BY RUSS HENKE

Transducers for position sensing

One of the primary load variables monitored in fluid power applications is position. Figure 1 illustrates the function for linear motion — to move a load from an initial reference location to a final target location. A tolerance, $\pm\Delta S$, is always a consideration and expresses the accuracy with which the move can be made. Repeatability and resolution of the sensor affect performance of the system.

Over the years, many types of sensors have evolved. The direction of this evolution has been determined by the ability of the transducer to relate a mechanical phenomenon — change of position — into a sensible electric signal.

Analog — Potentiometers are among the oldest analog position sensors, and they remain in widespread use today. The length of a resistance element (wound wire) is traversed by a moveable contact, or wiper, Figure 2. Applying a constant voltage across the ends of the resistance element and measuring the voltage from the wiper to one end of the resistance element provides an indication of the wiper's position.

Wire-wound potentiometers have a finite resolution, which is determined by spacing of the wires. Mechanical wear between the windings and the wiper limits the potentiometer's life. Conductive plastic film resistance elements have been substituted in many potentiometer sensors to reduce wear. Linearity problems may also occur because output impedance can vary as a function of wiper position. Potentiometers are available in linear and rotational versions.

More recently, position sensing has benefited from the application of ultrasonics technology. The application probably most familiar to those involved in fluid power uses an ultrasonic transducer in the cap end of a cylinder — a setup that resembles sonar. Ultrasonic signal pulses are directed toward the cylinder's rod end and bounce off the piston, Figure 3. The time required for the signal echo from any given pulse to return to the transducer can serve as an accurate measurement of piston position (stroke).

Digital — The popularity of digital position sensors has grown in the wake of computer-induced digital technology. Analog position transducers often are used in digital control circuits by interfacing an analog-to-digital (A/D) converter between the transducer and digital input. Probably the oldest versions of true digital position sensors are simple pulse generators. For example, a gear rack and a magnetic pickup, Figure 4, can produce a digital output. As each tooth on the rack moves past the magnetic pick-up (or as the pickup moves past each tooth), a pulse is generated. With this type of device, pitch of the rack determines resolution.

To understand how digital transducers work, assume the sensor generates 100 pulses/in of linear travel. Also assume a reference, or zero point, that coincides with the fully retracted position of a cylinder. If the application requires extending the rod 3.2 in, 320 pulses will occur. The control input will probably be the setting of a decade counter, sometimes called a predetermined counter, for 320 in this case.

As the piston rod extends, the transducer generates pulses. For each pulse the counter receives, it decreases its setting by one unit, until the counter is again zeroed.

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Fig. 1. The function of moving a load from an initial position to a target position.

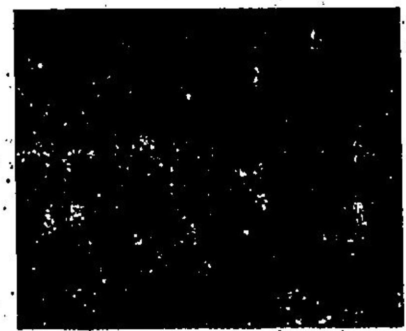


Fig. 2. A simplified circuit for a resistance type potentiometer.

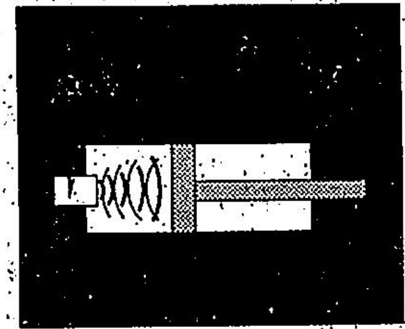


Fig. 3. Ultrasonics works much like sonar in sensing piston position.

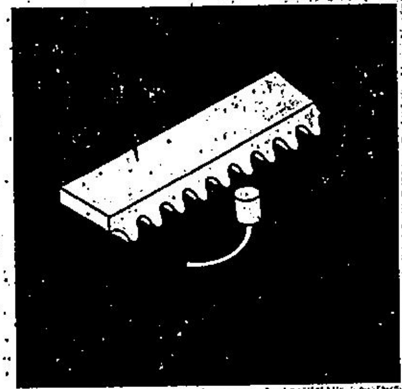
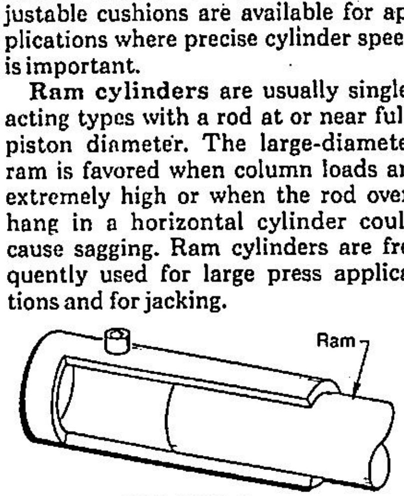


Fig. 4. A magnetic pickup indicates linear position by generating a pulse every time a gear-rack's tooth passes by it.

mering against the cylinder head, cushions are usually nonadjustable. But adjustable cushions are available for applications where precise cylinder speed is important.

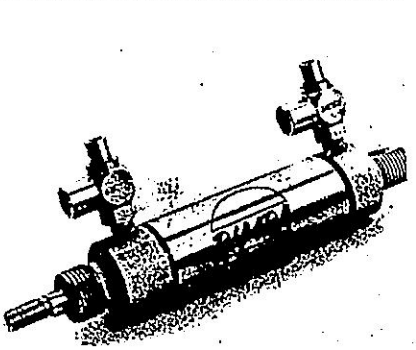
Ram cylinders are usually single-acting types with a rod at or near full-piston diameter. The large-diameter ram is favored when column loads are extremely high or when the rod overhang in a horizontal cylinder could cause sagging. Ram cylinders are frequently used for large press applications and for jacking.



RAM CYLINDER

Spring-return cylinders are like the low-cost single-acting types, with a spring added to return the piston to its starting point. This type is widely used in both pneumatic and hydraulic service, but is not always suitable for hydraulic service; if the spring is heavy enough for speedy piston return, it may require too much force to compress. The cylinder must be about twice as long as the required stroke to include space for the spring. Some cylinders are spring-loaded in the opposite direction, so they extend with spring action and retract pneumatically or hydraulically.

Double-acting cylinders contain two fluid chambers, so that pressure can be used to both extend and retract the rod. Sealing devices work in both directions. This type of cylinder is by far the most common, and can be used in nearly all types of applications. Effective working area of the rod side of the piston is less than that of the other side, so double-acting cylinders retract



Double-acting cylinders use fluid pressure to both extend and retract the rod. Compact, stainless steel body air cylinders from Bimba Mfg. Co. weigh less and are more compact than similarly sized tie-rod cylinders.

FEEDBACK IN ELECTROHYDRAULIC ACTUATORS

The coupling of electronic and hydraulic technology is becoming increasingly common, especially in electrohydraulic actuators. Advances in transducer logic and control capabilities have resulted in cylinders that transmit high forces with a high degree of positioning accuracy. Key to the operation of these actuators is the feedback system. A number of different feedback systems, both mechanical and electrical, are used, depending on the accuracy and durability required.

