APPLICATIONS INFORMATION

Application Note
27701B*

HALL-EFFECT IC APPLICATIONS GUIDE

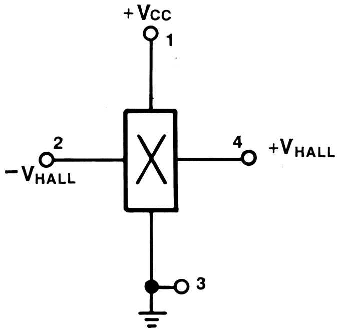

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Figure 1

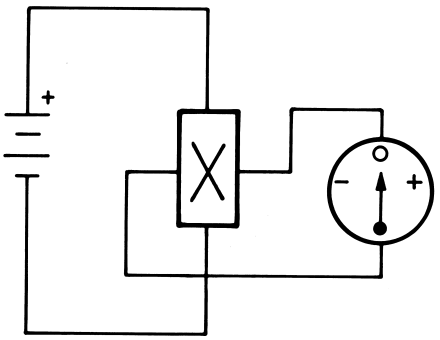

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Figure 2

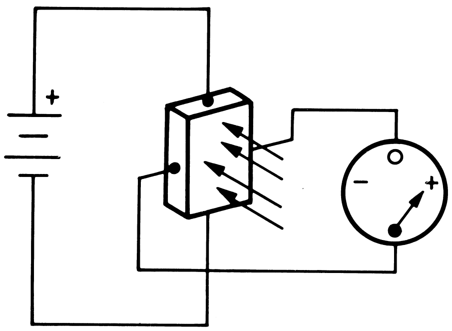

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Figure 3

Allegro MicroSystems uses the latest bipolar integrated circuit technology in combination with the century-old Hall effect to produce Hall-effect ICs. These are contactless, magnetically activated switches and sensors with the potential to simplify and improve systems.

LOW-COST SIMPLIFIED SWITCHING

Simplified switching is a Hall sensor's strong point. Hall-effect IC switches combine Hall voltage generators, signal amplifiers, Schmitt trigger circuits, and transistor output circuits on single integrated circuit chips. Output is clean, fast, and switched without bounce—an inherent problem with mechanical contact switches. A Hall-effect switch typically operates at up to a 100 kHz repetition rate, and costs less than many common electromechanical switches.

EFFICIENT, EFFECTIVE, LOW-COST LINEAR SENSORS

The linear Hall-effect sensor detects the motion, position, or change in field strength of an electromagnet, a permanent magnet, or a ferromagnetic material with an applied magnetic bias. Energy consumption is very low. The output is linear and temperature-stable. The sensor's frequency response is flat up to approximately 25 kHz.

A Hall-effect sensor is more efficient and effective than inductive or optoelectronic sensors, and at a lower cost.

SENSITIVE CIRCUITS FOR RUGGED SERVICE

The Hall-effect sensor is virtually immune to environmental contaminants and is suitable for use under severe service conditions. The circuit is very sensitive and provides reliable, repetitive operation in close tolerance applications. The Hall-effect sensor can see precisely through dirt and darkness.

CURRENT APPLICATIONS

Current applications for Hall-effect ICs include use in ignition systems, speed controls, security systems, alignment controls, micrometers, mechanical limit switches, computers, printers, disk drives, keyboards, machine tools, key switches, and pushbutton switches. They are also used as tachometer pickups, current limit switches, position detectors, selector switches, current sensors, linear potentiometers, and brushless dc motor commutators.

THE HALL EFFECT SENSOR: HOW DOES IT WORK?

The basic Hall sensor is a small sheet of semiconductor material represented by figure 1.

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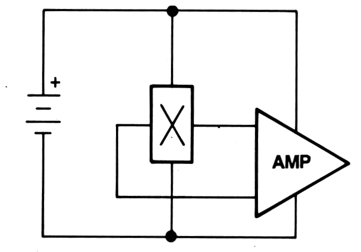

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Figure 4

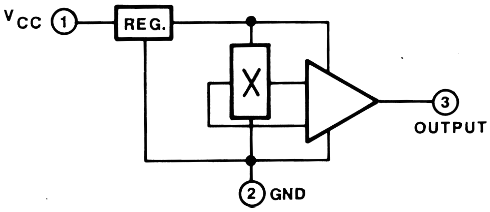

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Figure 5

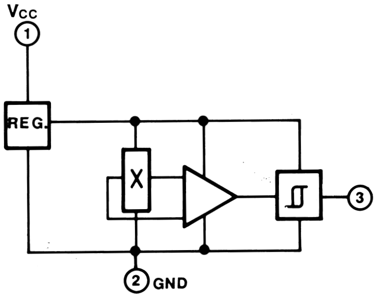

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Figure 6

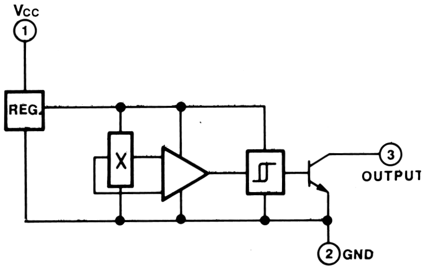

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Figure 7

A constant voltage source, as shown in figure 2, will force a constant bias current to flow in the semiconductor sheet. The output will take the form of a voltage measured across the width of the sheet that will have negligible value in the absence of a magnetic field.

If the biased Hall sensor is placed in a magnetic field with flux lines at right angles to the Hall current (figure 3), the voltage output is directly proportional to the strength of the magnetic field. This is the Hall effect, discovered by E. F. Hall in 1879.

LINEAR OUTPUT HALL-EFFECT DEVICES

The output voltage of the basic Hall-effect sensor (Hall element) is quite small. This can present problems, especially in an electrically noisy environment. Addition of a stable, high-quality dc amplifier and voltage regulator to the circuit (figures 4 and 5) improves the transducer's output and allows it to operate over a wide range of supply voltages. The modified device provides an easy-to-use analog output that is linear and proportional to the applied magnetic flux density.

The UGN3503 is this type of linear output device. The A3506/07/08 and A3515/16 have improved sensitivity and temperature-stable characteristics. The output is ratiometric; that is, its output is proportional to its supply voltage.

DIGITAL OUTPUT HALL-EFFECT SWITCHES

The addition of a Schmitt-trigger threshold detector with built-in hysteresis, as shown in figure 6, gives the Hall-effect circuit digital output capabilities. When the applied magnetic flux density exceeds a certain limit, the trigger provides a clean transition from OFF to ON without contact bounce. Built-in hysteresis eliminates oscillation (spurious switching of the output) by introducing a magnetic dead zone in which switch action is disabled after the threshold value is passed.

An open-collector NPN output transistor added to the circuit (figure 7) gives the switch digital logic compatibility. The transistor is a saturated switch that shorts the output terminal to ground wherever the applied flux density is higher than the ON trip point of the device. The switch is compatible with all digital families. The output transistor can sink enough current to directly drive many loads, including relays, triacs, SCRs, LEDs, and lamps.

The circuit elements in figure 7, fabricated on a monolithic silicon chip and encapsulated in a small epoxy or ceramic package, are common to all Hall-effect digital switches. Differences between device types are generally found in specifications such as magnetic parameters, operating temperature ranges, and temperature coefficients.

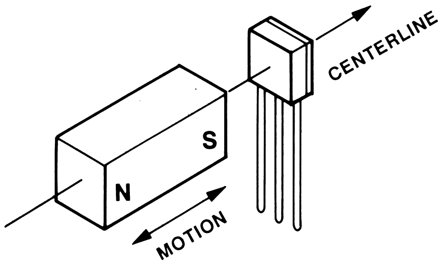

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Figure 8

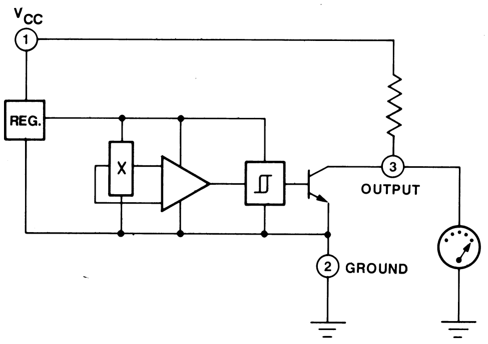

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Figure 9

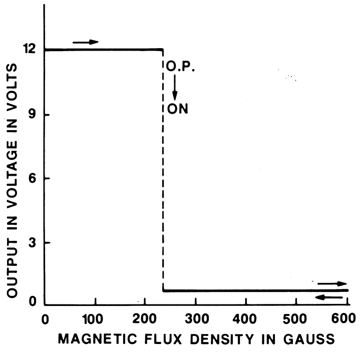

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Figure 10

OPERATION

All Hall-effect devices are activated by a magnetic field. A mount for the the devices, and electrical connections, must be provided; Parameters such as load current, environmental conditions, and supply voltage must fall within the specific limits shown in the appropriate documentation.

Magnetic fields have two important characteristics—flux density and polarity (or orientation). In the absence of any magnetic field, most Hall-effect digital switches are designed to be OFF (open circuit at output). They will turn ON only if subjected to a magnetic field that has both sufficient density and the correct orientation.

Hall switches have an active area that is closer to one face of the package (the face with the lettering, the branded face). To operate the switch, the magnetic flux lines must be perpendicular to this face of the package, and must have the correct polarity. If an approaching south pole would cause switching action, a north pole would have no effect. In practice, a close approach to the branded face of a Hall switch by the south pole of a small permanent magnet will cause the output transistor to turn ON (figure 8).

A Transfer Characteristics Graph (figures 10 and 11) plots this information. It is a graph of output as a function of magnetic flux density (measured in gauss; 1 G = 0.1 mT) presented to the Hall cell. The magnetic flux density is shown on the horizontal axis. The digital output of the Hall switch is shown along the vertical axis.

To acquire data for this graph, add a power supply and a pull-up resistor that will limit current through the output transistor and enable the value of the output voltage to approach zero (figure 9).

In the absence of an applied magnetic field (0 G), the switch is OFF, and the output voltage equals the power supply (12 V).
A permanent magnet's south pole is then moved perpendicularly toward the active area of the device. As the magnet's south pole approaches the branded face of the switch, the Hall cell is exposed to increasing magnetic flux density. At some point (240 G in this case), the output transistor turns ON and the output voltage approaches zero (figure 10). That value of flux density is called the operate point. If we continue to increase the field's strength, say to 600 G, nothing more happens. The switch turns ON once and stays ON.

To turn the switch OFF, the magnetic flux density must fall to a value far lower than the 240 G "operate point" because of the built-in hysteresis. For this example we use 90 G hysteresis, which means the device turns OFF when flux density decreases to 150 G (figure 11). That value of flux density is called the "release point".

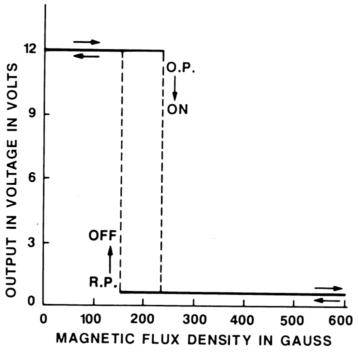

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Figure 11

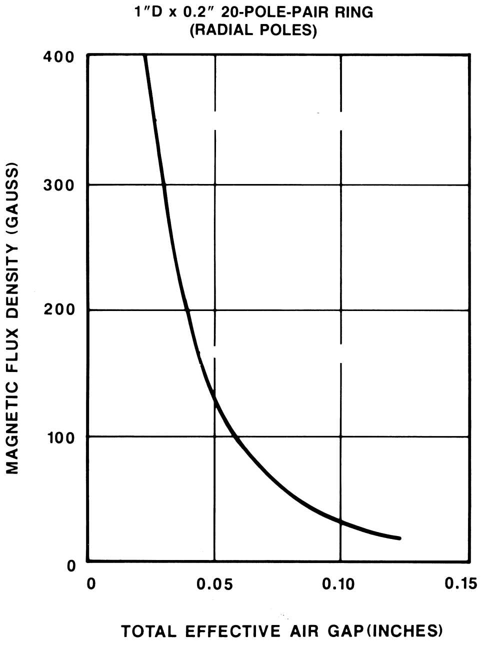

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Figure 12A

CHARACTERISTICS AND TOLERANCES

The exact magnetic flux density values required to turn Hall switches ON and OFF differ for several reasons, including design criteria and manufacturing tolerances. Extremes in temperature will also somewhat affect the operate and release points.

For each device type, worst-case magnetic characteristics for the operate value, the release value, and hysteresis are provided.

All switches are guaranteed to turn ON at or below the maximum operate point flux density. When the magnetic field is reduced, all devices will turn OFF before the flux density drops below the minimum release point value. Each device is guaranteed to have at least the minimum amount of hysteresis to ensure clean switching action. This hysteresis ensures that, even if mechanical vibration or electrical noise is present, the switch output is fast, clean, and occurs only once per threshold crossing.

GETTING STARTED

Because the electrical interface is usually straightforward, the design of a Hall-effect system should begin with the physical aspects. In position-sensing or motion-sensing applications, the following questions should be answered:

How much and what type of motion is there?

What angular or positional accuracy is required?

How much space is available for mounting the sensing device and activating magnet?

How much play is there in the moving assembly?

How much mechanical wear can be expected over the lifetime of the machine?

Will the product be a mass-produced assembly, or a limited number of machines that can be individually adjusted and calibrated?

What temperature extremes are expected?

A careful analysis will pay big dividends in the long term.

THE ANALYSIS

The field strength of the magnet should be investigated. The strength of the field will be the greatest at the pole face, and will decrease with increasing distance from the magnet. The strength of the magnetic field can be measured with a gaussmeter or a calibrated linear Hall sensor.

A plot of field strength (magnetic flux density) is a function of distance along the intended line of travel of the magnet. Hall device

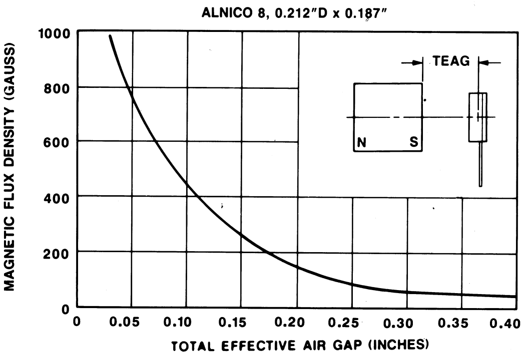

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Figure 12B

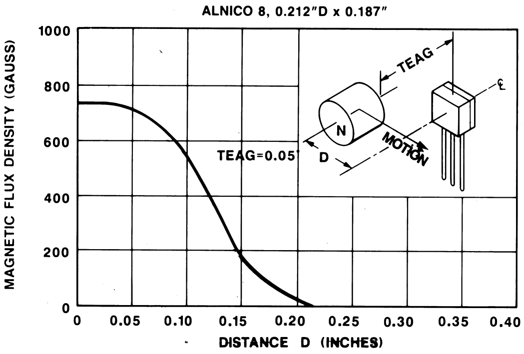

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Figure 13

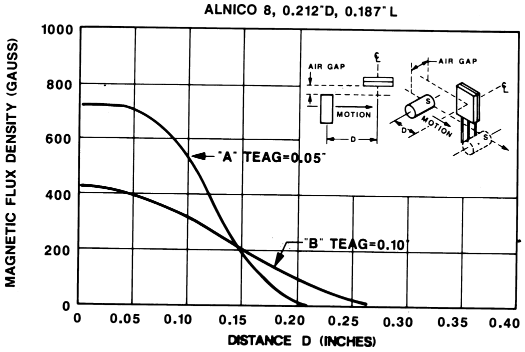

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Figure 14

specifications (sensitivity in mV/G for a linear device, or operate and release points in gauss for a digital device) can be used to determine the critical distances for a particular magnet and type of motion. Note that these field strength plots are not linear, and that the shape of the flux density curve depends greatly upon magnet shape, the magnetic circuit, and the path traveled by the magnet.

