often referred to as quadrature.

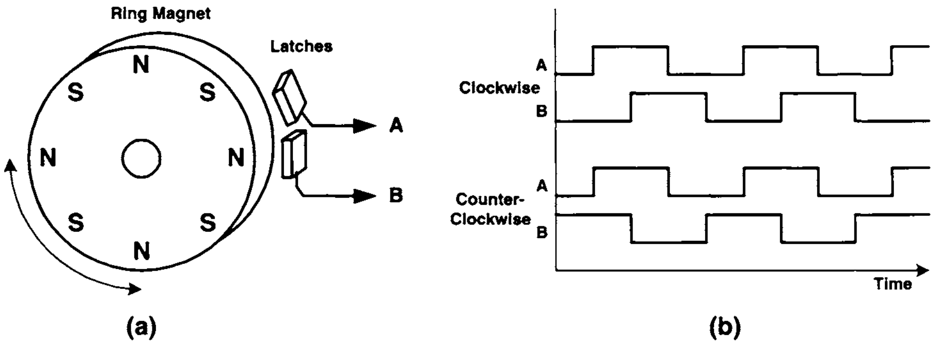


Figure 8-18: Using two sensors (a) to obtain quadrature output signals (b).

To determine rotational direction requires a circuit that can determine the lead-lag relationship between the two signals. One of the simplest circuits that can do this consists of a single D-type flip-flop (Figure 8-19a). The B channel signal is fed into the clock input, while the 'A' channel signal is fed into the D (data) input. The way a D-type flip-flop works is that, whenever there is a rising edge on the clock input, the flip-flop will instantaneously sample the state of the D input. It will then update its output (Q) to that sampled state and hold it until the clock input sees another rising edge. Figure 8-19b shows some sample waveforms resulting from a target that is moving forward, then reverses direction.

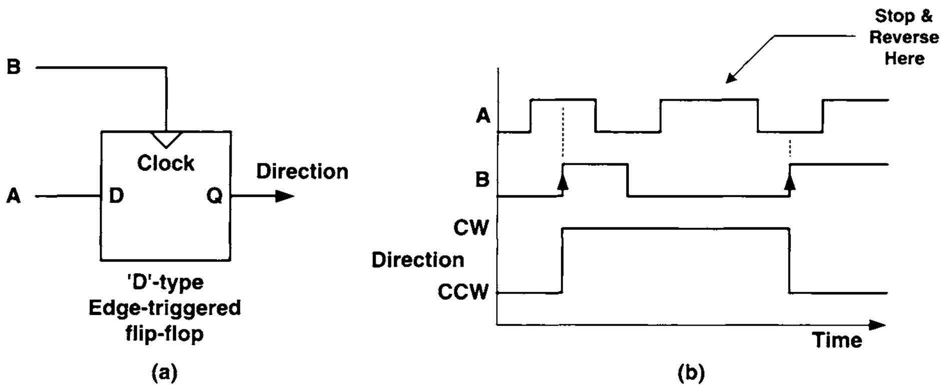


Figure 8-19: Using a D flip-flop (a) to determine direction from quadrature signals (b).

A direction signal can be used in conjunction with one of the sensor signals to track relative motion. The direction signal is used to determine whether a counter will increment (forward direction) or decrement (reverse direction) on receipt of a pulse from one of the sensors. The total count will represent relative motion from the time at which it was last reset. In practice, somewhat more complex logic than that described here is typically used to ensure the accuracy of the count, and therefore reduce position-tracking error.

While it is possible to implement a "speed and direction sensor" from a pair of digital Hall-effect latches and a D flip-flop, it is also possible to obtain this function in the form of a single integrated circuit. The Allegro Microsystems A3421 and A3422 ICs provide the necessary dual sensors, spaced 1.5 mm apart, as well as all the logic necessary to develop both direction and count output signals. For those situations in which one needs only the two sensor output signals (A and B) the Melexis MLX90224 omits the quadrature-decode logic and provides the digital quadrature signals only.

8.14 How Fast Do Speed Sensors Go?

One question that comes up frequently in the context of geartooth sensor performance is that of how fast a target can move and still reliably be detected by a particular geartooth sensor. The answer is quite complex and depends on a number of factors.