One method for accurately sensing cylinder rod position is with a linear displacement transducer. In one widely used system, the transducer housing is mounted to the cylinder end cap, with the sensor rod extending into the hollowed out piston rod. There is no physical contact between the sensor and cylinder rods.

To determine position, a magnet is attached to the cylinder piston. Current pulses transmitted down the sensor interact with the magnetic field and return a sonic pulse. Distance can be determined by measuring the transmission/reception time interval. Positioning accuracy is 0.001 to 0.003 in.

Another way to accurately control position is to hydraulically amplify the motion of a stepper motor. By combining a stepper motor, servovalve, cylinder, and ballscrew, positioning accuracy of 0.001 to 0.002 in. and repeatability of 0.0005 in. are possible. Stepper motor rotation moves a cam to shift the valve spool laterally. This permits oil flow to the cylinder.

As the cylinder piston moves, the ballnut attached to the piston rotates the ballscrew, which is connected to the spool. This spool rotation maintains the relative motion of the cam, so the speed of the cylinder is directly proportional to the rotational speed of the stepping motor.

Several choice of ballscrews and helical cams provide a selection of servovalves gains and speed ranges to suit most applications. Finer resolution can also be provided through microstepping, which gives standard stepper motors up to 25,000 steps per revolution.

A somewhat similar means of control is with a rotary encoder. Here, piston motion again causes ballscrew rotation. But in this case, the ballscrew is attached to the encoder. Precise measurement of the screw rotation corresponds

SIZING CYLINDERS

Cylinders may be the most over-specified component in the average fluid-power system. An oversize cylinder has a healthy extra margin of force that can override a bit of misalignment, binding, or overload. However, extra cylinder size can also boost cost, increase weight, and retard actuation.

Piston size is determined by required force F and available pressure P in the relationship $F = PA$. Piston diameter can be found from area A. For example, if a 10,000-lb force must be exerted by a 1,000-psi system, minimum piston area of 10 sq in. must be provided.

Speed of a piston is determined jointly by its size and the flow volume into the cylinder. As the piston is displaced, the volume swept must be fully replaced with fluid.

Rod size must be large enough to withstand the stresses imposed by load and cylinder. For pure tension applications, size determination is simple. Rod area is found by dividing piston force by rod yield strength and applying a safety factor.

Calculations for compression (thrust) applications are much more complicated. In compression, the rod acts like a slender column, and must be of adequate strength to prevent buckling. The extra strength required depends on the stroke length and connection between rod and cylinder.

For longer strokes, a stop tube may be required. Such a tube fits inside the cylinder, in front of the piston, and stops the piston before the end of its stroke. Thus, the tube acts as a spacer to keep the two cylinder bearing areas (rod and piston) separated and to keep buckling resistance high.

When this occurs, a switch usually opens or closes to command further action, such as reversing cylinder direction or energizing some other component.

A more recent version of the rack-type pulse generator uses a piston rod with a 0.100-in-pitch thread machined into its surface. The threaded rod has a non-magnetic, hard-chrome plating ground to finish size. Two Hall effect pulse generators are positioned near the rod so they can detect the thread peaks as they pass beneath the detectors. Each detector will generate an independent pulse train as the rod passes by. The two Hall effect detectors are placed electrically in quadrature so one pulse leads or lags the other (depending on direction of motion) by 90°. This out-of phase condition produces a resolution of 0.025 in. even though the thread pitch is 0.100 in.

A printed circuit board with closely spaced "contacts" and a wiper works on the same principle as the basic rack, but provides greater sensitivity. A pulse is produced each time the wiper crosses one of the contacts. In an optical version, a grid is etched into the surface of a glass strip. A light source is positioned on one side of the strip and a photoelectric cell on the other. As the grid moves relative to the lamp and the cell, the light beam is interrupted by the grid lines. A pulse is generated for each interruption.

A proprietary sensor design that has gained widespread acceptance in fluid power is based on magnetostrictive characteristics of specific alloys. Typically, the device has three elements: a tube made of a magnetostrictive alloy, a wire threaded through and returned outside the tube, and a magnet. As with all transducer applications, associated electronics complete the system.

Functionally, a current pulse is sent through the wire and the resulting magnetic field is concentrated in the tube, which acts as a waveguide. The tube and wire pass through the central hole in a doughnut shaped magnet. When the current pulse reaches the magnet, the two magnetic fields interact. The tube of magnetostrictive material experiences a local rotary strain at the point of interaction of the two magnetic fields. The rotary strain pulse travels along the tube at ultrasonic speed and is detected at the end of the tube. The time between generation of the initial current pulse and detection of the returning strain pulse is a measure of the distance between start or reference point and the magnet.

In a typical application, the

position sensor is integrated into a hydraulic cylinder. The pulse generator/receiver electronics are mounted to the cylinder's cap end; the sensing element is enclosed in a stainless steel outertube, which projects axially into the cylinder inside a hollow piston rod; and the magnet is embedded into the piston and moves with it. Transducer output can be either analog or digital. Standard stroke range is 1 to 30 in. Analog output is a DC voltage proportional to stroke position. Digital position resolution can be varied electronically, but ranges between 0.000125 and 0.004 in.

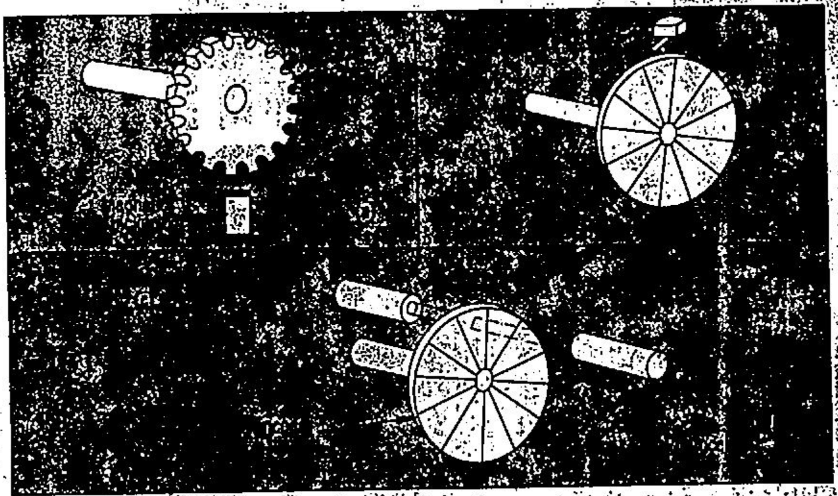


Fig. 5: Pulse-generating transducers for rotational motion: (a) gear with magnetic pickup; (b) wiper-etched contactor board; and (c) optically scanned encoder disc.

Rotation — Many of the techniques described for linear position sensors have also been adopted for rotational position sensing. Figure 5(a) shows the gear-magnetic pickup approach; Figure 5(b) a wiper-etched contactor board version. Both would exhibit limited resolution for position sensing and the wiper type would share, like its linear cousin, limited mechanical life. Current applications of the gear type are restricted to use as a speed sensor. The optically scanned, encoder disc type of Figure 5(c) is used for both position and speed sensing - typically with the same device. Resolutions for binary or Gray coded types (discussed in July 1988's "Electronic Input") can be quite high. A typical version exhibits 12 bit resolution, which corresponds to 1/4096th of a revolution.