TOTAL EFFECTIVE AIR GAP (TEAG)

Total effective air gap, or TEAG, is the sum of active area depth and the distance between the package's surface and the magnet's surface. A graph of flux density as a function of total effective air gap (figure 12A) illustrates the considerable increase in flux density at the sensor provided by a thinner package. The actual gain depends on the characteristic slope of flux density for a particular magnet.

MODES OF OPERATION

Even with a simple bar or rod magnet, there are several possible paths for motion. The magnetic pole could move perpendicularly straight at the active face of the Hall device. This is called the head-on mode of operation. The curve of figure 12B illustrates typical flux density (in gauss) as a function of TEAG for a cylindrical magnet.

The head-on mode is simple, works well, and is relatively insensitive to lateral motion. The designer should be aware that overextension of the mechanism could cause physical damage to the epoxy package of the Hall device.

A second possibility would be to move the magnet in from the side of the Hall device in the slide-by mode of operation, as illustrated in figure 13. Note that now the distance plotted is not total effective air gap, but rather the perpendicular distance from the centerline of the magnet to the centerline of the package. Air gap is specified because of its obvious mechanical importance, but bear in mind that to do any calculations involving flux density, the "package contribution must be added and the TEAG used, as before. The slide-by mode is commonly used to avoid contact if overextension of the mechanism is likely. The use of strong magnets and/or ferrous flux concentrators in well-designed slide-by magnetic circuits will allow better sensing precision with smaller magnet travel than the head-on mode.

Magnet manufacturers generally can provide head-on flux density curves for their magnets, but they often do not characterize them for slide-by operation, possibly because different air gap choices lead to an infinite number of these curves; however, once an air gap is chosen, the readily available head-on magnet curves can be used to find the peak flux density (a single point) in the slide-by application by noting the value at the total effective air gap.

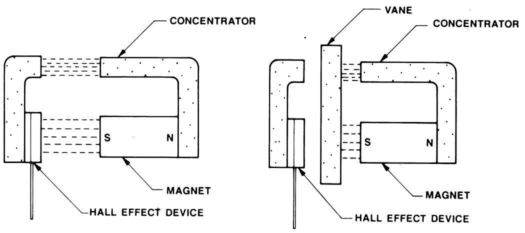

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Figure 15

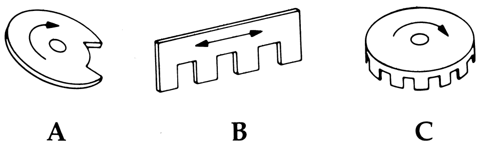

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Figure 16

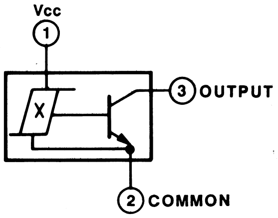

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Figure 17

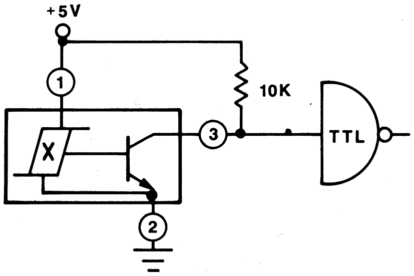

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Figure 18A

STEEP SLOPES—HIGH FLUX DENSITIES

For linear Hall devices, greater flux changes for a given displacement give greater outputs, clearly an advantage. The same property is desirable for digital Hall devices, but for more subtle reasons. To achieve consistent switching action in a given application, the Hall device must switch ON and OFF at the same positions relative to the magnet.

To illustrate this concept, consider the flux density curves from two different magnet configurations in figure 14. With an operate-point flux density of 200 G, a digital Hall-effect device would turn ON at a distance of approximately 0.14 inches in either case. If manufacturing tolerances or temperature effects shifted the operate point to 300 G, notice that for curve A (steep slope) there is very little change in the distance at which switching occurs. In the case of curve B, the change is considerable. The release point (not shown) would be affected in much the same way. The basic principles illustrated in this example can be modified to include mechanism and device specification tolerances and can be used for worse-case design analysis. Examples of this procedure are shown in later sections.

VANE-INTERRUPTER SWITCHING

In this mode, the activating magnet and the Hall device are mounted on a single rigid assembly with a small air gap between them. In this position, the Hall device is held in the ON state by the activating magnet. If a ferromagnetic plate, or vane is placed between the magnet and the Hall device, as shown in figure 15, the vane forms a magnetic shunt that distorts the flux field away from the Hall device.

Use of a movable vane is a practical way to switch a Hall device. The Hall device and magnet can be molded together as a unit, thereby eliminating alignment problems, to produce an extremely rugged switching assembly. The ferrous vane or vanes that interrupt the flux could have linear motion, or rotational motion, as in an automotive distributor. Ferrous vane assemblies, due to the steep flux density/distance curves that can be achieved, are often used where precision switching over a large temperature range is required.

The ferrous vane can be made in many configurations, as shown in figure 16. With a linear vane similar to that of figure 16B, it is possible to repeatedly sense position within 0.002 inch over a 125°C temperature range.

ELECTRICAL INTERFACE FOR DIGITAL HALL DEVICES

The output stage of a digital Hall switch is simply an open-collector npn transistor. The rules for use are the same as those for any similar switching transistor.

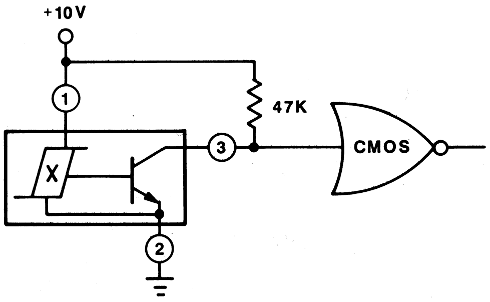

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Figure 18B

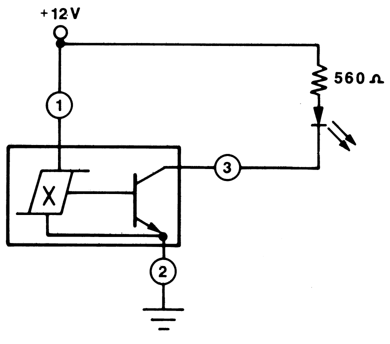

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Figure 19

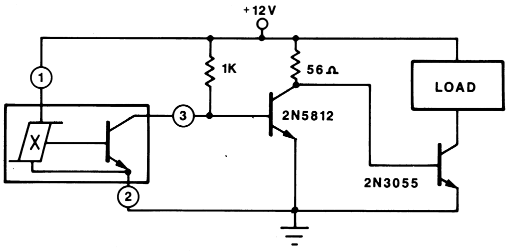

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Figure 20

When the transistor is OFF, there is a small output leakage current (typically a few nanoamperes) that usually can be ignored, and a maximum (breakdown) output voltage (usually 24 V), which must not be exceeded.

When the transistor is ON, the output is shorted to the circuit common. The current flowing through the switch must be externally limited to less than a maximum value (usually 20 mA) to prevent damage. The voltage drop across the switch ($V_{CE(sat)}$) will increase for higher values of output current. You must make certain this voltage is compatible with the OFF, or “logic zero,” voltage of the circuit you wish to control.

Hall devices switch very rapidly, with typical rise and fall times in the 400 ns range. This is rarely significant, because switching times are almost universally controlled by much slower mechanical parts.

COMMON INTERFACE CIRCUITS

Figure 17 illustrates a simplified schematic symbol for Hall digital switches. It will make further explanation easier to follow.

Interface for digital logic integrated circuits usually requires only an appropriate power supply and pull-up resistor.

With current-sinking logic families, such as DTL or the popular 7400 TTL series (figure 18A), the Hall switch has only to sink one unit-load of current to the circuit common when it turns ON (1.6 mA maximum for TTL). In the case of CMOS gates (figure 18B), with the exception of switching transients, the only current that flows is through the pull-up resistor (about 0.2 mA in this case).

Loads that require sinking currents up to 20 mA can be driven directly by the Hall switch.

A good example is a light-emitting diode (LED) indicator that requires only a resistor to limit current to an appropriate value. If the LED drops 1.4 V at a current of 20 mA, the resistor required for use with a 12 V power supply can be calculated as:

$$\frac{12\text{ V} - 1.4\text{ V}}{0.02\text{ A}} = 530\ \Omega$$

The nearest standard value is 560 Ω, resulting in the circuit of figure 19.

Sinking more current than 20 mA requires a current amplifier. For example, if a certain load to be switched requires 4 A and must turn ON when the activating magnet approaches, the circuit shown in figure 20 could be used.

When the Hall switch is OFF (insufficient magnetic flux to operate), about 12 mA of base current flows through the 1 kΩ resistor to the 2N5812 transistor, thereby saturating it and shorting the base of the 2N3055 to ground, which keeps the load OFF. When a magnet is brought near the Hall switch, it turns ON, shorting the base of the 2N5812 to ground and turning it OFF. This allows:

$$\frac{12\ \text{V}}{56\ \Omega} = 210\ \text{mA}$$

of base current to flow to the 2N3055, which is enough to saturate it for any load current of 4 A or less.

The Hall switch cannot source current to a load in its OFF state, but it is no problem to add a transistor that can. For example, consider using a 40669 triac to turn ON a 115 V or 230 V ac load. This triac would require about 80 mA of gate current to trigger it to the ON condition. This could be done with a 2N5811 PNP transistor, as shown below in figure 21.

When the Hall switch is turned ON, 9 mA of base current flows into the 2N5811, thereby saturating it and allowing it to supply 80 mA of current to trigger the triac. When the Hall switch is OFF, no base current flows in the 2N5811, which turns it OFF and allows no gate current to pass to the triac. The 4.7 kΩ and the 1 kΩ resistors were added as a safeguard against accidental turn-on by leakage currents, particularly at elevated temperatures.

Note that the +12 V supply common is connected to the low side of the ac line, and in the event of a mixup, the Hall switch and associated low-voltage circuitry would be 115 V above ground. *Be careful!*

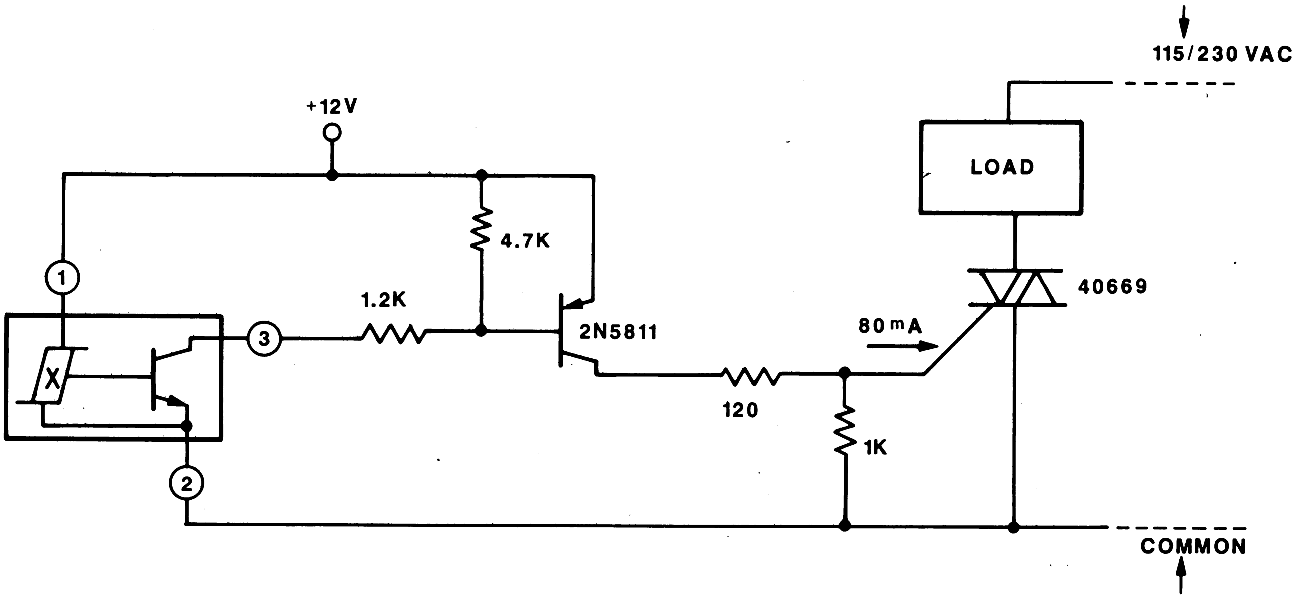

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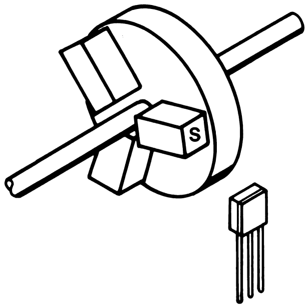
Figure 21

A. MAGNETIC ROTOR



B. FERROUS VANE ROTOR

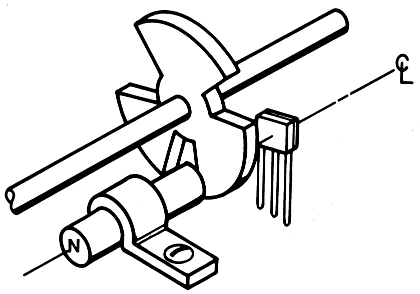


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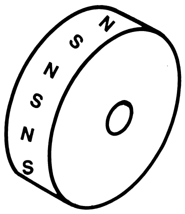
Figure 22

A. RADIAL



B. AXIAL

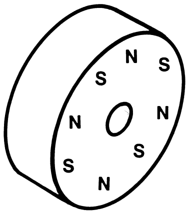


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Figure 23

ROTARY ACTIVATORS FOR HALL SWITCHES

A frequent application involves the use of Hall switches to generate a digital output proportional to velocity, displacement, or position of a rotating shaft. The activating magnetic field for rotary applications can be supplied in either of two ways:

MAGNETIC ROTOR ASSEMBLY

The activating magnet(s) are fixed on the shaft and the stationary Hall switch is activated with each pass of a magnetic south pole (figure 22A). If several activations per revolution are required, rotors can sometimes be made inexpensively by molding or cutting plastic or rubber magnetic material. Ring magnets can also be used. Ring magnets are commercially available disc-shaped magnets with poles spaced around the circumference. They will operate Hall switches dependably and at reasonable costs.

Ring magnets do have limitations:

The accuracy of pole placement (usually within 2 or 3 degrees).

Uniformity of pole strength (±5%, or worse).

These limitations must be considered in applications requiring precision switching.

FERROUS VANE ROTOR ASSEMBLY

Both the Hall switch and the magnet are stationary (figure 22B); the rotor interrupts and shunts the flux with the passing of each ferrous vane.

Vane switches tend to be a little more expensive than ring magnets, but because the dimensions and configuration of the ferrous vanes can be carefully controlled, they are often used in applications requiring precise switching or duty cycle control.

Properly designed vane switches can have very steep flux density curves, yielding precise and stable switching action over a wide temperature range.

RING MAGNETS FOR HALL SWITCH APPLICATIONS

Ring magnets suitable for use with Hall switches are readily available from magnet vendors in a variety of different materials and configurations. The poles may be oriented either radially (figure 23A) or axially (figure 23B) with up to 20 pole-pairs on a one-inch diameter ring. For a given size and pole count, ring magnets with axial poles have somewhat higher flux densities.

Materials most commonly used are various Alnicos, Ceramic 1, and barium ferrite in a rubber or plastic matrix material. Manufacturers usually have stock sizes with a choice of the number of pole pairs. Custom configurations are also available at a higher cost.