First, let's define "speed" in terms of the number of passing targets-per-second that the sensor can detect without error (adding or losing output pulses). This lets us define maximum operating speed in hertz. As an example, a 25-tooth target moving at 6000 RPM would present 2500 teeth per second to the sensor, equivalent to an operating frequency of 2.5 kHz. Let us also assume that the sensor is operating with a suitable target at an airgap well within its operating range, and therefore has a strong magnetic signal from which to operate. A sensor that operates marginally at low speeds will probably fail at slightly higher ones.

The first limitation is within the sensor IC itself. While the frequency response of the Hall transducer itself is very high (well in the megahertz range for those used on Hall ICs), the signal-processing circuitry can impose additional limitations. Chopper-stabilization circuitry can limit the IC's bandwidth to a few tens of kilohertz. Many signal-processing systems have bandwidths that extend beyond several hundred kilohertz. The exact frequency response of the sensor IC is dependent on the design and the process technology with which it was implemented. Many (but not all) Hall-effect sensor ICs, however, are capable of accurately sensing targets at frequencies in excess of 25 kHz. If this doesn't sound very fast, remember that we are discussing mechanical systems. A 25-kHz output signal corresponds to a 25-tooth target rotating at 60,000 RPM.

In many cases, however, the silicon is not the limiting factor when it comes to maximum target-sensing speed. The techniques used to package the sensor assembly, and even the IC, can introduce significant speed limitations.

While objects made from nonferrous metals, such as brass or aluminum, don't have many significant interactions with steady-state DC magnetic fields, they can interact strongly with time-varying ones. This is because a time-varying field tends to set up eddy-currents in any conductive body inside the field. These eddy currents flow in a manner that tries to prevent an externally applied magnetic field from entering the conductive body. Conversely, once a magnetic field is established inside a conductive body, eddy currents will flow in a manner that tries to prevent the field from leaving. Qualitatively, this effect is illustrated in Figure 8-20.

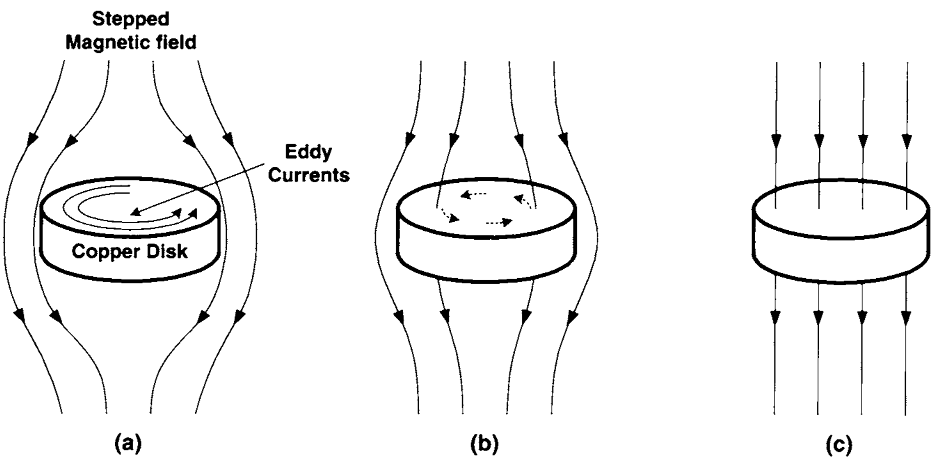


Figure 8-20: Stepped magnetic field entering conductive disk. Field immediately after field turns on (a), a few microseconds later (b), steady-state condition (c).

When an external magnetic field is initially applied to a conductive disk as a time-step function, eddy currents formed in the disk will try to exclude the external field (Figure 8-20a). After a short amount of time, these eddy currents will begin to die out, and the field will begin to enter the disk (Figure 8-20b). Finally, after some additional time, the eddy currents will have diminished to insignificant values, and the steady-state field will pass through the disk as if it weren't there (Figure 8-20c).

This effect occurs to varying degrees in all metal parts of a sensor housing through which sensed flux must travel. In general, the larger and thicker the metal body, the more it will attenuate time-varying fields. Also, materials with high electrical conductivities, such as copper and aluminum, will exhibit more pronounced effects than those with lower conductivities, such as bronze or zinc. This effect even occurs to some extent in the leadframes used in the Hall-effect sensor IC packages, although the time constants involved for structures this small can be measured in microseconds.

Since these dynamic eddy current effects are very complex to model analytically (or even with finite element analysis), it is difficult, if not impossible, to quantitatively predict their effects on sensor performance. Being aware of their existence, however, can provide at least a little insight that may be useful in helping to design sensors that meet your performance goals.