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to a linear piston position. The controller processes this information and signals the servovalve to maintain or change flow accordingly.

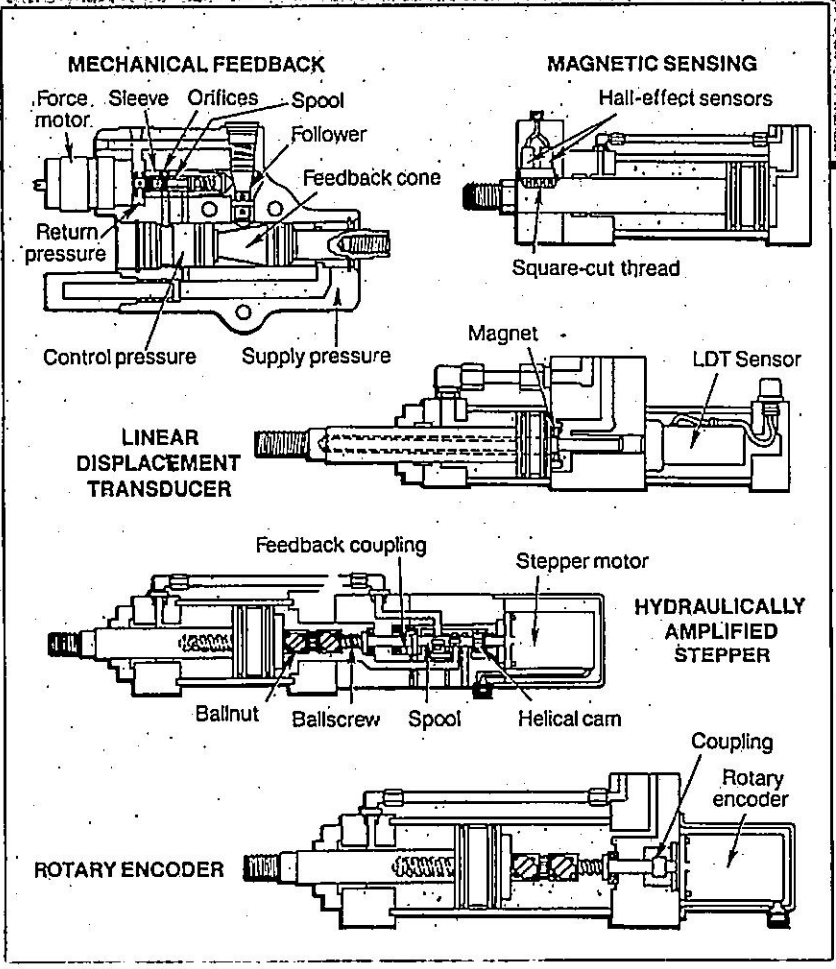
Another approach for position sensing uses a precision-cut square thread on the cylinder rod exterior. After machining, the rod is plated to fill the thread grooves, returning the finish and dimensions to original specifications.

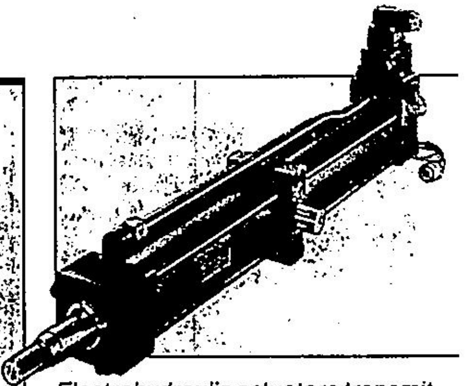
Two Hall-effect sensors, which detect the presence of a magnetic material, are positioned at the rod surface one-quarter thread pitch apart. These sensors "see through" the nonmagnetic chrome plating, but detect the square thread peaks. Output is in the form of two square waves which are 90° out of phase. Accuracy of this system is 0.025 ± 0.005 in.

In one mechanical feedback system, rod displacement is directly proportional to the magnitude and polarity of an electrical input to a force motor. Here, system supply pressure is routed to the control valve and the rod end of the piston. Flow at the control valve passes through two equal size orifices to tank when in a neutral condition. Between the orifices, flow is ported to the cylinder piston. Because flow through two equal orifices gives equal pressure drop, pressure at the piston is one-half supply pressure. The piston is sized to be twice the area of the rod-side area; thus, forces on the piston are balanced.

The valve spool rides in a sleeve, which is held in contact with the follower by a compression spring. Likewise, the follower is held in contact with the feedback cone on the piston. As the piston moves back and forth, the follower moves up and down, forcing the valve sleeve to move through a proportional distance.

An electrical input to the force motor moves the valve spool through a distance and direction corresponding to the magnitude and polarity of the signal. When the spool is displaced relative to the sleeve, it meters flow in or out of the cylinder, causing the piston to move. As the piston moves, the follower rides along the feedback cone, which moves the sleeve until control valve flow to the piston is shut off. Thus, every value of electrical input has a corresponding rod position.





Electrohydraulic actuators transmit high forces with a high degree of positioning accuracy. This Parker Hannifin cylinder can use a directiona proportional, or servovalve for control depending on the precision required. Close coupling of the cylinder and valve improves system response, and minimizing hydraulic line runs increases reliability.

faster than they extend, and exert les
force on the retraction stroke.

Double-end rod cylinders ar
double-acting types with a rod extend
ing from each side of the piston. A chie
advantage of this type is that workin
areas of both piston sides are equal. S
the piston moves at the same rate an
delivers equal forces in each directio
Double-end rod cylinders are availabl
with a hollow rod, so that fluid or ar
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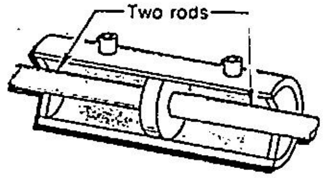
through the cylinder. In a design vari
ation often used on planers, the hollo
piston rod is restrained and the cylinde
body is forced back and forth to shi
the moving table.



DOUBLE-END ROD CYLINDER

Tie-rod cylinders, the oldest an
most common, are typically used i
industrial jobs. The cylinder body
held together by four or more tie ro
that extend the full length of the bod
and pass through the end caps c
mounting plate. In operation, they ma
perform any of the common cylind
functions except telescoping.

One-piece cylinders are most ofte
used on mobile equipment and far
machinery. The body is either cast i
tegrally, or head and body may b
welded together. This is the least e
pensive type of cylinder; it is compa
and simple. But it cannot be repaire
when damaged or worn.

the scale, then the slider windings will see terminal voltages of

$$V(S1 \text{ to } S3) = V\sin(\omega t)\sin(2\pi X/S)$$
$$V(S4 \text{ to } S2) = V\sin(\omega t)\cos(2\pi X/S)$$

Since slider output signals arise from an average of several spatial cycles, small residual errors in conductor spacing have little effect. When combined with 12-bit digital interface modules, 0.1-in.-pitch linear Inductosyns readily provide 25-μin. resolutions.