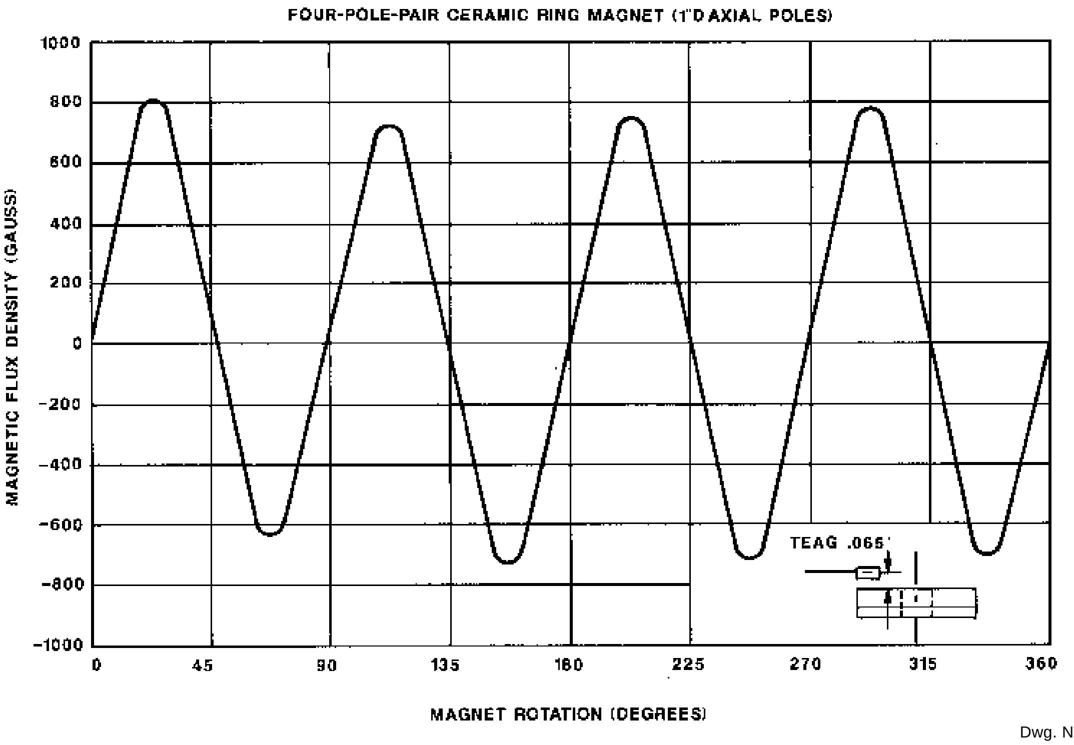
Alnico is a name given to a number of aluminum nickel-cobalt alloys that have a fairly wide range of magnetic properties. In general, Alnico ring magnets have the highest flux densities, the smallest changes in field strength with changes in temperature, and the highest cost. They are generally too hard to shape except by grinding and are fairly brittle, which complicates the mounting of bearings or arbor.

Ceramic 1 ring magnets (trade names Indox, Lodex) have somewhat lower flux densities (field strength) than the Alnicos, and their field strength changes more with temperature, However, they are considerably lower in cost and are highly resistant to demagnetization by external magnetic fields. The ceramic material is resistant to most chemicals and has high electrical resistivity. Like Alnico, they can withstand temperatures well above that of Hall switches and other semiconductors, and must be ground if reshaping or trimming is necessary. They may require a support arbor to reduce mechanical stress.

The rubber and plastic barium ferrite ring magnets are roughly comparable to Ceramic 1 in cost, flux density, and temperature coefficient, but are soft enough to shape using conventional methods. It is also possible to mold or press them onto a shaft for some applications. They do have temperature limitations ranging from +70°C to +150°C, depending on the particular material, and their field strength changes more with temperature than Alnico or Ceramic 1.

Regardless of material, ring magnets have limitations on the accuracy of pole placement and uniformity of pole strength which, in turn, limit the precision of the output waveform. Evaluations have shown that pole placement in rubber, plastic, and ceramic magnets usually falls within ±2° or ±3° of target, but ±5° errors have been measured. Variations of flux density from pole to pole will commonly be ±5%, although variations of up to ±30% have been observed.

Figure 24 is a graph of magnetic flux density as a function of angular position for a typical 4 pole-pair ceramic ring magnet, one inch



Dwg. No. A-13,125

Figure 24

in diameter, with a total effective air gap of 0.065" (0.050" clearance plus 0.015" package contribution). It shows quite clearly both the errors in pole placement and variations of strength from pole to pole.

A frequent concern with ring magnets is ensuring sufficient flux density for reliable switching. There is a trade-off between the number of pole-pairs and the flux density for rings of a given size. Thus, rings with large numbers of poles have lower flux densities. It is important that the total effective air gap (TEAG) is kept to a minimum, because flux density at the Hall active area decreases by 5 G or 6 G per 0.001" for many common ring magnets. This is clearly shown in figure 25, a graph of flux density at a pole as a function of TEAG for a typical 20-pole-pair plastic ring magnet. Also shown in figure 25 is the effect of “package contribution” to the TEAG. The standard “U” package contributes about 0.016". The other factor contributing to TEAG is mechanical clearance, which should be as small as possible, consistent with dimensional tolerances of the magnet, bearing tolerances, bearing wear, and temperature effects on the Hall switch mounting bracket.

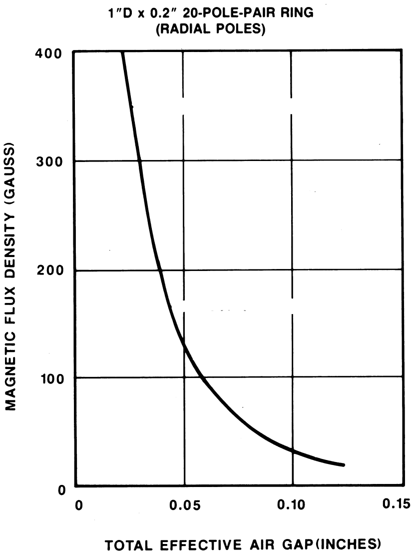


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Figure 25

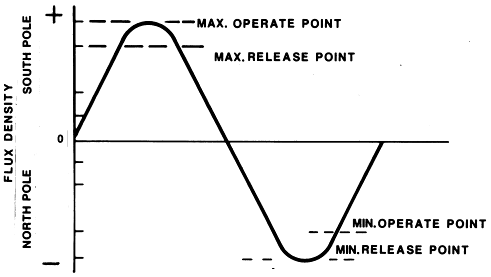

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Figure 26A

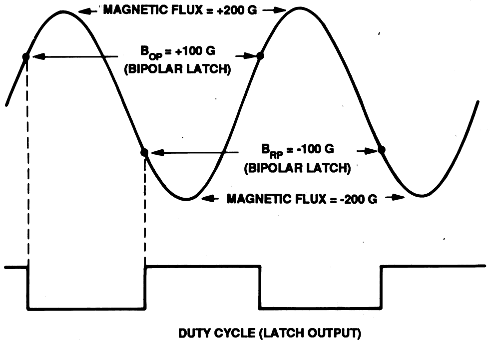

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Figure 26B

WHAT IS A BIPOLAR SWITCH?

A bipolar switch, the A3134, has a maximum operate point of +45 G, a minimum release point of -40 G, and a minimum hysteresis of 15 G at + 25°C; however, the operate point could be as low as -25 G (-40 G minimum release, 15 G minimum hysteresis) and the release could be as high as +30 G (+45 G maximum operate, 15 G minimum hysteresis). Figure 26A shows two cases of operate and release with one device operating at the maximum operate and release points, and the other with minimum operate and release points.

In applications previously discussed, the Hall switch was operated (turned ON) by the approach of a magnetic south pole (positive flux). When the south pole was removed (flux approaches zero), the Hall switch had to release (turn OFF). On ring magnets, both north and south poles are present in an alternating pattern. The release point flux density becomes less important because if the Hall switch has not turned OFF when the flux density goes to zero (south pole has passed), it will certainly turn OFF when the following north pole causes flux density to go negative. Bipolar Hall switches take advantage of this extra margin in release-point flux values to achieve lower operate-point flux densities, a definite advantage in ring magnet applications.

THE BIPOLAR LATCH

Unlike the A3134 bipolar switch, which may release with a south pole or north pole, the bipolar latch offers a more precise control of the operate and release parameters. This Hall integrated circuit has been designed to operate (turn ON) with a south pole only; it will then remain ON when the south pole has been removed. In order to have the bipolar latch release (turn OFF), it must be presented with a north magnetic pole. This alternating south pole-north pole operation, when properly designed, will produce a duty cycle approaching 50%.

The UGN3175 was designed specifically for applications requiring a tightly controlled duty cycle, such as in brushless dc motor commutation. This was accomplished with the introduction of the bipolar latch in 1982. The UGN3175 has become very popular as a brushless dc motor commutator, shaft encoder, speedometer element, and tachometer sensor.

Duty cycle is controlled with an alternating magnetic field, as shown in figure 26B.

DESIGN EXAMPLE

Given:

operating temperature range of -20°C to +85°C, and

bipolar Hall switch in standard “U” package:

maximum operate point +200 G from -20° to + 85°C,

minimum release point -200 G from -20°C to + 85°C,

air gap package contribution 0.016", and

necessary mechanical clearance 0.030".

First, find the total effective air gap:

TEAG = clearance + package contribution

TEAG = 0.030" + 0.016" = 0.046"

Now, determine the necessary flux density sufficient to operate the Hall switch, plus 40%.

To operate the Hall switch, the magnet must supply a minimum of ±200 G at a distance of 0.046" over the entire temperature range. Good design practice requires the addition of extra flux to provide some margin for aging, mechanical wear, and other imponderables. If we add a pad of 100 G, a reasonable number, the magnet required must supply ±300 G at a distance of 0.046" over the temperature range.

TEMPERATURE EFFECTS

Unfortunately, magnet strength is affected by temperature to some degree. Temperature coefficients of some common magnetic materials are given below:

Material	Temperature coefficient
Rubber/plastic	-0.2% to -0.3% per °C
Ceramic 1	-0.15% to -0.2% per °C
Alnico 2, 5	-0.02% to -0.03% per °C
Alnico 8	±0.01% per °C

If we are considering a ceramic ring magnet with a worst-case temperature coefficient of -0.2%/°C, we must add some extra flux density to the requirement at room temperature to ensure that we still have +300 G per south pole at +85°C. This amount is:

[(85°C - 25°C) x 0.2%/°C] 300 G = +36 G

Thus, the flux density that will ensure that the Hall switch will operate over temperature is 300 G + 36 G = 336 G per south pole at +25°C.

Follow the same procedure for the north pole requirements. If the magnet will supply +300 G per south pole and -300 G per north pole at +85°C, it will supply even more flux density per north pole at -20°C because of the negative temperature coefficient.

In applications where temperature conditions are more severe, Alnico magnets are considerably better than the ceramic magnets we considered. It is also possible to order custom Hall switches with specifications tailored to your application. For example, you can specify a range of operate and release points at a particular temperature, with temperature coefficients for operate and release points, if that is better suited to your application. On a custom basis, Hall switches are available with operate and release point temperature coefficients of less than 0.3 G/°C, and with operate flux densities of less than 100 G.

If you intend to use a low-cost, low flux density ring magnet, then a device in the 0.060" package would be a good choice. The package contribution is 0.016", which results in a significant improvement in peak flux density from a magnet, as shown in figure 25.

If the rotor drive can withstand an increased torque requirement, consider a ferrous flux concentrator. Flux density can be increased by 10% to 40% in this manner. A concentrator of 0.03125" mild steel

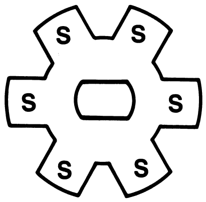

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Figure 27

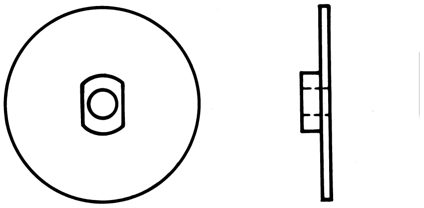

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Figure 28

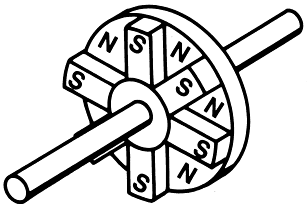

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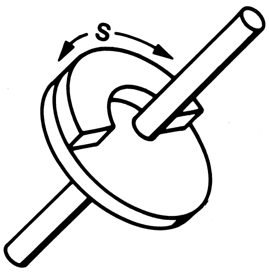
Figure 29



Dwg. No. A-13,132

Figure 30

having the same dimensions as, and cemented to, the back surface of the Hall switch, will increase flux density by about 10%. A return path of mild steel from the back side of the device to the adjacent poles can add even more. Often the functions of mounting bracket and flux concentrator can be combined. Additional information can be found in the section on flux concentrators.

RING MAGNETS —DETAILED DISCUSSION

An Inexpensive Alternative

Innovative design can produce surprisingly good results. Rubber and plastic magnet stock comes in sheets. One side of the sheet is magnetic north; the other side is south. This material is relatively inexpensive and can easily be stamped or die-cut into various shapes.

These properties prompted one designer to fabricate an inexpensive magnetic rotor assembly that worked very well. The rubber magnet stock was die-cut into a star-shaped rotor form, as shown in figure 27. A nylon bushing formed a bearing, as shown in figure 28.

Finally, a thin mild-steel backing plate was mounted to the back of the assembly to give mechanical strength and to help conduct the flux back from the north poles on the opposite side. This actually served to form apparent north poles between the teeth; the measured flux between south pole teeth is negative. Figure 29 shows the completed magnetic rotor assembly, essentially a ring magnet with axial poles.

The Hall switch was mounted with its active surface close to the top of the rotor assembly, facing the marked poles. There is some versatility in this approach, as asymmetrical poles can be used to fabricate a rotor that wll allow trimmable ON time and, thus work as a timing cam. Figure 30 illustrates a cam timer adjusted to 180° ON and 180° OFF.

RING MAGNET SELECTION

When you discuss your application with a magnet vendor, the following items should be considered:

Mechanical Factors

- Dimensions and tolerances
- Mounting hole type and maximum eccentricity
- Rotational speed
- Mechanical support required
- Coefficient of expansion

Magnetic Factors

- Poles: number, orientation, and placement accuracy
- Flux density at a given TEAG (remember to add the Hall switch package contribution to the clearance figure)
- Magnetic temperature coefficient

Environmental Factors

- Tolerance of the material to the working environment (temperature, chemical solvents, electric potentials)

Flux density curves from several typical ring magnets are included to present an idea of what can be expected from various sizes and materials. Figure 31 shows the curve for a ring similar in size and material to that of figure 25, but with 10 pole-pairs instead of 20 (note

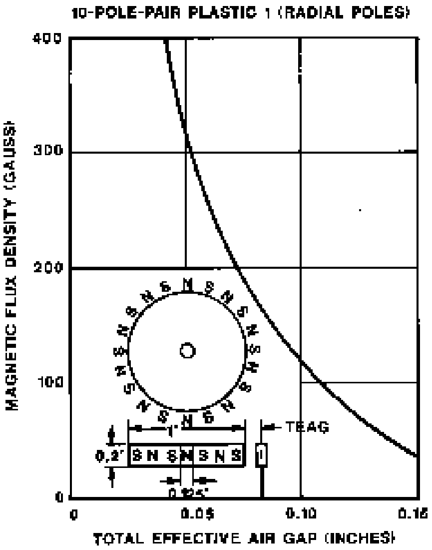


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Figure 31

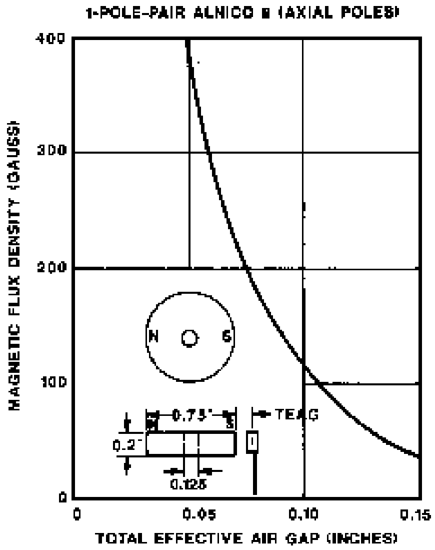

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Figure 32

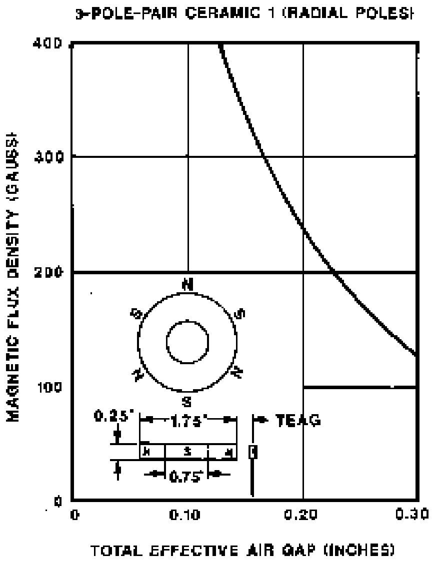

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Figure 33

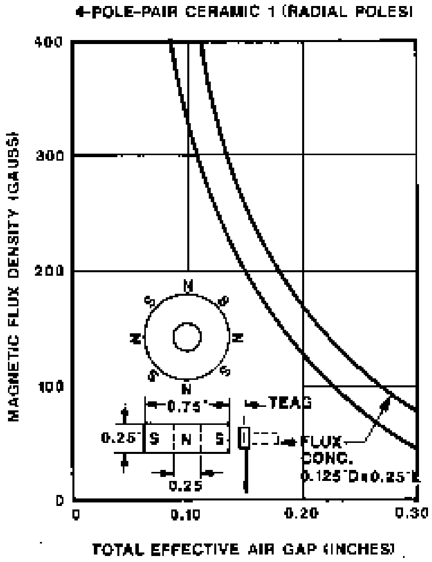

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Figure 34

increased flux density values). Figure 32 shows the curve from a one pole-pair Alnico 8 ring. Figure 33 shows the curve from a three-pole-pair Ceramic 1 ring. Figure 34 shows the curves from a four-pole-pair Ceramic 1 ring, with and without a ferrous flux concentrator.

Incoming inspection of ring magnets is always advisable. You can ensure the magnets are within the agreed upon magnetic specifications by making measurements with a commercial gaussmeter, or a calibrated linear Hall device mounted in a convenient test fixture. Calibrated Hall devices and technical assistance are available.

FERROUS VANE ROTARY ACTIVATORS

A ferrous vane rotor assembly is the alternative to magnetic rotors for rotary Hall switch applications. As shown previously, a single magnet will hold a Hall switch ON except when one of the rotor vanes interrupts the flux path and shunts the flux path away from the Hall switch. The use of a single stationary magnet allows very precise switching by eliminating ring magnet variations, placement, and strength. Unlike the evenly spaced poles on ring magnets, the width of rotor vanes can easily be varied. It is possible to vary the Hall switch OFF and ON times, which gives the designer control over the duty

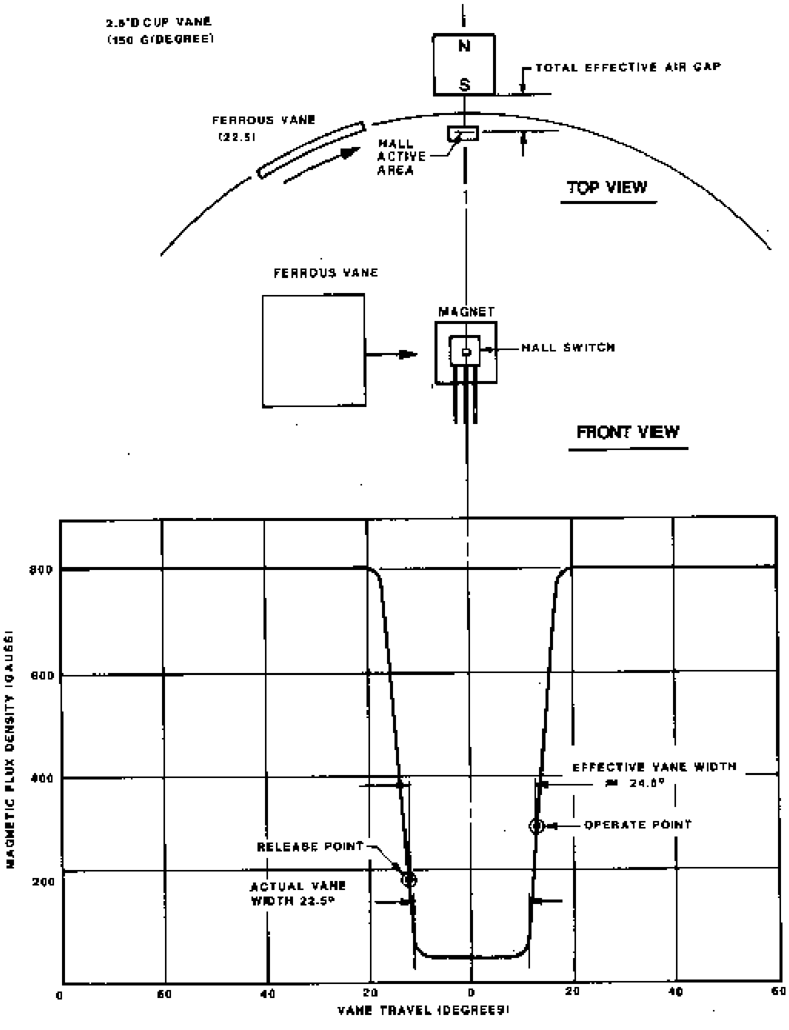

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Figure 35

cycle of the output waveform. Ferrous-vane rotors are a good choice where precise switching is desired over a wide range of temperatures. As the vane passes between magnet and Hall switch, progressively more flux will be blocked or shunted. Small variations in lateral position have a very small effect on the transition point.

A FERROUS VANE IN OPERATION

Figure 35 combines top and front views of a ferrous-vane magnet/Hall switch system with the graph of flux density as a function of vane travel produced by this system. Note that the drawings and the graph are vertically aligned along the horizontal axis. Position is measured from the leading edge of the vane to the centerline of the magnet/Hall device.

Initially, when the vane is located entirely to the left of the magnet, the vane has no effect and the flux density at the sensor is at a maximum of 800 G. As the leading edge of the vane nears the magnet, the shunting effect of the vane causes the flux density to decrease in a nearly linear fashion. There, the magnet is covered by the vane and flux density is at a minimum. As the vane travels on it starts to uncover the magnet. This allows the flux to increase to its original value. After that, additional vane travel has no further influence on flux density at the sensor.

A Hall switch located in the position of the sensor would initially be ON because of the presence of the magnetic field. Somewhere in the linearly decreasing region, the flux would fall below the release point, and the Hall switch would turn OFF. It would remain OFF until the increasing flux reaches the operate point for that particular Hall switch. Recall that the operate point flux density is greater than the release point flux density by the amount of hysteresis for that particular Hall switch.

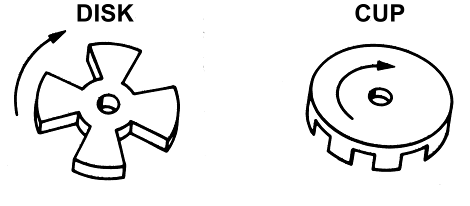

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Figure 36

The interval during which the Hall switch remains OFF is determined by the actual width of the vane and the steepness of the magnetic slope, as well as by the operate and release point flux density values for the Hall switch. This interval is called the effective vane width, and it is always somewhat greater than the physical vane width.

ROTOR DESIGN

Two commonly used rotor configurations are the disk and the cup, as shown in figure 36.

The disk is easily fabricated and, hence, is often used for low-volume applications such as machine control. Axial movement of the rotor must be considered. Vane-activated switches tolerate this quite well, but the rotor must not hit the magnet or the Hall switch.

Cup rotors are somewhat more difficult to fabricate and so are more expensive, but dealing with a single radial distance simplifies calculations and allows precise control of the output waveforms. For cup rotors, radial bearing wear or play is the significant factor in determining the clearances, while axial play is relatively unimportant. Cup rotors have been used very successfully in automotive ignition systems. The dwell range is determined by the ratio of the vane-to-window widths when the rotor is designed. Firing point stability may be held to ±0.005 distributor degrees per degree Celsius in a well-designed system.

MATERIAL

Vanes are made of a low-carbon steel to minimize the residual magnetism and to give good shunting action. The vane thickness is chosen to avoid magnetic saturation for the value of flux density it must shunt. Vanes usually are between 0.03" and 0.06" thick.

VANE / WINDOW WIDTHS, ROTOR SIZE

Generally, the smallest vanes and window on a rotor should be at least one and one-half times the width of the magnet pole to provide adequate shunting action and to maintain sufficient differential between the OFF and ON values of flux density.

In table 1, the maximum flux density (obtained with window centered over the magnet, the minimum flux density (vane centered over the magnet), and the difference between the two values are tabulated for three cases:

1. Vane and window width the same as magnet pole width.

2. Vane and window width one and one-half times magnet pole width.

3. Vane and window width two times the magnet pole width.

In each case the magnet is 0.25" x 0.25" x 0.125" samarium cobalt; the air gap is 0.1"; the rotor vanes are made of 0.04" mild-steel stock.

Table 1

Window vane width factor	**1.0**	**1.5**	**2.0**
Flux density with window centered	630 G	713 G	726 G
Flux density with vane centered	180 G	100 G	80 G
Flux change density	450 G	613 G	646 G

If a small rotor with many windows and vanes is required, a miniature rare-earth magnet must be used to ensure sufficient flux density for reliable operation. For example, a 0.1" cubical samarium cobalt magnet makes it practical to fabricate a 1.25" diameter rotor with as many as 10 windows and vanes. With fewer vanes, even further size reduction is possible.

Table 2

Curve	Magnet	Air gap	Slope G/mil	*Concentrator
A	0.25"D, 0.25"L samarium cobalt	0.1"	14	Yes
B	0.25"D, 0.25"L samarium cobalt	0.1"	9.85	No
C	0.25"D, 0.125"L samarium cobalt	0.1"	9.0	Yes
D	0.25"D, 0.125"L samarium cobalt	0.125"	8.7	Yes
E	0.25"D, 0.125"L samarium cobalt	0.1"	7.8	No
F	0.25"D, 0.125"L samarium cobalt	0.125"	6.3	No
G	0.25"D, 0.125"L samarium cobalt	0.125"	5.6	Yes
H	0.25"D, 0.125"L Ssamarium cobalt	0.125"	4.5	No

NOTE: The “U” package is used for all measurements.*

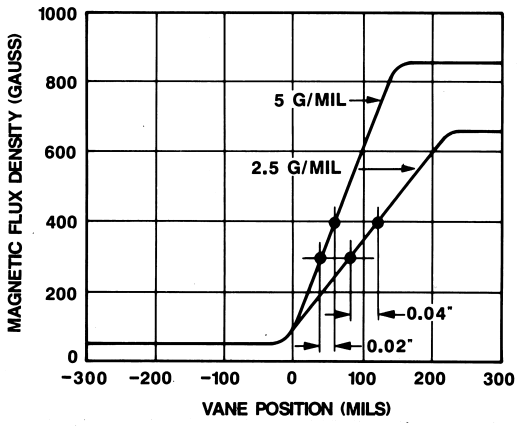

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Figure 37

STEEP MAGNETIC SLOPES FOR CONSISTENT SWITCHING

The flux density vane travel graph for most common vane configurations (figure 35) is very nearly linear in the transition regions. The Hall switch operate and release points fall in these linear transition regions, and it is easily seen that if these values change, the position of the vane which causes the switching must change also. Figure 37 shows the flux density as a function of vane position for two different magnetic circuits. In one case, the magnetic slope is 2.5 G/mil. In the second case, it is 5.0 G/mil.

If the 2.5 G/mil system is used with a Hall switch known to have an operate point flux density of 300 G at +25°C, the device would switch ON when the vane is 85 mils past the center of the window at this temperature. If the Hall switch operate point went up to 400 G at a temperature of +125°C (this represents Hall switch temperature coefficient of 1 G/°C), the vane must move to 120 mils past center, a change in switching position of 45 mils. If the same Hall switch is used in the second system having the 5 mil/G slope, the operate point would shift only 20 mils, or half as much, because the slope is twice as steep.

Slopes in typical vane systems range from 1 G/mil to 15 G/mil, and are affected by magnet type and size, the magnetic circuit, and the total effective air gap. It is interesting to note that, although slide-by operation can give very steep slopes, the transition point is much affected by lateral motion (change in air gap); therefore, vanes are often preferred for applications involving play or bearing wear.

SMALL AIR GAPS FOR STEEP SLOPES

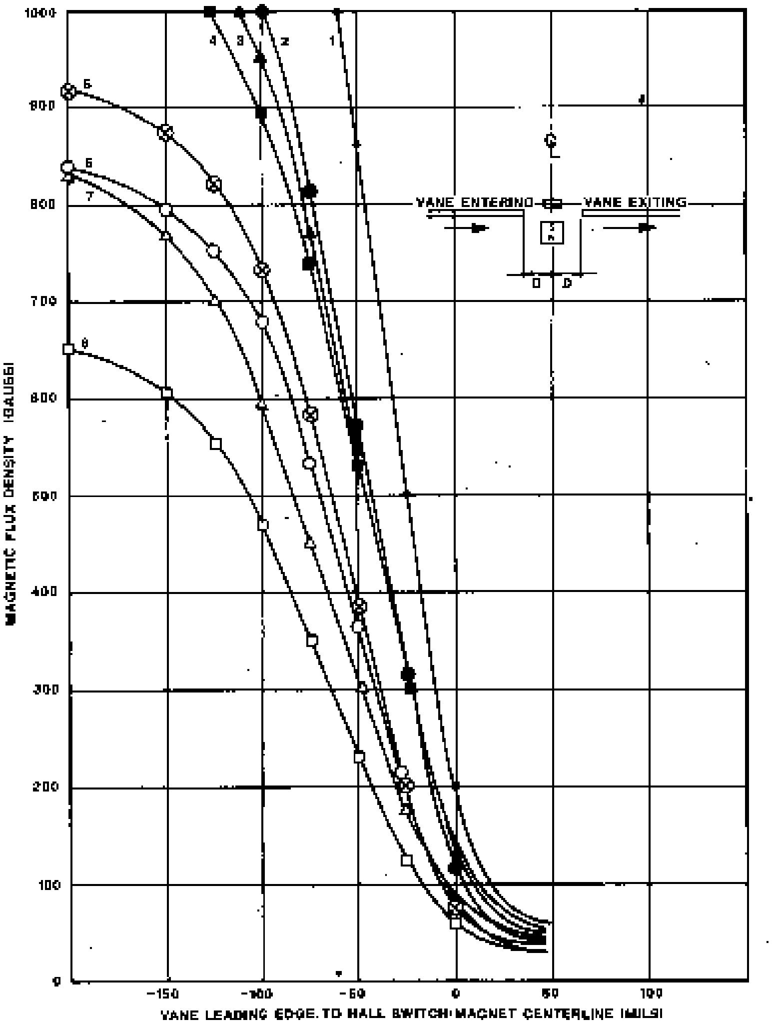
The air gap should be as small as the mechanical system allows. Factors to be considered are:

vane material thickness and vane radius,

maximum eccentricity for cup vanes,

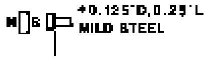
bearing tolerance and wear, and

change in air gap with temperature due to mounting considerations.