Rotary Inductosyns are created by forming the scale and slider in a loop. These devices achieve very high resolutions. For instance, a typical rotary Inductosyn may have 360 cyclic pitches/rotation and might use a 12-bit Inductosyn-to-digital converter. The converter effectively divides each pitch into 2^{12} or 4,096 sectors. With 360 pitches, the rotary Inductosyn resolves a total of 1,474,560 sectors for each rotation. This corresponds to an angular resolution of less than 0.9 arc-second.

LVDTs: An LVDT provides position feedback using mutual inductance between its primary and secondary windings. A moveable core couples the excitation voltage in the primary to the two secondaries, located on either side of the primary. The phase and amplitude of the output voltage vary with the position of the magnetic core.

The amplitude of the secondary voltage is proportional to the magnitude of position. The phase indicates the position of the core relative to the null.

With the core centered between the two secondaries, at the null position, secondary voltages have equal amplitudes and are 180° out of phase. The net voltage across the secondaries is zero. As the core moves toward positive full-scale the amplitude of the in-phase sine wave increases. As the core moves toward negative full-scale, the amplitude of the 180° out-of-phase sine wave increases.

LINEAR ENCODERS

Optical linear encoders are available in open and closed configurations. Open linears simply consist of a glass scale and read head containing the light source, photosensing optics, and some processing electronics. Closed encoders, on the other hand, include a housing for these components. The read head is coupled to a junction plate that extends through a slotted lip seal. The plate then fastens to the moving device to be encoded. In many systems, the encoder body may be attached to the moving part with the junction plate fixed.

Enclosed encoders are preferred when the environment contains contaminants such as smoke, mist, or solid debris. However, closed encoders experience friction from the lip seal and the read head sliding along the glass scale. Consequently, open encoders generally are used if possible. Their accuracy and resolutions also exceed those of closed versions.

As in any optical encoder, linear devices use the relative motion of scale and photosensing optics to modulate the intensity of light from a source. Light intensity is modulated into a pair of sine wave signals which are in quadrature.

Frequency of the raw encoder output is expressed in cycles per inch (or per millimeter), corresponding to the line spacing on the glass scale that modulates the LED light. A standstill (zero frequency), the encoder signals sit at dc levels.

A single-axis linear system consists of a linear encoder and a direction sensing counter. System error E_x is the difference between the actual position X of the read head on error is a changing function of read head displacement and can have both positive and negative peak values and standard deviations.

Linear encoders involve three basic error components: quantization error E_q, cycle interpolation error E_{ci}, and instrument error E_i. Total error E_T is the algebraic sum of these three.

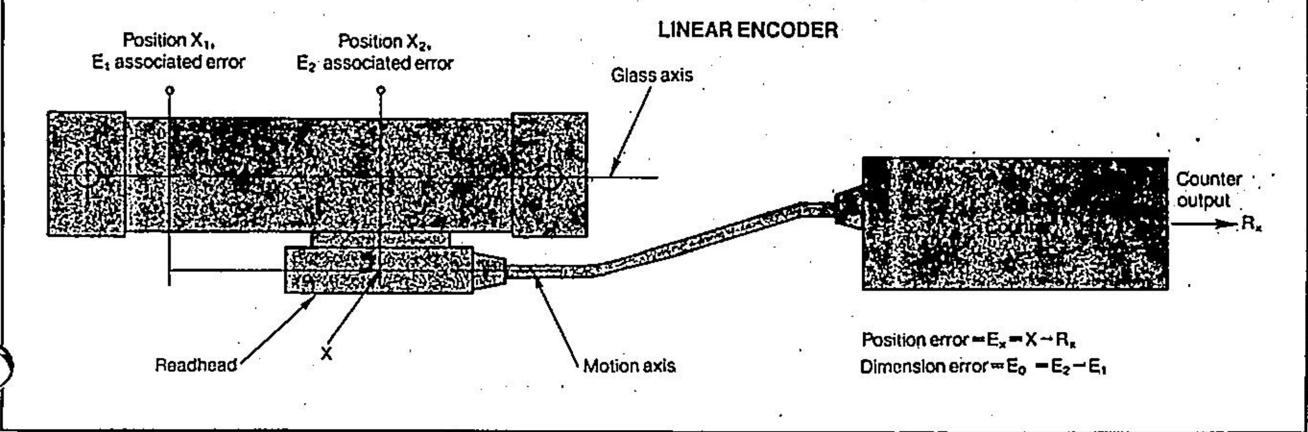
Quantization error arises because the encoder cannot indicate motion occurring with one resolution quantum or least significant bit (LSB). As in any analog-to-digital conversion system, quantization error is zero at the midpoint between two successive transitions and rises to ±0.5 quantum at the transition points.

Cycle interpolation errors arise from imperfections in the analog photoelectric signals and their subsequent processing. These imperfections consist of phase shifts or dc offsets in the quadrature encoder sine waves. The offsets cause an error in the position of the signal zero crossings. These errors, in turn, affect the count produced by a given amount of movement, because zero crossings are counted as a measure of motion.

Instrument error is the slowly varying error caused by scale pattern errors, distortions in the scale glass, and mechanical coupling and misalignment errors. Imperfect linear ways may also contribute.

Magnetic scales, as feedback encoders, detect motion using a small ferromagnetic rod imprinted with magnetic domains. The magnetic domains repel each other and, consequently, extend lines of flux into the surrounding air. Coils of copper wire in a read head sense the magnetic fields as the rod

LINEAR ENCODER



moves to produce an indication of distance and direction.

The low-impedance copper windings shunt electrical interference to ground without affecting sensor signals. One consequence is that digital readouts can reside 50 m from the sensor and still provide accurate measurements. The body of a magnetic scale may also be much smaller than that of an equivalent glass scale. For example, some magnetic-scale bodies are pencil thin. Encoding mechanisms within magnetic scales contain no active components; hence, they have no characteristics that can degrade.

Such qualities Have allowed magnetic scales to be used in a wide range of machine tools such as lathes, mills, comparators, jig bores, and numerous other kinds of industrial equipment.

Magnetic encoders use read heads that operate analogously to the magnetic recording heads in video recorders and disk drives. Basically, the head senses magnetic domains on a scale rod that moves under a gap. Coils in the head generate signals that are proportional to dynamic interactions with the magnetic moving rod.

However, the read heads in disk drives or video recorders depend on rapid movements between the head and media to produce sufficiently high output signals. Linear encoders, however, need to output position even when stationary. Thus, the read heads in magnetic scales need external power to produce adequate signal levels. A set of windings called exciters provides this power.

Exciter windings produce a 25 kHz signal. Flux fields from this signal sum trigonometrically with the flux fields from the scale rod. The resulting signal couples into two sense windings. These sense windings are physically separated to produce sine and cosine output. They also pass the second harmonic of the excitation signal, 50 kHz.

The sine and cosine outputs from the sense windings go to remotely located amplifiers and a bandpass filter. This signal processing produces a single phase-modulated wave centered at 50 kHz. Its instantaneous phase and period either lag or lead the nominal, depending on the direction in which the scale rod moves.

Ancillary electronics measure the period of the resulting waveform to determine how far the scale rod has moved. Magnetic scales typically can maintain submicron resolutions at slew rates beyond 1 m/s.

So far, magnetic scales have been used exclusively in linear encoding. However, magnetic technology is also coming to surgical instruments, robots, office machines, and other uses that must gage the position of rotating shafts. Here, magnetic rotary encoders replace the rotary optical encoders normally found in these applications.