SYMBOL	MAGNET	AIR GAP	SLOPE(G/MIL)	*CONC.
1 •	0.25"D,0.25"L SAM.CO.	0.1"	14	YES
2 ●	0.25"D,0.25"L SAM.CO.	0.1"	9.65	NO
3 ▲	0.25"D,0.125"L SAM.CO.	0.1"	9.0	YES
4 ■	0.25"D,0.25"L SAM.CO.	0.125"	8.7	YES
5 ⊘	0.25"D,0.125"L SAM.CO.	0.1"	7.8	NO
6 ○	0.25"D,0.25"L SAM.CO.	0.125"	8.3	NO
7 △	0.25"D,0.125"L SAM.CO.	0.125"	5.8	YES
8 □	0.25"D,0.125"L SAM.CO.	0.125"	4.5	NO

NOTE - THE "U" PACKAGE IS USED FOR ALL MEASUREMENTS



*0.125"D,0.25"L MILD STEEL

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Figure 38

In figure 38, two different samarium cobalt magnets are used in a vane system to illustrate the effects of changes in air gap and magnet size. Note that only the falling transition region is shown (transition regions are symmetrical). The distances on the horizontal axis have been measured from the leading edge of the vane.

The term “air gap” as used in figure 38 is not the total effective air gap; but is simply the distance from the face of the magnet to the surface of the Hall switch. It does not include the package contribution. The “U” package is often used in ferrous vane applications because it has a shallow active area depth.

FLUX CONCENTRATORS PAY DIVIDENDS

What if economic or size considerations dictated the smaller magnet used in figure 38, and mechanical considerations dictated the larger (0.125") air gap, but the resulting flux density and slope (curve 8) were not good enough? Curve 7 in figure 38 shows the very substantial improvement that can be achieved by adding simple flux concentrators. Those used in the example were 0.125" in diameter by 0.250" long, and were fastened behind the Hall switch.

DESIGN EXAMPLE

The magnet/concentrator configuration we just considered (curve 7, figure 38) seems to offer a high performance/cost ratio. Following is an evaluation of its use in an automotive ignition system using a 2.5" diameter cup rotor.

The initial timing and wide operating temperature range requirements for this application have generally led designers to specify custom Hall switches in terms of the minimum and maximum operate or release point at +25°C, plus a maximum temperature coefficient on these parameters over the operating temperature range. Representative specifications might be:

+25°C operate point, minimum	300 G
+25°C operate point, maximum	450 G
+25°C release point, minimum	200 G

Temperature Coefficients:

Δ O.P./Δ T, maximum = +0.7 G/°C

Δ R.P./Δ T, maximum = +1.0 G/°C

Solid-state Hall-effect ignition systems can be designed to fire either on operate or release of the Hall switch. We have arbitrarily chosen to have the system in this example fire when the switch operates and, thus, the operate point specifications of the Hall switch (between 300 and 450 G at +125°C) will determine the amount of uncertainty in the initial timing of the spark. It is possible that the mechanical system would also make a contribution, but that is not considered here.

Figure 39 shows the measured flux density at the position of the sensor as a function of the vane travel. The shape of the curve

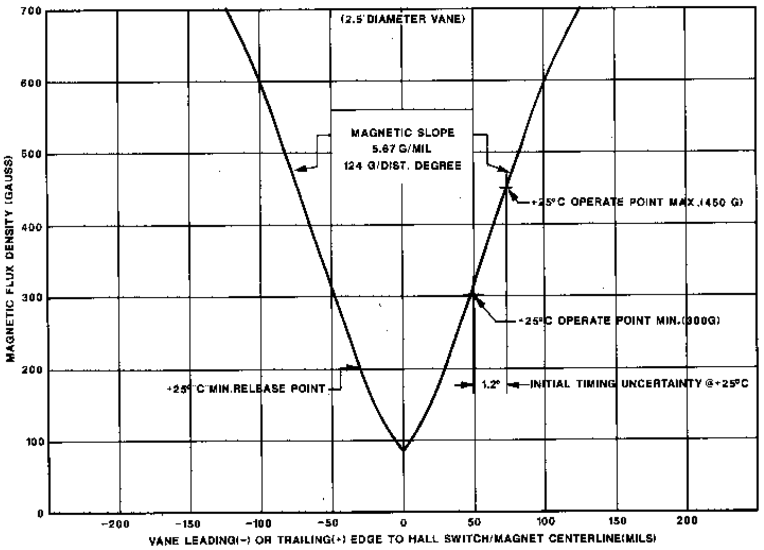

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Figure 39

requires explanation. Because the flat minimum and maximum flux regions are irrelevant, it is convenient to measure from the vane's leading edge to edge of the vane to the magnet centerline while plotting data for the rising transition. The same presentation would result if all data were plotted while a vane passed the magnet the center low flux areas were snipped out, and the ends containing the linear transitions were pulled together. From this graph, we can identify the magnetic slope of the transition regions for our system—approximately 5.67 G per 0.001" of vane travel.

Calculations based on the rotor diameter (2.5") show we have 22 mils of vane travel per distributor degree. The 5.67 G/mil slope obtained from figure 39 is equivalent to 125 G per distributor degree. From the specifications, it is known that the Hall switch will operate when flux is between 300 G and 450 G, leaving a 150 G window of uncertainty. At +25°C, this will be:

$$150\text{ G} \times \frac{\text{Distributor Degree}}{125\text{ G}} =$$

$$1.2\text{ Distributor Degrees}$$

Additional contributions to the initial timing uncertainty will result if the total effective air gap is changed, as that would affect the shape or slopes of the magnetic flux density/vane travel curve of figure 39. Factors to be considered are the magnet peak energy product tolerances, as well as manufacturing tolerances in the final Hall switch/ magnet assembly.

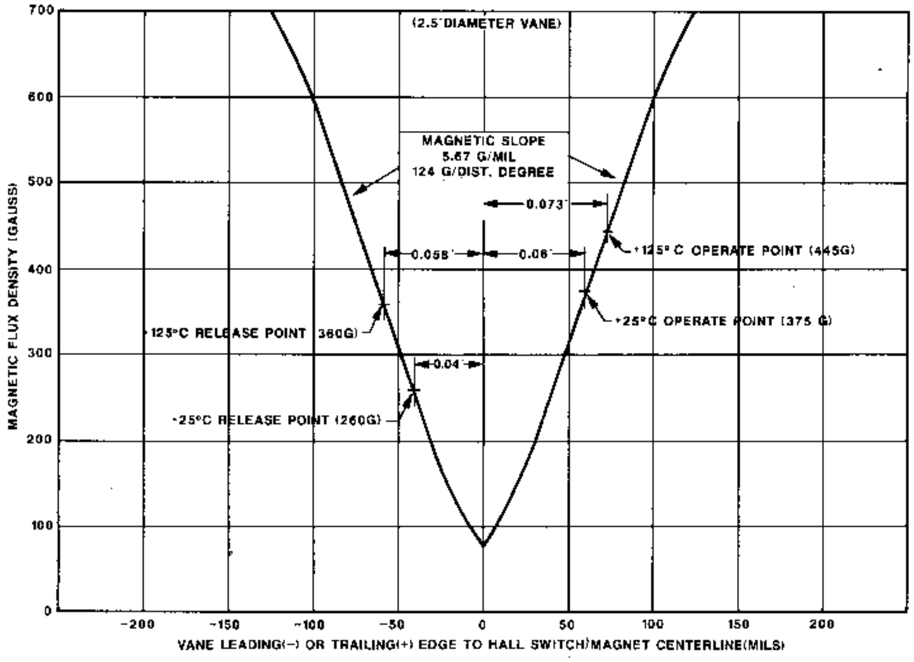
TEMPERATURE STABILITY OF OPERATE POINT

An early Hall switch operate-point temperature coefficient was approximately 0.2 G/°C. To translate this into distributor degrees per degree Celsius, we take:

$$\frac{0.2\text{ G}}{1^\circ\text{C}} \times \frac{\text{Distributor Degrees}}{125\text{ G}} =$$

$$0.0016\text{ Distributor Degrees}/^\circ\text{C}$$

The distributor timing would, therefore, change 0.16 degrees for a temperature change of 100°C.



Dwg. No. A-13,142

Figure 40

A typical samarium cobalt magnet temperature coefficient is -0.04%/°C. A magnetic field of 375 G at +25°C would decrease to 360 G at +125°C. For figure 40, our system has a magnetic slope of 5.67 G/mil, giving an additional vane travel requirement at +125°C of:

$$(375\text{ G} - 360\text{ G}) \times \frac{1\text{ mil}}{5.67\text{ G}} = 2.7\text{ mils}$$

This translates to timing change of:

$$2.7\text{ mils} \times \frac{\text{Distributor Degree}}{22\text{ mils}} =$$

0.12 Distributor Degrees

for a temperature change of 100°C.

CALCULATING DWELL ANGLE AND DUTY CYCLE VARIATIONS

The dwell angle in a conventional system is the number of distributor degrees during which the points are closed, which corresponds to the amount of time current can flow in the coil's primary winding. In our example, current flows in the coil primary from the time the Hall switch releases until it operates, which is called the effective vane width. For nostalgic reasons we will assume an eight-cylinder engine, which requires a distributor rotor with eight windows and eight vanes of equal size. One window-vane segment thus occupies 45 distributor degrees and will fire one cylinder. Let us further assume a typical Hall switch operate point of 375 G at +25°C (A), and a +25°C release point of 260 G (B). From figure 40 we find that the points will close 40 mils before the vane's leading edge passes the magnet centerline; they open 60 mils after the vane's trailing edge passes the magnet centerline. The effective vane width is greater than the mechanical vane width by an amount:

$$(60\text{ mils} + 40\text{ mils}) \times \frac{\text{Distributor Degree}}{22\text{ mils}} =$$

4.54 Distributor Degrees

This gives a dwell angle of (45° + 4.54°) = 49.54 distributor degrees at +25°C. The duty cycle is:

$$\frac{49.54^\circ}{90^\circ} = 55.0\%\text{ at }+25^\circ\text{C.}$$

Using the specified worst-case temperature coefficients, we calculate the new operate and release points at +125°C to be 445 G (C) and 360 G (D), also shown in figure 40. The dwell angle at +125°C would then be:

$$45^\circ + \left[(73\text{ mils} + 58\text{ mils}) \times \frac{\text{Distributor Degree}}{22\text{ mils}}\right] =$$

50.9 Distribution Degrees

The duty cycle is then:

$$\frac{50.9^\circ}{90^\circ} = 56.6\%$$

EFFECTS OF BEARING WEAR

A ±10 mil radial movement of the vane, with its position adjusted to the approximate operate point of the Hall switch, gave a measured change of ±6 G. This translates into a change of:

$$6\text{ G} \times \frac{\text{Distributor Degrees}}{125\text{ G}} =$$

0.048 Distributor Degrees,

which is equivalent to 0.097 crankshaft degrees.

MOUNTING ALSO AFFECTS STABILITY

In the example above, it was assumed that the physical relationship between the Hall switch and the magnet was absolutely stable. In practice, it is necessary to design the mountings with some care if this is to be true. It has been found that supporting the magnet or Hall switch with formed brackets of aluminum or brass will often contribute a significant temperature-related error to the system. Use of molded plastic housings has proven to be one of the better mounting techniques.

INDIVIDUAL CALIBRATION TECHNIQUES

In some applications, it may be desirable to have the vane switch assemblies operate within a narrower range of vane edge positions than is possible with a practical operate point specification for the Hall switch, for example, if it were necessary to reduce the initial timing window in the previous case. One solution would be individual calibration. Possible techniques include:

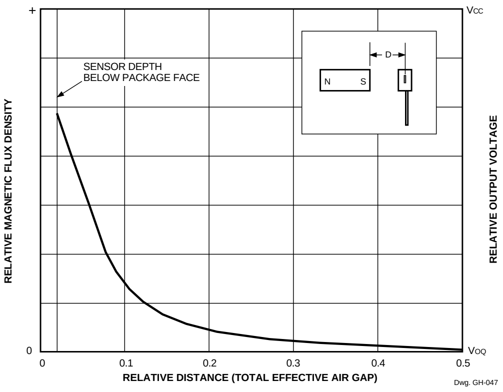


Figure 41

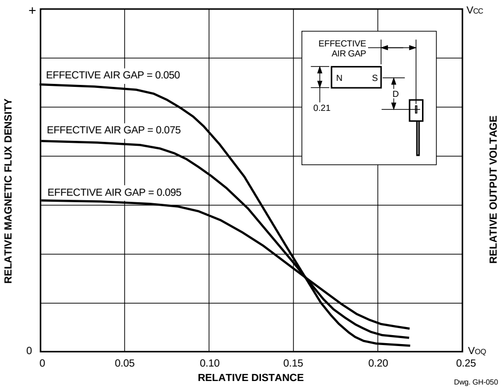
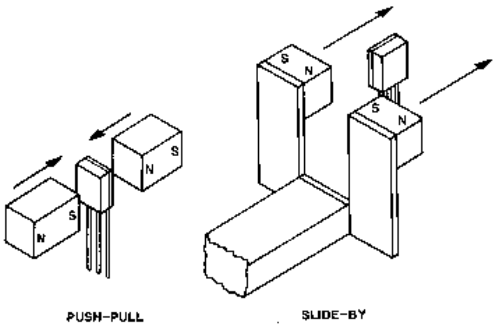


Figure 42



Dwg. No. 13,145

Figure 43

1) adjusting the air gap by changing the magnet position,
2) adjusting the position of a flux concentrator behind the Hall switch,
3) adjusting the position of a small bias magnet mounted behind the Hall switch,
4) demagnetizing the magnet in small increments that would decrease the magnetic slope and, thus, increase the temperature effects, and/or
5) adjusting the position of the Hall switch-magnet assembly relative to the rotor in a manner similar to rotating an automotive distributor to change the timing.

OPERATING MODES

HEAD-ON AND SLIDE-BY MODES

The most common operating modes are head on and slide by. The head-on mode is simple and relatively insensitive to lateral motion, but cannot be used where overextension of the mechanism might damage the Hall switch. The flux-density plot for a typical head-on operation (figure 41) shows that the magnetic slope is quite shallow for low values of flux density, a disadvantage that generally requires extreme mechanism travel and extreme sensitivity to flux changes in operate and release points of the Hall switch. This problem can be overcome by selecting Hall switches with higher operate and release properties.

The slide-by mode is also simple, can have reasonably steep slopes (to about 10 G/mil) and has no problem with mechanism overtravel. It is, however, very sensitive to lateral play, as the flux density varies dramatically with changes in the air gap. This can be seen clearly in the curves of figure 42, in which the flux density curves are plotted for actual slide-by operation with various air gaps. It is apparent that the operating mechanism can have little side play if precise switching is required.

OPERATING MODE ENHANCEMENTS —COMPOUND MAGNETS

PUSH-PULL

Because the active area of a Hall switch is close to the branded face of the package, it is usually operated by approaching this face with a magnetic south pole. It is also possible to operate a Hall switch by applying a magnetic north pole to the back side of the package. While a north pole alone is seldom used, the push-pull configuration (simultaneous application of a south pole to the branded side and a north pole to the back side) can give much greater field strengths.

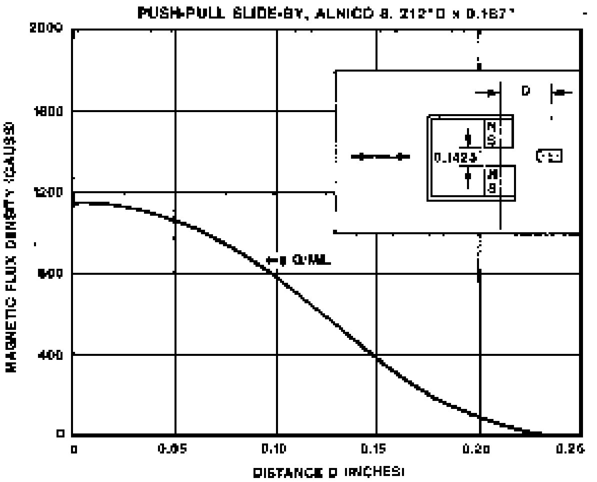
than are possible with any single magnet (figure 43). Perhaps more important, push-pull arrangements are quite insensitive to lateral motion and are worth considering if a loosely fitting mechanism is involved.

Figure 44 shows the flux-density curve for an actual push-pull slide-by configuration that achieves a magnetic slope of about 8 G/mil.

PUSH-PUSH

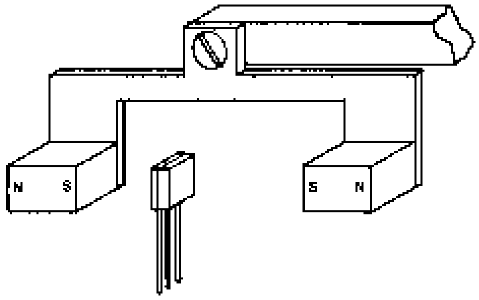
Another possibility, a bipolar field with a fairly steep slope (which is also linear), can be created by using a push-push configuration in the head-on mode (figure 45).

In the push-push mode, head-on configuration as shown in figure 45, the magnetic fields cancel each other when the mechanism is centered, giving zero flux density at that position. Figure 46 shows the flux-density plot of such a configuration. The curve is linear and



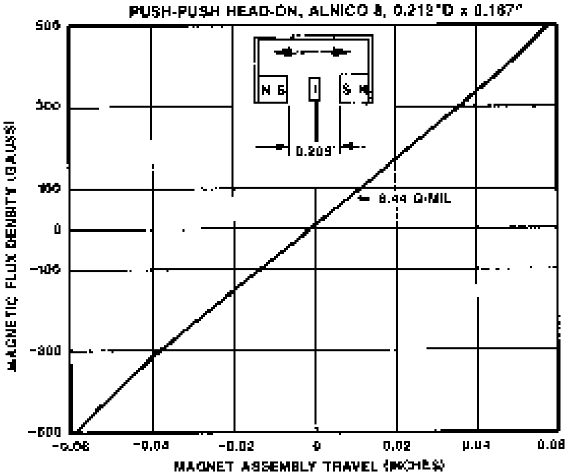
Dwg. No. A-13,146

Figure 44



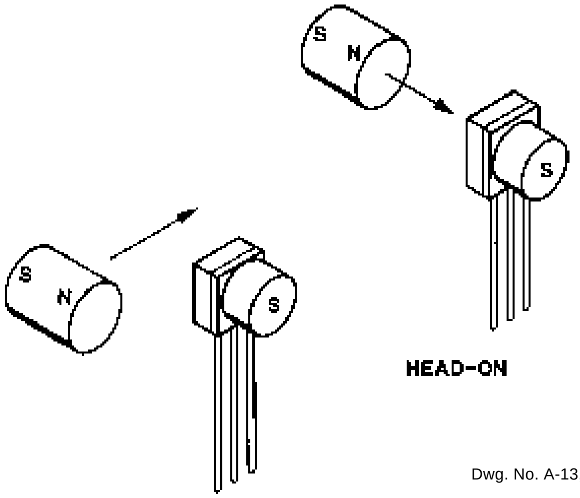
Dwg. No. A-13,147

Figure 45



Dwg. No. A-13,148

Figure 46



Dwg. No. A-13,149

Figure 47

moderately steep at better than 8 G/mil. The mechanism is fairly insensitive to lateral motion.

BIASED OPERATION

It is also possible to bias the Hall switch by placing a stationary north or south pole behind it to alter the operate and release points. For example, a north pole attached to the reverse face would turn the device normally ON until a north pole providing a stronger field in the opposite direction approached the opposite face (figure 47).

Figures 48-51 demonstrate four additional slide-by techniques. Compound magnets are used in push-pull, slide-by, edgewise configurations to achieve a magnetic slope of 17.4 G/mil. Rare-earth magnets may be used to obtain substantially steeper slopes. A flux density curve of up to 100 G/mil is obtainable.

INCREASING FLUX DENSITY BY IMPROVING THE MAGNETIC CIRCUIT

Magnetic flux can travel through air, plastic, and most other materials only with great difficulty. Because there is no incentive for flux from the activating magnet to flow through the (plastic and silicon) Hall device, only a portion of it actually does. The balance flows around the device and back to the other pole by whatever path offers the least resistance (figure 52).

However, magnetic flux easily flows through a ferromagnetic material such as mild steel. The reluctance of air is greater by a factor of several thousand than that of mild steel.

In a Hall device application, the goal is to minimize the reluctance of the flux path from the magnetic south pole, through the Hall device, and back to the north pole. The best possible magnetic circuit for a Hall device would provide a ferrous path for the flux, as shown in figure 53, with the only “air gap” being the Hall device itself.

While a complete ferrous flux path is usually impractical, unnecessary, and even impossible in applications requiring an undistorted or undisturbed flux field, it is a useful concept that points the way to a number of very practical compromises for improving flux density.

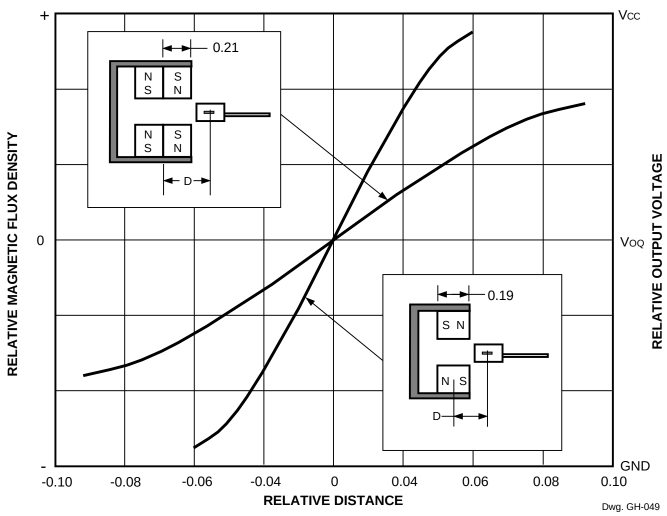


Figure 48

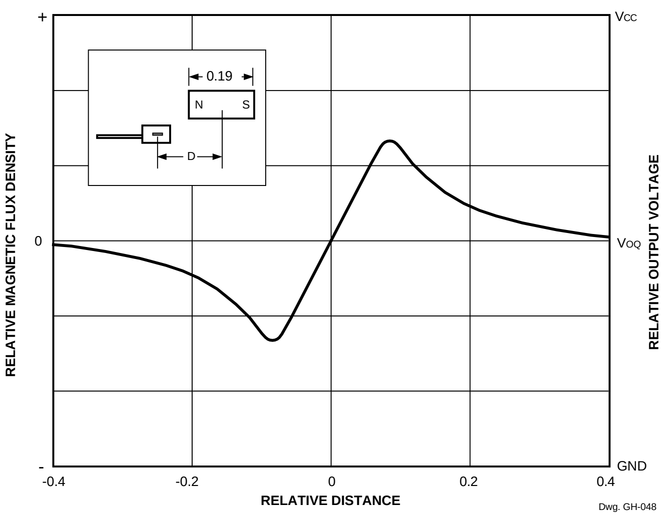


Figure 49

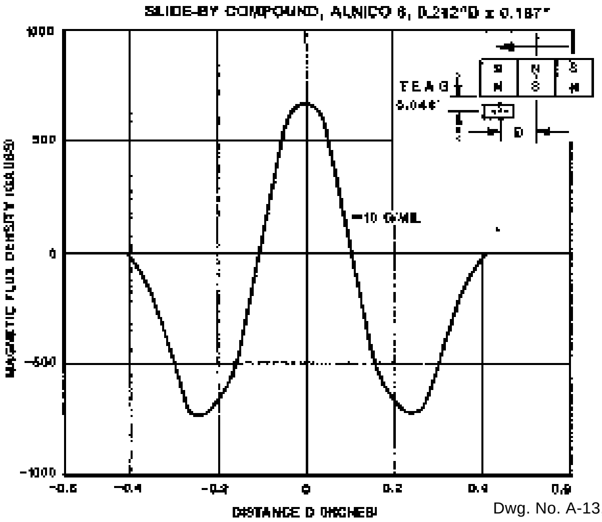
FLUX CONCENTRATORS

Flux concentrators are low-carbon (cold-rolled) steel magnetic conductors. They are used to provide a low reluctance path from a magnet's south pole, through the Hall sensor, and back to the north pole. Flux concentrators can take many forms and will often allow use of smaller or less expensive magnets (or less expensive, less sensitive Hall devices) in applications where small size or economy are important. They are of value whenever it is necessary or desirable to increase flux density at the Hall device. Increases of up to 100% are possible.

An example of the effectiveness of a concentrator is illustrated in figures 54A and 54B.

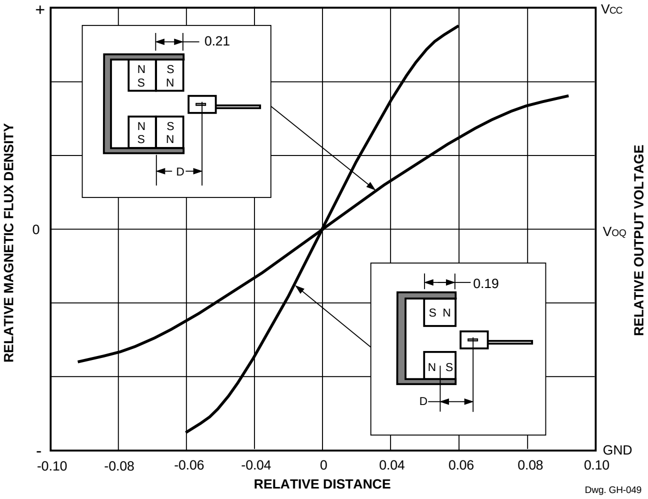
(A) The south pole of a samarium cobalt magnet 0.25" square and 0.125" long, is spaced 0.25" from the Hall switch. There is a flux density of 187 G at the active area.

(B) With a concentrator 0.125" in diameter and 0.5" long, the flux density increases to 291 G.



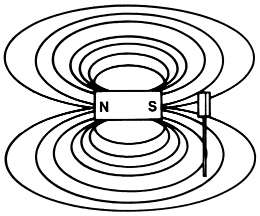
Dwg. No. A-13,152

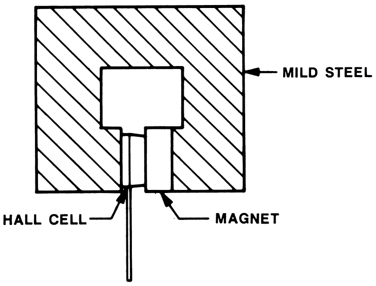
Figure 50

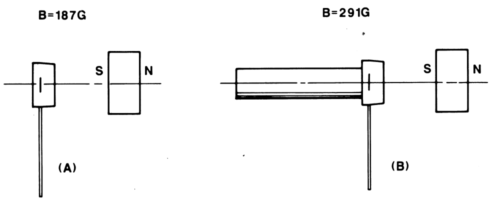


Dwg. GH-049

Figure 51







Dwg. No. A-13,154

Dwg. No. A-13,155

Dwg. No. A-13,156

Figure 52

Figure 53

Figure 54

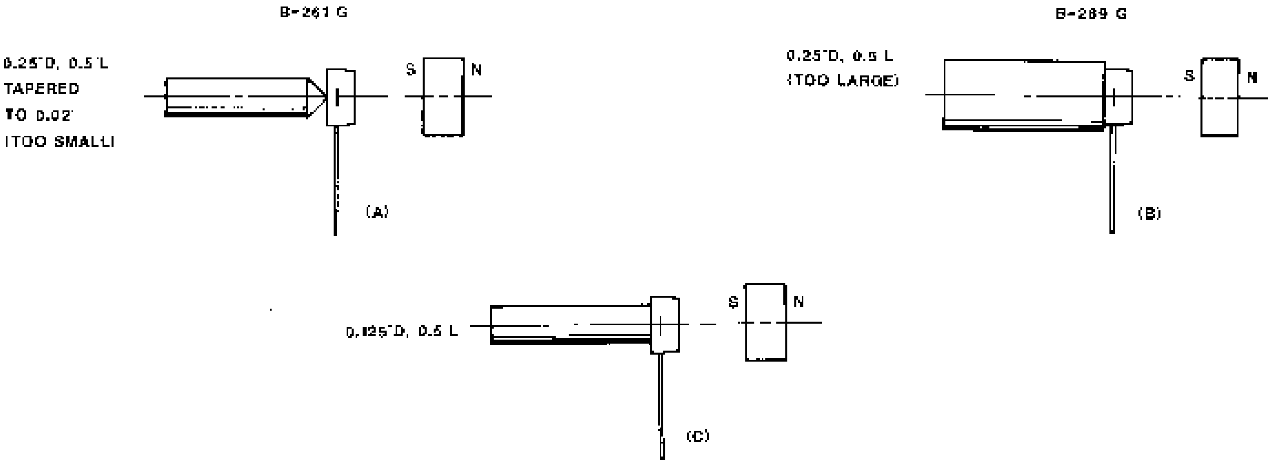
SIZE OF THE CONCENTRATOR

The active area of the Hall device is typically 0.01" square. Best results are obtained by tapering the end of the concentrator to approximately the same dimensions. With the “U” package, however, there is 0.044" from the active area to the rear surface of the package. Due to this 0.044" distance, a slightly larger end to the concentrator results in higher values of flux density at the active area. If the end is too large, the flux is insufficiently concentrated. Figures 55A, 55B, and 55C illustrate these effects using cylindrical flux concentrators and a 0.25" gap.

The length of the concentrator also has an effect on the flux density. This is illustrated in figure 56.

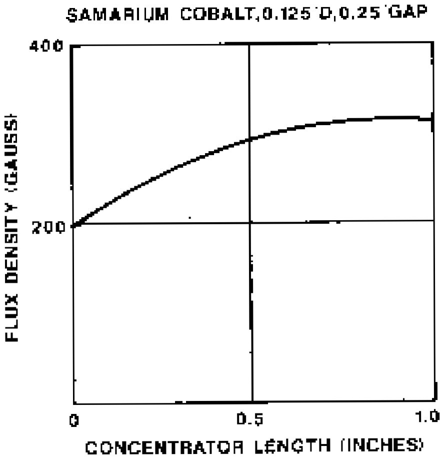
Cylindrical concentrators were used here for convenience, but the body of the concentrator has little effect. The important factors are the shape, position, and surface area of the magnet end nearest the Hall sensor.

The effectiveness of other concentrator configurations can be measured easily by using a calibrated linear Hall device or a commercial gaussmeter.