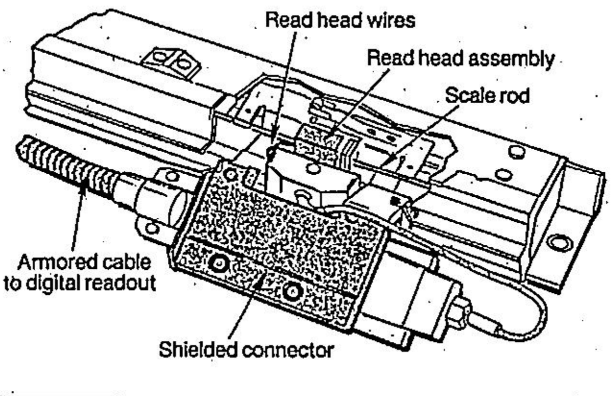
Rotary magnetic encoders have become feasible because of newly developed techniques that can imprint magnetic domains around the circumference of discs. The techniques can encode a unique magnetic perturbation at one point on the disc edge to serve as an absolute reference point. Sensing circuits then count off radians of arc from this reference as the disk turns.

Magnetic encoding strips have also been developed in the form of flexible tapes. The cost of this material is about 10% of that for other magnetic scales, per unit length. The rubber material can be glued to a floor or attached to a wall to serve in a wide variety of applications. It can also be cut and spliced to nearly any length.

The active material looks like a strip of dark rubber. It glues into a credit card-thick sandwich of stainless steel tapes and is actually read through the protective stainless steel face.

Resolution of the material is lower than that of conventional magnetic scale, on the order of 0.002 in. But the read head can operate at slew rates of up to 200 in./s and does not need to touch the scale. These attributes make the encoders suitable for applications that include robotic welders, sky hooks, and virtually any kind of instrumented vehicle that travels at speeds of up to 10 mph.

TYPICAL MAGNETIC SCALE



LVDTs used in applications such as aviation have either dual or quadruple redundancy, so that they are extremely reliable. Some units have a mean time between failure of almost three million hours; over 300 years. That kind of reliability is a result of design and construction practices. Many manufacturers use Inconel or stainless steel housings, electron beam welding, and spherical bearings to reduce rod misalignment. And because the coils are wound by computer control, unit interchangeability is high.

The primary limitation is the full scale displacement. This is the maximum distance the core travels without a serious decrease in linearity. The linear operating range is twice the full-scale displacement since the core can travel in either direction from the null position. The actual linear range will always equal or exceed the nominal value.

Linearity is the deviation from an ideal straight-line response. The output voltage of an LVDT is a function of the core displacement and is a straight line within a specified range. Beyond the nominal range, the output begins to deviate from a straight line in a gentle curve. Linearity is given as a percentage of full scale output or as a percentage of reading. Linearity is inherent in the transducer and largely determines the absolute accuracy.

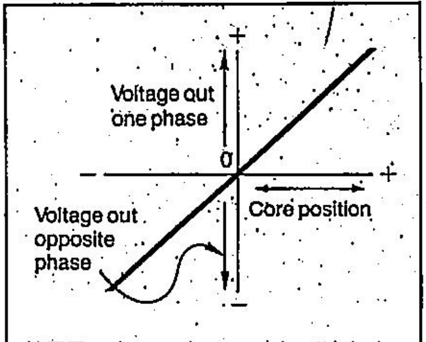
LVDT nonlinearities are typically 0.25%. Precision units have maximum nonlinearities of 0.05%. For example, an LVDT with 0.25% nonlinearity and output of 0.39 m V/V/mil, with a 1.0V_{rms} excitation and 390 m V_{rms} full-scale output, will exhibit a maximum nonlinearity of 2.5 mil.

Linearity can be improved by using an LVDT at less than the nominal range. Conversely, an LVDT can be used beyond the nominal range where linearity is not important. The range sets the full-scale ouput of the LVDT. This is matched to the full-scale input range of the LVDT-to-digital converter.

Until recently, signal conditioners for LVDTs used multiple ICs and required a relatively large amount of board real-estate. Now conditioners come in the form of a single monolithic chip. The designer simply adds a few passive components to set operating frequency and phase sync. Once such device is the SE/NE5521 from Signetics Corp. The IC simplifies design, lowers costs and power dissipation, decreases board size, and increases the reliability of resulting circuitry.

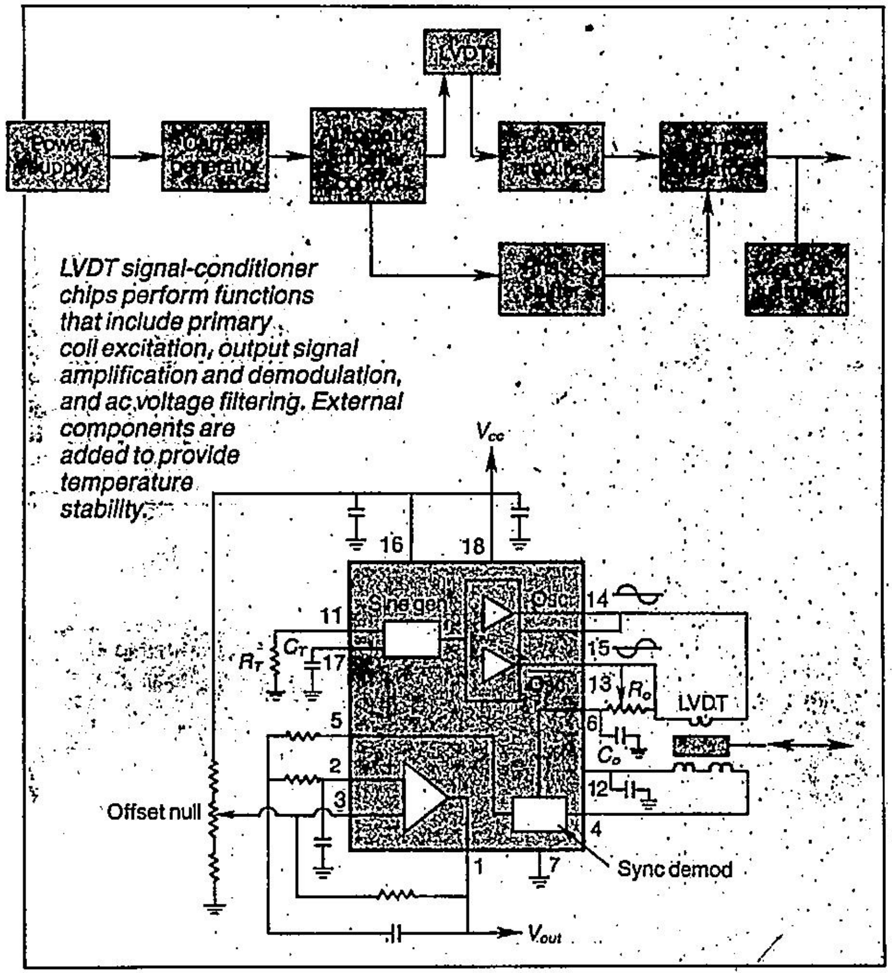
Signal conditioning circuits provide LVDT excitation signals, amplify and demodulate output signals, and perform ac voltage filtering.