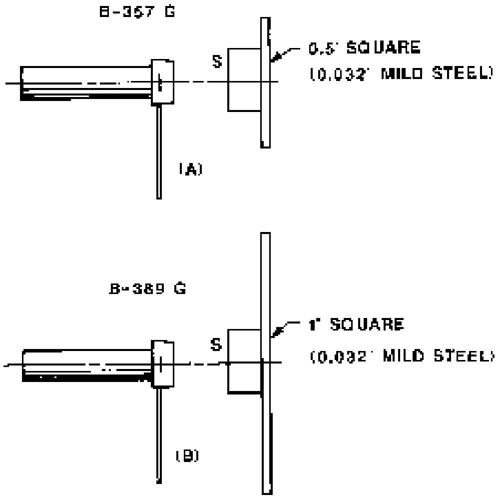
Dwg. No. A-13,157

Figure 55



Dwg. No. A-13,158

Figure 56



Dwg. No. A-13,159

Figure 57

MOUNTING THE MAGNET TO A FERROUS PLATE

Mounting the magnet to a ferrous plate will give an additional increase in flux density at the Hall element. Using the same configuration as in figure 55C, which produced 291 G, note the available flux attained in figures 57A and 57B with the addition of the ferrous plate.

Figure 58 shows a possible concentrator for a ring-magnet application. Using a flux concentrator that extends to both of the adjacent north poles, flux density increases from 265 G to 400 G (0.015" air gap). Note that the concentrator has a dimple, or mesa, centered on the Hall device. In most applications, the mesa will give a significant increase in flux density over a flat mounting surface.

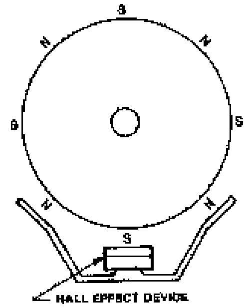
ATTRACTIVE FORCE AND DISTORTED FLUX FIELD

Whenever a flux concentrator is used, an attractive force exists between magnet and concentrator. This may be undesirable.

FEED-THROUGHS

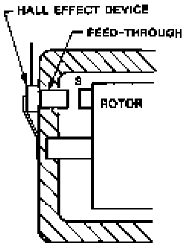
An example of the use of a magnetic conductor to feed flux through a nonferrous housing is shown in figure 59. A small electric motor has a 0.125" cube samarium cobalt magnet mounted in the end of its rotor, as shown. A 0.125" cube ferrous conductor extends through the alloy case with a 0.031" air gap between it and the magnet's south pole. The Hall switch is mounted at the other end with a flux concentrator behind it.

In general, the feed through should be of approximately the same



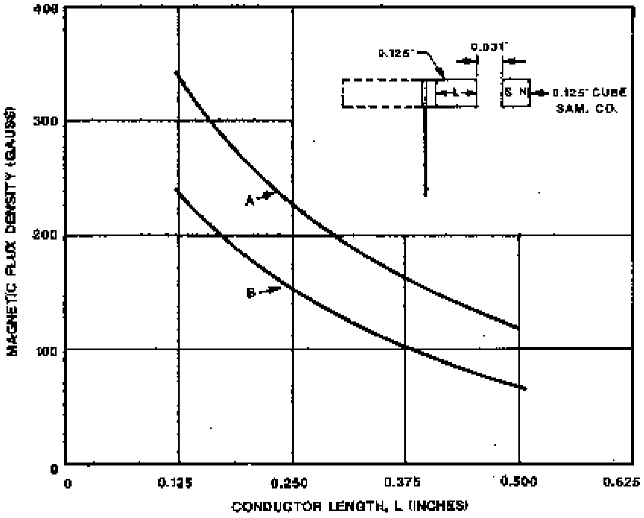
Dwg. No. A-13,160

Figure 58



Dwg. No. A-13,161

Figure 59



Dwg. No. A-13,162

Figure 60

cross-sectional area and shape as is the magnet pole.

This concept can be used to feed flux through any non-ferrous material, such as a pump case, pipe, or panel.

The two curves of figure 60 illustrate the effects on flux density of increasing the length of the feed through, as well as the contribution by the flux concentrator behind the Hall switch. Values for curve A were obtained with the flux concentrator in place, those for curve B without it. In both cases, the highest flux densities were achieved with the shortest feed-through dimension L, which was 0.125". Peak flux density was 350 G with flux concentrator in place, 240 G without it.

MAGNET SELECTION

A magnet must operate reliably with the total effective air gap in the working environment. It must fit the available space. It must be mountable, affordable, and available.

FIGURES OF MERIT

The figures of merit commonly applied to magnetic materials are:

residual induction (B_r) in gauss. How strong is the magnetic field?

coercive force (H_c) in oersteds. How well will the magnet resist external demagnetizing forces?

maximum energy product (BH_{max}) in gauss-oersteds times 10^6. A strong magnet that is also very resistant to demagnetizing forces has a high maximum energy product. Generally, the larger the energy product, the better, stronger, and more expensive the magnet.

temperature coefficient. The rate of change of the operate or release point over temperature, measured in gauss per degree Celsius. How much will the strength of the magnet change as temperature changes?

MAGNETIC MATERIALS

neodymium (Ne-Fe B). The new neodymium-iron-boron alloys fill the need for a high maximum-energy product, moderately priced magnet material. The magnets are produced by either a powdered-metal technique called orient-press-sinter or a new process incorporating jet casting and conventional forming techniques. Current work is being directed toward reducing production costs, increasing operating temperature ranges and decreasing temperature coefficients. Problems relating to oxidation of the material can be overcome through the use of modern coatings technology. Maximum energy products range from 7 to 15 MGOe depending on the process used to produce the material.

rare-earth cobalt is an alloy of a rare-earth metal, such as samarium, with cobalt (abbreviated RE cobalt). These magnets are the best in all categories, but are also the most expensive by about the same margins. Too hard for machining, they must be ground if shaping is necessary. Maximum energy product, perhaps the best single measure of magnet quality, is approximately 16×10^6.

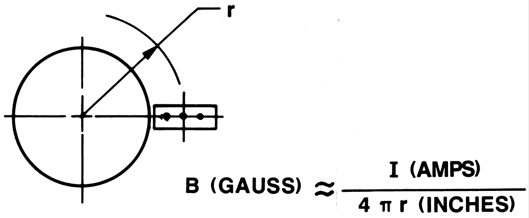
Alnico is a class of alloys containing aluminum, nickel, cobalt, iron, and additives that can be varied to give a wide range of properties. These magnets are strong and fairly expensive, but less so than RE cobalt. Alnico magnets can be cast, or sintered by pressing metal powders in a die and heating them. Sintered Alnico is well suited to mass production of small, intricately shaped magnets. It has more uniform flux density, and is mechanically superior. Cast Alnico magnets are generally somewhat stronger. The non-oriented or isotropic Alnico alloys (1, 2, 3, 4) are less expensive and magnetically weaker than the oriented alloys (5, 6, 5-7, 8, 9). Alnico is too hard and brittle to be shaped except by grinding. Maximum energy product ranges from 1.3×10^6 to 10×10^6.

ceramic magnets contain barium or strontium ferrite (or another element from that group) in a matrix of ceramic material that is compacted and sintered. They are poor conductors of heat and electricity, are chemically inert, and have-high values of coercive force. As with Alnico, ceramic magnets can be fabricated with partial or complete orientation for additional magnetic strength. Less expensive than Alnico, they also are too hard and brittle to shape except by grinding. Maximum-energy product ranges from 1×10^6 to 3.5×10^6.

Cunife is a ductile copper base alloy with nickel and iron. It can be stamped, swaged, drawn, or rolled into final shape. Maximum energy product is approximately 1.4×10^6.

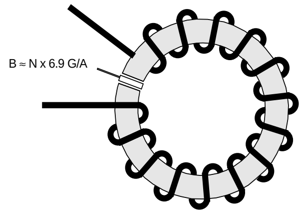
iron-chromium magnets have magnetic properties similar to Alnico 5, but are soft enough to undergo machining operations before the final aging treatment hardens them. Maximum energy product is approximately 5.25×10^6.

plastic and rubber magnets consist of barium or strontium ferrite in a plastic matrix material. They are very inexpensive and can be formed in numerous ways including stamping, molding, and machining, depending upon the particular matrix material. Because the rubber used is synthetic, and synthetic rubber is also plastic, the distinction between the two materials is imprecise. In common practice, if a plastic magnet is flexible, it is called a rubber magnet. Maximum energy product ranges from 0.2×10^6 to 1.2×10^6.



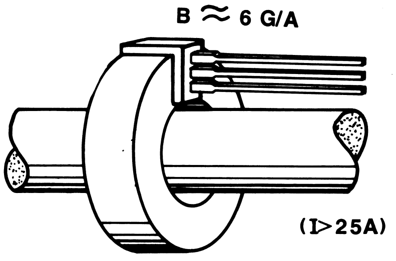
Dwg. No. A-13,163

Figure 61



Dwg. AH-005A

Figure 62A



Dwg. No. A-13,165

Figure 62B

CHOOSING MAGNET STRENGTH

A magnet must have sufficient flux density to reach the Hall switch maximum operate-point specification at the required air gap. Good design practice suggests the addition of another 50 G to 100 G for insurance and a check for sufficient flux at the expected temperature extremes.

If the Hall switch data sheet specifies a 350 G maximum operate point at +25°C. After adding a pad of 100 G, we have 450 G at +25°C. If operation to +70°C is needed, the requirement is 450 G + 45 G = 495 G. (For calculations, we use 0.7 G/°C operate point coefficient and 1 G/°C release point coefficient.) Because the temperature coefficient of most magnets is negative, this factor would also require some extra flux at room temperature to ensure high-temperature operation.

COERCIVE FORCE

Coercive force becomes important if the operating environment will subject the magnet to a strong demagnetizing field, such as that encountered near the rotor of an ac motor. For such applications, a permanent magnet with high coercive force (ceramic, Alnico 8, or, best of all, RE cobalt) is clearly indicated.

PRICE AND PEAK ENERGY PRODUCT

The common permanent magnet materials and their magnetic properties are summarized in table 4. The cost column shows the relationship between the price paid for a magnet and its peak energy product.

CURRENT LIMITING AND MEASURING

CURRENT SENSORS

Hall-effect devices are excellent current-limiting or measuring sensors. Their response ranges from dc to the kHz region. The conductor need not be interrupted in high-current applications.

The magnetic field about a conductor is normally not intense enough to operate a Hall effect device (figure 61).

The radius (r) is measured from the center of the conductor to the active area of the Hall device. With a radius of 0.5" and a current of 1,000 A, there would be a magnetic flux density of 159 G at the Hall device. At lower current, use a toroid or closed magnetic circuit to increase the flux density, as illustrated in Figure 62A and 62B.

With a 0.06" air gap for the “U” package, there would be 6 G/A per turn for figure 62A, and 6 G/A for figure 62B.

The core material can be of either ferrite or mild steel (C-1010) for low-frequency applications, and ferrite for high-frequency measurements.

Table 4
Properties of Magnetic Materials

Material	Maximum energy product (gauss-oersted)	Residual induction (gauss)	Coercive force (oersteds)	Temperature coefficient	Cost	Comments
R.E. cobalt	16 x 10^6	8.1 x 10^3	7.9 x 10^3	-0.05%/°C	Highest	Strongest, smallest, resists demagnetizing best
Alnico 1, 2, 3, 4	1.3 - 1.7 x 10^6	5.5 - 7.5 x 10^3	0.42 - 0.72 x 10^3	-0.02%/°C to -0.03%/°C	Medium	Non-oriented
Alnico 5, 6, 5-7	4.0 - 7.5 x 10^6	10.5 - 13.5 x 10^3	0.64 - 0.78 x 10^3	-0.02%/°C to -0.03%/°C	Medium-high	Oriented
Alnico 8	5.0 - 6.0 x 10^6	7 - 9.2 x 10^3	1.5 - 1.9 x 10^3	-0.01%/°C to +0.01%/°C	Medium-high	Oriented, high coercive force, best temperature coefficient
Alnico 9	10 x 10^6	10.5 x 10^3	1.6 x 10^3	-0.02%/°C	High	Oriented, highest energy product
Ceramic 1	1.0 x 10^6	2.2 x 10^3	1.8 x 10^3	-0.2%/°C	Low	Nonoriented, high coercive force, hard, brittle, non-conductor
Ceramic 2, 3, 4, 6	1.8 - 2.6 x 10^6	2.9 - 3.3 x 10^3	2.3 - 2.8 x 10^3	-0.2%/°C	Low-medium	Partially oriented, very high coercive force, hard, brittle, non-conductor
Ceramic 5, 7, 8	2.8 - 3.5 x 10^6	3.5 - 3.8 x 10^3	2.5 - 3.3 x 10^3	-0.2%/°C	Medium	Fully oriented, very high coercive force, hard, brittle, non-conductor
Cunife	1.4 x 10^6	5.5 x 10^3	0.53 x 10^3	—	Medium	Ductile, can cold form and machine
Fe-Cr	5.25 x 10^6	13.5 x 10^3	0.60 x 10^3	—	Medium-	Can machine prior to final aging treatment
Plastic	0.2 - 1.2 x 10^3	1.4 - 3 x 10^3	0.45 - 1.4 x 10^3	-0.2%/°C	Lowest	Can be molded, stamped, machined
Rubber	0.35 - 1.1 x 10^6	1.3 - 2.3 x 10^3	1 - 1.8 x 10^3	-0.2%/°C	Lowest	Flexible
Neodymium	7 - 15 x 10^6	6.4 11.75 x 10^3	5.3 - 6.5 x 10^3	-0.157%/°C to -0.192%/°C	Medium-high	Non-oriented

The main concerns are:

that the core retains minimal field when the current is reduced to zero,

that the flux density in the air gap is a linear function of the current, and

that the air gap is stable over the operating temperaturerange.

The cross-sectional dimensions of the core are at least twice the air gap dimension to ensure a reasonably homogeneous field in the gap. For example, a toroid with a 0.06" gap would have at least a 0.12" x 0.12" cross-section.

Another simple and inexpensive application is illustrated in figure 63. A toroid of the appropriate diameter is formed from mild-steel stock, 0.0625" thick and 0.1875" wide. The ends are formed to fit on each side of the central portion of the Hall device. One advantage of this technique is that the toroid can be placed around a conductor without disconnecting the conductor.

MULTI-TURN APPLICATIONS

There are several considerations in selecting the number of turns for a toroid such as the one in figure 62A.

Hall Switches

Keep the flux density in the 100 G to 200 G range for a trip point. Devices can be supplied with a narrow distribution of magnetic parameters within this range. If, for example, you want the Hall switch to turn ON at 10 A:

$$N = \frac{300\text{ G}}{6\text{ G/A} \times 10\text{ A}} = 5\text{ turns}$$

Hall Linears

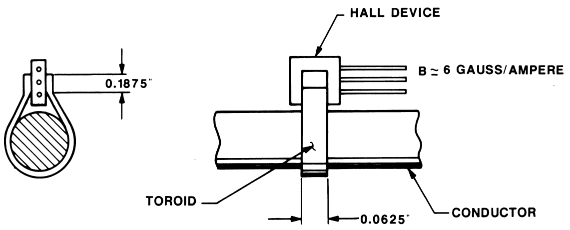
It is desirable to have flux density above 100 G to maximize the output signal/quiescent output drift ratio. The quiescent output drift for ratiometric sensors is typically 0.2 mV/°C, while the sensitivity temperature coefficient is typically 0.02%/°C.

For low-current applications in which many turns are required, one can wind a bobbin, slip it over a core, and complete the magnetic circuit through the Hall device with a bracket-shaped pole piece, as shown in figure 64.

With this bobbin-bracket configuration, it is possible to measure currents in the low milliampere range or to replace a relay using a Hall switch. To activate a Hall switch at 10 mA (±20%), using a device with a 200 G (±40 G) operate point, bobbin windings require:

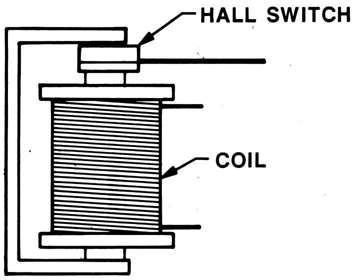
$$N = \frac{200\ \text{G}}{6\ \text{G/A} \times 0.01\ \text{A}} = 3333\ \text{turns}$$

It would be practical to tweak the air gap for final, more precise calibration. In all cases, *be careful not to stress the package.*



Dwg. No. A-13,166

Figure 63



Dwg. No. A-13,167

Figure 64

OTHER APPLICATIONS FOR LINEAR SENSORS

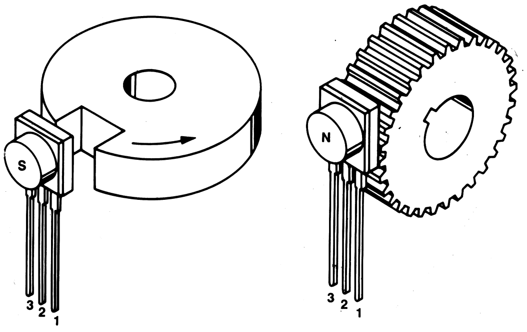
Hall-effect linear sensors are used primarily to sense relatively small changes in magnetic field—changes too small to operate a Hall-effect switching device. They are customarily capacitively coupled to an amplifier, which boosts the output to a higher level.

As motion detectors, gear tooth sensors, and proximity detectors (figure 65), they are magnetically driven mirrors of mechanical events. As sensitive monitors of electromagnets, they can effectively measure a system's performance with negligible system loading while providing isolation from contaminated and electrically noisy environments.

Each Hall-effect integrated circuit includes a Hall-sensing element, linear amplifier, and emitter-follower output stage. Problems associated with handling tiny analog signals are minimized by having the Hall cell and amplifier on a single chip.

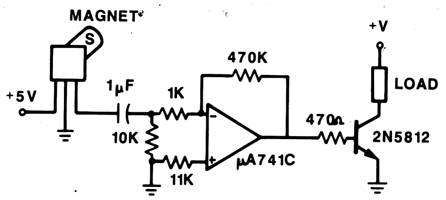
The output null voltage is nominally one-half the supply voltage. A south magnetic pole presented to the branded face of the Hall-effect sensor will drive the output higher than the null voltage level. A north magnetic pole will drive the output below the null level.

In operation, instantaneous and proportional output-voltage levels are dependent on magnetic-flux density at the most sensitive area of the device. Greatest sensitivity is obtained with the highest supply



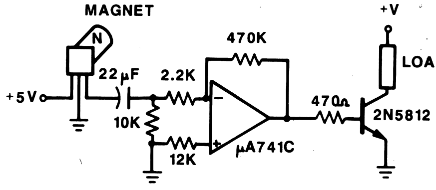
Dwg. No. A-13,168

Figure 65



Dwg. No. A-13,169

Figure 66



Dwg. No. A-13,170

Figure 67

voltage allowed, but at the cost of increased supply current and a slight loss of output symmetry. The sensor's output is usually capacitively coupled to an amplifier that boosts the output above the millivolt level.

In the two applications shown in figures 66 and 67, permanent bias magnets are attached with epoxy glue to the back of the epoxy packages. The presence of ferrous material at the face of the package then acts as a flux concentrator.

The south pole of a magnet is attached to the back of the package if the Hall-effect IC is to sense the presence of ferrous material. The north pole of a magnet is attached to the back surface if the integrated circuit is to sense the absence of ferrous material.

Calibrated linear Hall devices, which can be used to determine the actual flux density presented to the sensor in a particular application, are available.

FERROUS METAL DETECTORS

Two similar detector designs are illustrated in figures 68 and 69. The first senses the presence of a ferrous metal; the other senses an absence of the metal. The two sensing modes are accomplished simply by reversing the magnet poles relative to the sensor. The pole of the magnet is affixed to the unbranded side of the sensor in both cases.

Frequency response characteristics of this circuit are easily controlled by changing the value of the input decoupling capacitor for the low-frequency break-point. If high-frequency attenuation is desired, a capacitor can be used to shunt the feedback resistor.

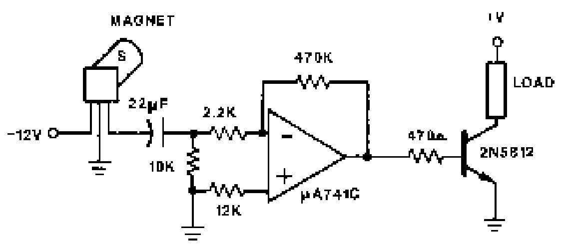
METAL SENSOR

The north pole of the magnet is affixed to the back side of a linear sensor. The sensor is in contact with the bottom of a 0.09375" epoxy board. An output change (decrease) is produced as a 1" steel ball rolls over the sensor. This signal is amplified and inverted by the µA741C operational amplifier and drives the 2N8512 ON.

NOTCH SENSOR

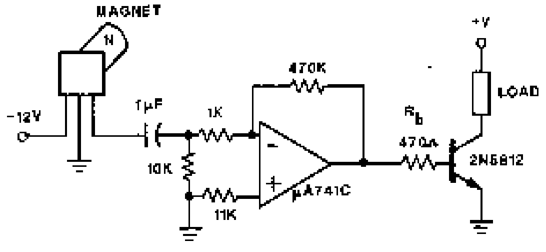
The south pole of the magnet is fixed to the backside of a linear sensor. The sensor is 0.03125" from the edge of a steel rotor. A 0.0625" wide by 0.125" deep slot in the rotor edge passing the sensor causes an output change (decrease). This signal is amplified and inverted by the µA741C op amp and drives the 2N5812 ON.

Note that, in both examples, the branded side of the sensor faces the material (or lack of material) to be sensed. In both cases, the presence (or absence) of the ferrous metal changes the flux density at the Hall-effect sensor so as to produce a negative-going output pulse.



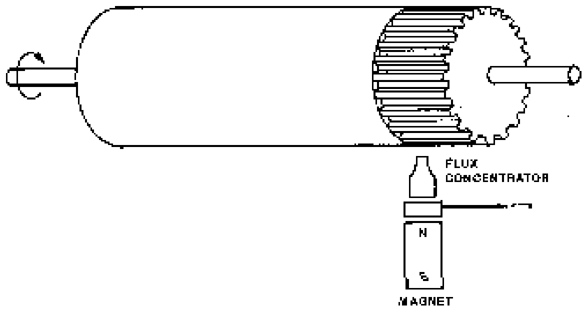
Dwg. No. A-13,171

Figure 68



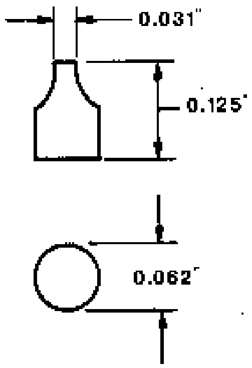
Dwg. No. A-13,172

Figure 69



Dwg. No. A-13,173

Figure 70



Dwg. No. A-13,174

Figure 71

The pulse is inverted by the amplifier to drive the transistor ON.

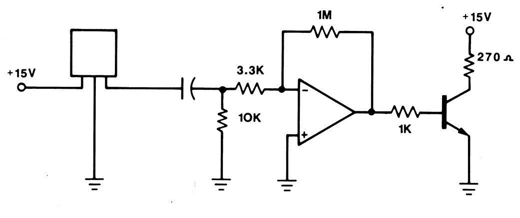
PRINTER APPLICATION

The device in figure 70 senses lobes on a character drum. Lobes are spaces 0.1875" apart around the circumference, 0.25" long and rise 10 to 15 mils from the surface of the drum.

A Hall-effect linear IC sensor is used with an Indiana General Magnet Products Company SR8522 magnet. The north pole is affixed to the reverse side of the package.
A flux concentrator is affixed to the branded face. Though it does not provide a flux return path, a concentrator will focus the magnetic field through the switch.

The concentrator blade, shown in figure 71, is aligned with the drum lobe at an air gap distance of 0.01". The output change is amplified as shown to develop a +3 V output from the operational amplifier, driving the transistor ON, as illustrated in figure 72.

Sensitivity is so great in this configuration that the output signal's baseline quite closely tracks eccentricities in the drum. This affects lobe resolution, but lobe position can still be measured.



Dwg. No. A-13,175

Figure 72

USING CALIBRATED DEVICES

The calibrated linear sensor is an accurate, easy-to-use tool for measuring magnetic flux densities. Each device is individually calibrated and furnished with a calibration curve and sensitivity coefficient. Although calibration is performed in a north and south 800 G field, the sensor is useful for measuring fields in both polarities.

A closely regulated (±10 mV) power supply is necessary to preserve accuracy in calibrated flux measurements. An ambient temperature range of +21°C to +25°C must also be maintained.

Connect Pin 1 to voltage V_{CC}, Pin 2 to ground, and Pin 3 to a high-impedance voltmeter. Before use, the device should be powered-up and allowed to stabilize for one minute.

The calibration curve affords the most convenient method of flux measurement. Subject the device to the field in question. Read the output voltage from the voltmeter and find that value on the chart X axis. Locate the intersection of the output level with the calibration trace and read the corresponding flux density on the chart's Y axis.

The sensitivity coefficient can be used to calculate flux densities somewhat more precisely. First, determine the null output voltage of the device under 0 G or null field condition. Then, read the output of the device under an applied field condition by subjecting it to the flux in question. Magnetic flux density at the device can be calculated by:

$$B = \Delta V_{OUT(B)} - V_{OUT(0)} *1000/S$$

where $\Delta V_{OUT(B)}$ = Output voltage under applied field in volts,

$V_{OUT(0)}$ = Output null voltage in volts,

S = Sensitivity coefficient in mV/G, and

B = Magnetic flux density at the device in gauss.

GLOSSARY

active area: the site of the Hall element on the encapsulated IC chip.

air gap: the distance from the face of the magnetic pole to the face of the sensor.

ampere-turn (NI): the mks unit of magnetomotive force.

ampere-turns/meter (NI/m): the mks unit of magnetizing force. One ampere-turn per meter equals 79.6 oersteds.

bipolar: a method of operating a Hall sensor using both north and south magnetic poles.

coercive force (H_c): the demagnetizing force that must be applied to reduce the magnetic flux density in a magnetic material to zero; measured in oersteds.

concentrator: any ferrous metal used to attract magnetic lines of force.

gauss (G): the CGS unit of magnetic flux density. Equivalent to one maxwell per square centimeter (Mx/cm^2). One gauss equals 10^{-4} tesla.

gilbert: the CGS unit of magnetomotive force.

head on: a method by which the Hall sensor is actuated. The magnetic field is increased and decreased by moving the magnetic pole toward and away from the sensor face.

maximum energy product (BH_{max}): the highest product of B and H from the demagnetization curve of a magnetic material. Given in gauss-oersteds x 10^6 (MGOe).

maxwell (Mx): the CGS unit of total magnetic flux. One maxwell equals 10^{-8} webers.

oersteds (Oe): the CGS unit of magnetizing force. Equivalent to gilberts per centimeter (gilberts/cm). One oersted equals 125.7 ampere-turns per meter.

remanent induction (B_d): the magnetic induction that remains in a magnetic circuit after removal of an applied magnetomotive force. When there is no air gap in the magnetic circuit, remanent and residual induction are equal. With an air gap, remanence will be less than residual induction. Measured in gauss.

residual induction (B_r): the flux density remaining in a closed magnetic circuit of magnetic material when the magnetizing force adequate to saturate the material is reduced to zero. Measured in gauss.

slide by: a method by which a Hall sensor is actuated. The magnetic field is increased and decreased as a permanent magnet is moved laterally past the sensor face.

tesla (T): the mks unit of magnetic flux density. Equivalent to one weber per square meter (Wb/m^2). One tesla equals 10^4 gauss.

toroid: a doughnut-shaped ring often composed of iron, steel, or ferrite.

total effective air gap (TEAG): the distance from the face of a magnetic pole to the active area of a Hall-effect sensor.

unipolar: a method of operating a Hall sensor using a single magnetic pole, usually the south pole.

vane: any ferrous metal used to shunt a magnetic field away from the Hall sensor (at least 1.5 times the width of an associated magnet).

window: an opening in a vane at least 1.5 times the width of an associated magnet.

SOURCES FOR FERRITE TOROIDS AND MAGNETS

As a convenience, some sources for ferrite toroids and magnets are listed below.
Addresses and telephone numbers are correct to the best of our knowledge at time of printing.

TOROID SUPPLIERS

Allstar Magnetics Inc.
6205 NE 63rd Street
Vancouver, WA 98661
(360) 693-0213

Dexter Magnetic Materials Division
10 Fortune Drive
Billerica, MA 01865
(508) 663-7500

Eastern Components, Inc.
21636 Lassen Street
Chatsworth, CA 91311
(818) 727-7023

Fair-Rite Products Corp.
P.O. Box J
Wallkill, NY 12589-0288
(914) 895-2055

Magnetics
900 East Butler Road
P.O. Box 391
Butler, PA 16001
(412) 282-8282

J.W. Miller Co.
Division of Bell Industries
19070 Reyes Avenue
P.O. Box 5825
Rancho Dominguez, CA 90224
(213) 537-5200

Philips Components
5083 Kings Highway
Saugerties, NY 12477
(914) 246-2811

MAGNET SUPPLIERS

Arnold Engineering 300 North West Street Marengo, IL 60152 (815) 568-2000	Alnico, rare earth, ceramic, plastic, multipole ring
Bunting Magnetics Company 1165 Howard Street Elk Grove Village, IL 60007 (312) 593-2060	Alnico, ceramic, plastic
Ceramic Magnetics, Inc. 87 Fairfield Road Fairfield, NJ 07006 (201) 227-4222	Ceramic, multipole ring
Crucible Magnetics 101 Magnet Drive Elizabethtown, NJ 42701 (502) 769-1333	Alnico, rare earth
Dexter Magnetic Materials 400 Karin Lane Hicksville, NY 11801 (516) 822-3311	Representatives of various manufacturers Also, custom grinding
Dynacast Co. 921 Albion Avenue Schaumburg, IL 60193 (312) 351-6100	Plastic
The Electrodyne Company 4188 Taylor Road Batavia, OH 45103 (513) 732-2822	Plastic
Hitachi Magnetics, Corp. 7800 Neff Road Edmore, MI 48829 (517) 427-5151	Alnico, ceramic, rare earth
Kane Magnetics International (Formerly Stackpole Carbon Co.) 700 Elk Avenue Kane, PA 16735 (814) 837-7000	Ceramic, flexible plastic
Magnaquench Div. of Gen. Motors 6435 S. Scatterfield Road Anderson, IN 46011 (317) 646-2763	Neodymium
Quadrant Technology Corp. 1247 Reamwood Avenue Sunnyvale, CA 94089 (408) 261-3589	Alnico, neodymium, rare earth, ceramic
Shin-Etsu Magnetics Inc. 2362-A Qume Drive San Jose, CA 95131-1841 (408) 383-9240	Neodymium, samarium, cerium
TDK Corporation of America 1600 Feehanville Drive Mount Prospect, IL 60056 (312) 803-6100	Rare earth
UGIMAG 405 Elm Street Valparaiso, IN 46383 (219) 462-3131	Multipole ring, rare earth
Xolox Corporation 6932 Gettysburg Pike Ft. Wayne, IN 46804 (219) 432-0661	Plastic, multipole ring