The part of the signal conditioner that excites the LVDT is called the carrier generator. Because LVDT signal output is proportional to the input, the carrier generator must have a stable amplitude and frequency. Input amplitude variations cause output signals that are interpreted as false movement signals. And because LVDTs are inductive transducers, changes in excitation frequency alter the LVDT primary impedance. Flux density then varies, also causing output errors.



LVDT output voltage varies linearly with core position. As the core passes through a null position, the output undergoes a phase change.

Signal conditioners amplify and demodulate LVDT output in various ways. The classical method uses a carrier amplifier and synchronous demodulator. This system has the advantage of high gain, excellent stability, and isolated output.



LVDT signal-conditioner chips perform functions that include primary coil excitation, output signal amplification and demodulation, and ac voltage filtering. External components are added to provide temperature stability.

Demodulator reference signals are derived from the carrier generator and are in phase with the primary excitation signal. But phase shift between the primary and secondary voltages of the LVDT is common. And phase shift also occurs in the cables connecting the LVDT and the signal conditioner. To compensate, it is necessary to shift the reference signal phase at the synchronous demodulator input, relative to the carrier generator output. When using the NE5521, this phase shift is done with an external R-C network.

Typically, synchronous demodulators are used rather than rectifier demodulators. The primary reason is that synchronous demodulators are sensitive to phase and are also simple to implement. These demodulators have the additional advantage of being insensitive to quadrature components present in the LVDT null voltage. As a result, demodulator output is truly zero at the core null position.

Maximum linearity occurs when the phase of the LVDT output is exactly synchronized with the demodulator reference signal. When in sync, the conducting half cycle of the demodulator corresponds with the half cycle (between zero-crossings) of the LVDT output. To achieve synchronization and maximum linearity, it is often necessary to vary the phase of the demodulator reference signal. This is done with a RC network. The amount of phase shift is given by −arctan (ω RC). The reference-signal phase is adjusted so that demodulator output is a maximum for a given core position, primary excitation signal, and constant gain. Reference phase should be adjusted before the final setting of the amplifier gain.

Not all measurement applications necessitate a phase sensitive demodulator, however. A rectifier circuit can be used when linearity is not particularly critical or where the LVDT is only operated on one side of its null position. The main disadvantage of rectifier demodulator is that they do not indicate which direction from null the core is displaced. And rectifier circuits are inherently non-linear at small signal levels, because diodes require a minimum voltage drop before current flows.

Shrinking conditioners: In order to produce a sine wave for LVDT excitation, the SE/NE5521 first generates a stable triangle wave. Peak-to-peak amplitude of the triangle wave is equal to one-half the voltage difference between V_{ref} and pin 7 (ground or negative supply). Generator output goes to a sine converter circuit which produces a three-step piecewise approximation of a sine wave. This sine wave is amplified to provide enough current to drive a 300 Ω load over the rated temperature range. This signal is also inverted to provide a second sine wave 180° out of phase with the first. Together, the two signals differentially drive the LVDT primary.

LVDT output goes to pin 4 of the SE/NE5521, the signal input of the synchronous demodulator. The carrier is fed to the sync input, pin 6. As the sync input signal swings below its reference. The synchronous switch output goes low, giving the synchronous demodulator an inverting gain of one. When the carrier swings above its reference, the synchronous demodulator has a non-inverting unity gain. In this manner, a change in LVDT output phase causes the synchronous demodulator output (pin 5) to change polarity.

The output from the synchronous demodulator is a rectified dc voltage that usually must be filtered and amplified. This amplification can come from an auxiliary amplifier on the chip as an active filter with gain. A typcial active filter circuit constructed with this amplifier is known as a VCVS (Voltage Controlled Voltage Source) filter. It provides a second-order response, with good tracking and matching capabilities. In addition, the filter can often be constructed with equal-value components, thus reducing costs in high-value designs.

The frequency of the NE5521 sine wave output is determined by two components, R_T and C_T, according to:

$$f = \frac{V_{ref} - 1.3\ V}{V_{ref} \times (1500 + R_T) \times C_T}$$

However, to maintain temperature stability, R_T should be kept at 18K Ω while C_T used to set frequency.

Transformers cause a delay in the signal phase. Therefore, the phase of the sync or carrier signal must be delayed for the synchronous demodulator. R_o and C_o supply a delay calculated from

$$\phi = -\arctan(\omega_o R_o C_o)$$

R_o is varied until a maximum output is attained from pin 1 (dc output), when the core is away from the center of null position.

Magnetic sensing

Metal sensors also detect moving ferrous metal. The simplest metal sensor consists of a wire coiled around a permanent magnet, although variations of this approach are available. A ferrous object approaching the sensor changes magnetic flux through the coil, generating a voltage at the coil terminals.

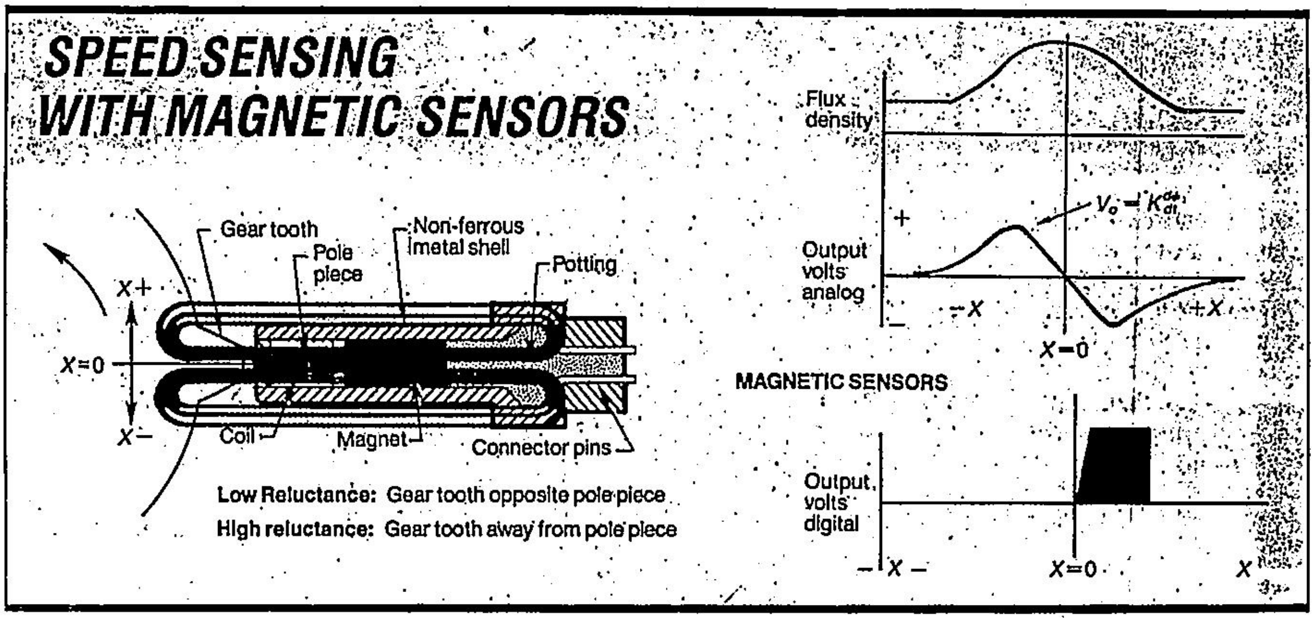
Magnetic pick-ups require no external power source and sense linear or rotary motion. They have high resolution, generating many pulses/in. of target travel, and can sense very small ferrous objects. For example, one sensor responds to 96-pitch gears, whereas Hall-effect sensors can only register 16-pitch gear teeth. In this application, magnetic transduction can be accurate to hundredths of a mechanical degree. For sensing rotating shaft speed, output-pulse frequency is proportional to shaft speed and is converted to rpm by digital-conversion electronics at an accuracy of less than 0.1%.

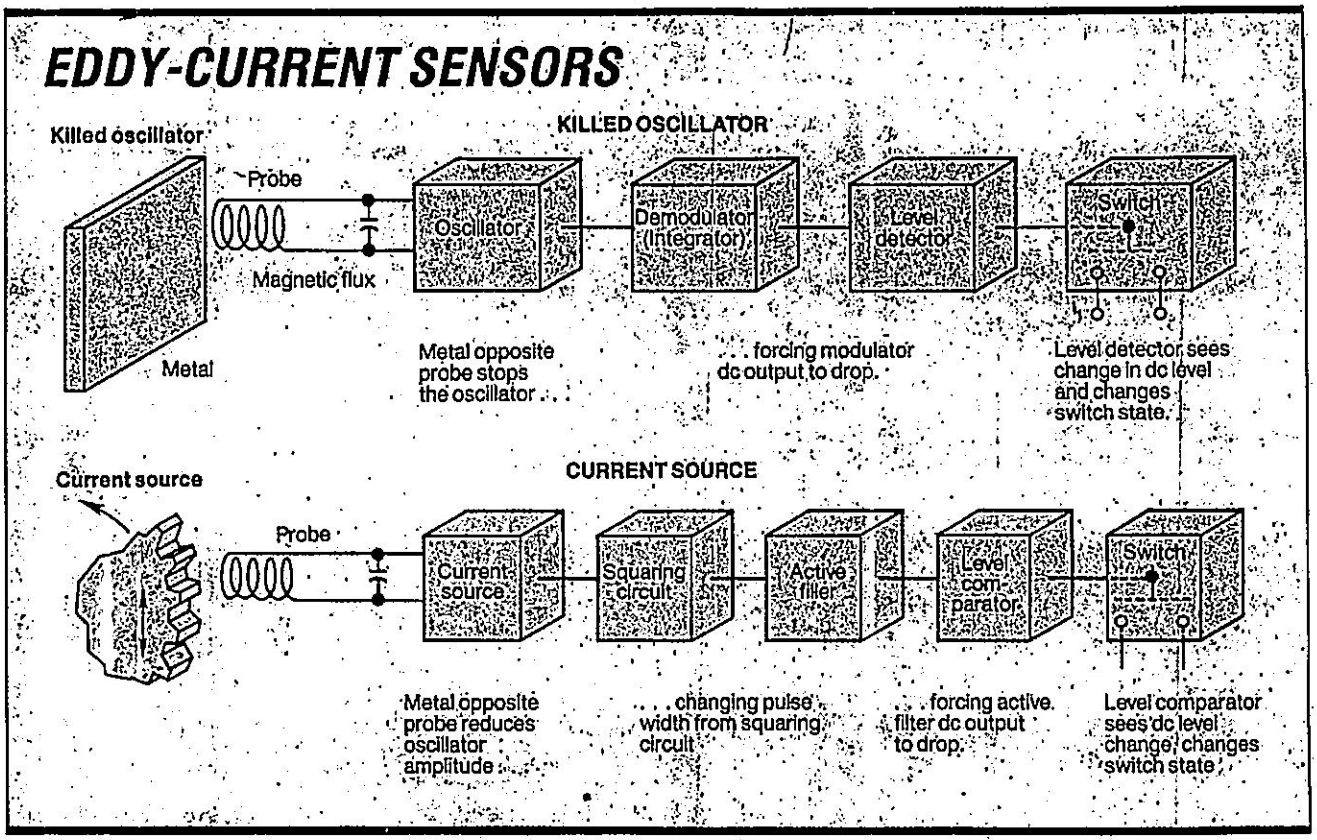
Magnetic sensors have measured speeds up to 600,000 rpm. Maximum sensor frequency is in the megahertz region, with usable frequencies limited by the internal sensor impedance and external load.

The sensors do not sense speeds near zero because output voltage depends on the rate-of-change of flux through the coil. As frequency approaches zero, sensor outputs drop to the millivolt range.

The absence of electronic elements in a magnetic sensor allows operation beyond temperatures (−65 to +300°F) associated with solid-state devices. Magnetic sensors built with special materials operate at cryogenic temperatures and withstand temperature excursions greater than 400°F. Magnetic sensors are almost impervious to shock. Such devices have operated at shock levels exceeding 30,000 g.

Since magnetic sensors can detect ferrous discontinuities through nonferrous metals, they can be hermetically sealed within nonferrous housings to withstand 100% humidity or complete immersion in water and oil. Sensors enclosed in stainless steel can operate in salt-spray or sand and dust environments, and under differential pressures up to 20,000 psi.


SPEED SENSING WITH MAGNETIC SENSORS



EDDY-CURRENT SENSORS

Eddy currents: Eddy-current sensors detect ferrous and nonferrous metals. A high-frequency magnetic field is generated that induces eddy currents in metal targets. The eddy currents generally change the sensor's oscillation amplitude, which is sensed by a coil to create an output signal. For measuring speed, these sensors register metallic discontinuities in a moving target at a rate of about 5 kHz, but some models respond up to about 20 kHz.

Maximum speed response is determined by the method used to sense oscillator amplitude. Devices sensing amplitude changes with conventional demodulator/integrator circuits are slower than those that convert oscillator amplitude into a string of pulses whose widths vary with frequency.

Eddy-current devices also produce pulses with high positional accuracy. Because eddy-current sensors do not depend on a time rate-of-change to register motion, their response does not diminish near zero speed like that of magnetic pickups.

Eddy-current devices are seldom contaminated by dirt or metal particles, but sensing distance is typically limited to the diameter of the sensor (usually 0.06 to 3 in.). These sensors must also be enclosed in nonmetallic packages because they cannot sense through metals.

Hall-effect sensors: A constant current flows through a silicon chip in a Hall-effect sensor. In the presence of an external magnetic field, a voltage proportional to magnetic field strength appears across the chip. Hall-effect sensors can be fabricated on an IC containing amplifiers and control circuits.

Metal plates are often used to interrupt the field between a stationary Hall sensor and magnet. Operating speed is usually 30 kHz. The devices can also be used as current sensors, where the magnetic flux impinging on the sensor is typically proportional to the current through a coil.

Hall-sensor switching has a slight hysteresis that prevents the device from switching on at the same magnetic field level as it switches off. This hysteresis ensures that the sensor does not oscillate during slow switching.

Hall sensors do not have resolutions as fine as that of optoelectronic or eddy-current devices. A certain amount of Hall sensor material must be exposed to the magnetic field before the device registers a voltage, and the magnetic field strength available is sometimes limited by the thickness of the Hall sensor package. Consequently, magnets can approach the sensing element no closer than about 0.05 in., and moving vanes interrupting the field between a magnet and Hall sensor cannot be as closely spaced as those operating an optoelectronic device. However, Hall-device operation is generally not impaired by the proximity of foreign material.

Some Hall-effect devices are now fabricated using a cross-coupled quad structure containing four Hall cells wired electrically in parallel. Here, two sets of Hall cells are oriented orthogonally to each other. One set is used to reduce mechanical offset caused by stress when the chip is bonded to the metal header. The other set is used to reduce photomask and chip manufacturing errors.

The four cells are connected electrically in parallel so error voltages tend to average out and be minimized over the four devices. A simplified model suitable for circuit simulation consists of two force terminals for current input and ground, two terminals for the differential output voltage, and four identical resistor values connected as in a Wheatstone bridge. Magnetic fields impinging on the device are modeled as a flux density-controlled current source. The value of each of the four resistors is equal to the voltage across the force pins divided by the current. The nominal resistance value for these Hall cells is on the order of 4kΩ. The high impedance allows low power consumption.

Hall-effect devices can operate as digital on/off transducers, sensitive to the presence or absence of a magnet, or as analog devices capable of providing a dc output proportional to a magnetic field.

Analog Hall-effect sensors provide a dc output proportional to magnetic field strength. Digital types provide digital voltages triggered by a specific magnetic field strength. Some Hall-effect sensors combine digital signal-conditioning circuits on the Hall-sensor chip. Typical circuits consist of an amplifier, flip-flop, offset voltage adjustment, and comparator. Since Hall-element voltages are small (about 1 mV for a 50-Gs field), an amplifier whose temperature coefficient cancels that of the Hall element amplifies the Hall voltage to produce a linear temperature-compensated dc signal.

The amplifier output feeds a hysteresis flip-flop and comparator that provide a precise switching action between on and off states, thereby preventing oscillation as the magnetic field approaches threshold. The comparator output switches from low to high as the amplified Hall voltage exceeds the offset voltage, which is adjusted during manufacture to allow output switching at required magnetic-field levels. The comparator output is fed back to the hysteresis flip-flop, which in turn changes state. The sum of the amplifier, flip-flop, and offset voltages fix the comparator in a high state. When a reduced magnetic field decreases the amplifier output, comparator output drops and the hysteresis circuit switches to stabilize the output at a low level.

Because of their ability to operate in hot, dirty environments, Hall effect devices are used in automotive applications. Ten years ago, Hall effect devices began replacing the points in automotive ignition systems. Now some manufacturers use these sensors to eliminate the distributor altogether in high performance engines.

The problem with measuring distance with Hall effect sensors has been that the relationship of output voltage to the magnetic field is linear; output voltage as a function of distance is not. This nusance is solved by first converting the output to a digital signal. Then it is linearized by a microprocessor that either uses a look-up table or an algorithm.

Linear sensors are used more in analog control systems. Rotor movement can be sensed in dc motors, and feed back to the controller, providing precise position control. In other applications they sense current in a wire or coil. Hall effect devices of this type use an iron core which serves as a "flux concentrator" to help detect the magnetic field. Automobile manufacturers use this method to detect faulty lights and to prevent power surges in electrical systems. The advantage of Hall effect devices in this application is that they present low impedance and current drains, along with high isolation.

Temperature sensors

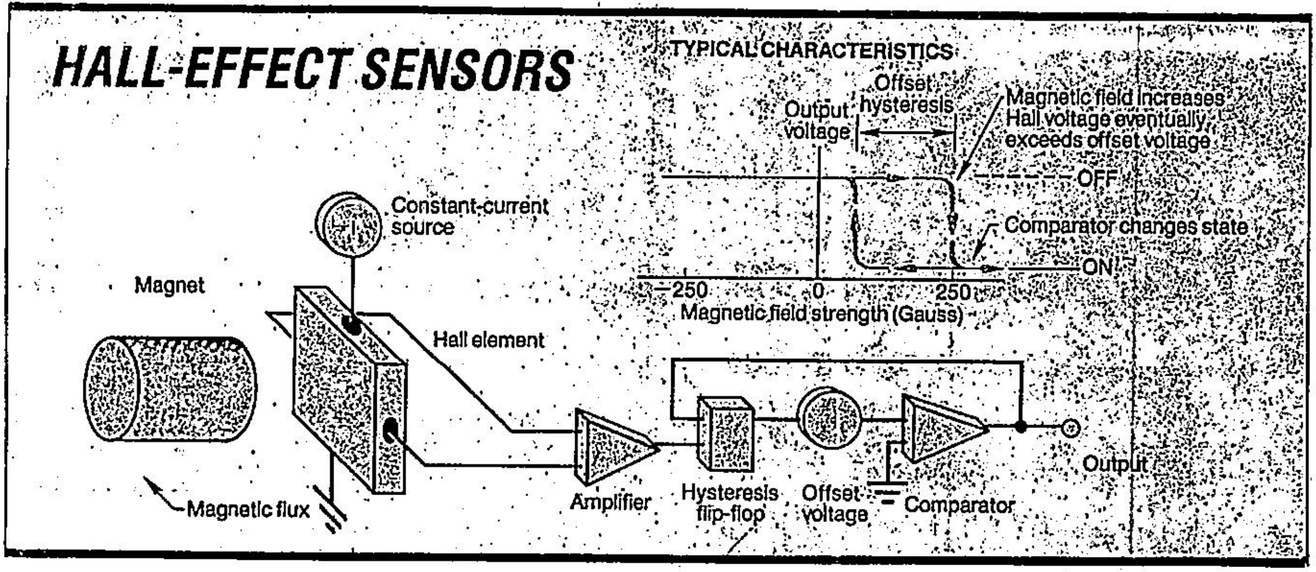
Temperature sensors are usually thermocouples, resistive temperature detectors (RTDs), or thermistors. Each device has limits associated with measurement accuracy. The character and amount of error associated with a given measurement approach is a factor that must be considered when choosing a sensor.

Thermocouples are devices for temperature measurement despite low sensitivity and moderate accuracy. They feature a wide temperature span, up to 1,800° C for noble (precious) metal types and low cost for basemetal types J, K, T, and E. They are available in sizes ranging from fine wire for millisecond response times, up to heavy gages for durability and high temperatures. They are particularly useful for point-sensing temperature measurements.

Thermocouples generate voltage proportional to temperature differences rather than to absolute temperature. They consist of two wires, each made from dissimilar metals of known composition, electrically connected at one end to form the measurement, or hot, junction. The other ends, though not electrically connected, must be kept at the same temperature. This isothermal connection is called reference or "cold" junction. The National Bureau of Standards tables fix the reference junction at the ice point of water (0°C).

The thermocouple, with its junctions at the measurement temperature and ambient, is compensated by a voltage equal to that generated by the same thermocouple with its measurement junction at ambient and its reference junction at the ice point. This is called ice-point or cold-junction compensation.

Thermocouples produce nonlinear voltage output over their temperature


HALL-EFFECT SENSORS