Organizations

AGA	American Gas Association
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
DICA	Direction Des Carburants (France)
DIN	German Standard
DNV	Det Norske Veritas (Norway)
DOT	U.S. Department of Transportation
GRI	Gas Research Institute (U.S.)
IEC	International Electrotechnical Commission
IP	Institute of Petroleum (U.K.)
ISO	International Standards Organization
NACE	National Association of Corrosion Engineers (U.S.)
NDP	Norwegian Petroleum Directorate
PHMSA	Pipeline & Hazardous Material Safety Administration
PPSA	Pigging Products & Services Association
PSF	Pipeline Simulation Facility
TUV	Technischer Uberwachungs Verein (Germany)

Bibliography

Albuquerque Industrial, Manual thickness detectors (ultrasonic), (2015) http://www.abqindustrial.net/store/wall-thickness-gauges-c-2.html?gclid=COOf55D3qLECFcHb4AodfVwAfw.

Antaki, G.A., *Piping and Pipeline Engineering* (2003), Dekker, https://www.crcpress.com/Piping-and-Pipeline-Engineering-Design-Construction-Maintenance-Integrity/Antaki/9780824709648.

Böcker, W. Reliable and cost effective leak detection with an new generation of ultrasonic pigs (2012), http://www.pipeline-conference.com/abstracts/reliable-and-cost-effective-leak-detection-new-generation-ultrasonic-pigs.

Bonny, B.N., The development of an intelligent sensor for pipeline integrity (2008), *Oil & Gas Journal*, http://www.researchgate.net/publication/254528535_THE_DEVELOPMENT_OF_AN_INTELLIGENT_SENSOR_FOR_THE_MONITORING_OF_PIPELINE_SYSTEM_INTEGRITY.

De La Camp, H.J., High precision ultrasonic pigging (2010), *Pipeline & Gas Journal*.

DOT stats indicate need to refocus pipeline accident prevention (March 1999), *Oil & Gas Journal*, http://www.ogj.com/articles/print/volume-97/issue-11/in-this-issue/general-interest/dot-stats-indicate-need-to-refocus-pipeline-accident-prevention.html.

IST Molcvhtechnik GmbH, (2012), http://www.piggingsystems.com/en/products/pigs/duo-pig.html.

Kandroodi, M.R. et al. Detection of Natural Gas Pipeline Defects using Magnetic Flux Leakage Measurements (2009), http://confnews.um.ac.ir/images/41/conferences/icee2013/1872_2.pdf.

Kennedy, J.L., (1993), *Oil and Gas Pipeline Fundamentals*, PennWell Books, http://www.worldcat.org/title/oil-and-gas-pipeline-fundamentals/oclc/9757418/editions?referer=di&editionsView=true.

Miller, S. and Fenyvesi, L., Determining corrosion growth accurately and reliability (2009), http://www.pipeline-conference.com/sites/default/files/papers/4.1%20Sander.pdf.

Morrison, T., Mangat, N., Desjardins, G., and Bhatia, A., Validation of an in-line inspection metal loss tool, Presented at *International Pipeline Conference*, Calgary, Alberta, Canada (2000), http://www.ogj.com/articles/print/volume-104/issue-18/transportation/in-line-inspection-conclusion-tool-performance-corrosion-data-drive-poe-approach.html.

Nestleroth, J.B. and Bubenik, T.A., Magnetic Flux Leakage (MFL) technology—For The Gas Research Institute, United States National Technical Information Center (1999), http://www.osti.gov/scitech/biblio/6761628.

PMSA (Pipeline & Hazardous Material Safety Administration), (2015), http://www.netl.doe.gov/technologies/oil-gas/publications/td/dtrs56-benchmark_report_final.pdf.

PPSA, (1990), *An Introduction to Pipeline Pigging*, http://www.pipedata.net/store/books/Book04/Book04_TOC.pdf.

PPSA. *An Introduction to Pipeline Pigging* (2015), http://www.ppsa-online.com/introduction-to-pigging.php.

Pure Technologies. Pipe wall assessment (2015), https://www.puretechltd.com/solutions/inspection-services/wall-assessment.

Rempel, R., Anomaly detection using Magnetic Flux Leakage (MFL) technology, Presented at the *Rio Pipeline Conference and Exposition*, Rio de Janeiro, Brazil, 2005.

Riggzone, (2015), How does pipeline pigging work?, http://www.rigzone.com/training/insight.asp?insight_id=310&c_id=19.

Sabath, M.M. Intelligent Pigging (2011), https://maliksabbah.wordpress.com/construction/mechanical/intelligent-pigging/.

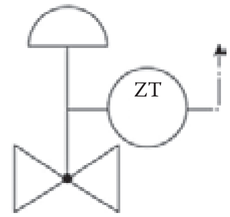
Servinox, (2014), Pig's speed regulation, http://servinox.com/wordpress/index.php/systeme-de-raclage/?lang=en.

Tiratsoo, J., (1988), *Pipeline Pigging and Inspection Technology*, Gulf Publishing, http://www.amazon.com/Pipeline-Pigging-Inspection-Technology-Edition/dp/0872014266.

UMI, (2009), Capacitive sensor for polyethylene pipe fault detection, http://gradworks.umi.com/14/71/1471527.html.

7.9 Position Measurement, Linear and Angular

J. BERGE (2003) **B. G. LIPTÁK and D. S. NYCE** (2017)



Flow sheet symbol

Technology	A. Potentiometer B. Linear variable differential transformer C. Inductive D. Magnetostrictive E. Magnetoresistive F. Hall effect G. Distributed impedance H. Encoder
Linear/rotary	A. Linear, rotary B. Linear (rotary) C. Linear, rotary D. Linear E. Linear, rotary F. Linear, rotary G. Linear, rotary H. Linear, rotary
Nonlinearity	A. 0.1% or 0.25% FS B. 0.1%, 0.25%, or 0.5% FS C. 0.25% or 0.5% FS D. 0.01%, 0.025%, 0.05% FS E. 0.25% or 0.5% FS F. 0.5% or 1% FS G. 0.1% FS H. 0.025% FS
Noncontact	A. No B. Yes C. Yes D. Yes E. Yes F. Yes G. Yes H. Yes
Costs	A. \$50, \$500, or more for smart or Fieldbus transmitter B. \$200 plus conditioning electronics C. \$350 D. \$350 w/V, current output, \$450 for digital E. \$500 F. \$350 G. \$250 w/V or current output, \$300 w/digital H. \$500 or more

(*Continued*)

Partial list of suppliers

Alliance Sensors (B, G) (http://alliancesensors.com/linear-position-sensor-me-7-series)
Ametek (D) (http://www.ametekapt.com/Linear-Feedback/index.aspx)
Austria Microsystems (F) (www.ams.com/eng/Products/Position-Sensors)
Balluff (D) (www.balluf.com/balluff/MUS/en/products/overview-micropulse-transducers.jsp)
Betatronix (A) (www.betatronix.com/products/linear-motion-petentiometers/default.aspx)
BI Technologies (A) (http://bitechnologies.com/products/precision_pot_Linear.htm)
Bourns (A) (www.bourns.com/ProductLine.aspx?name = contacting_linear_motion)
Daytronic (B) (www.daytronic.com/transducers/ds20b)
Durham Instruments (B) (http://disensors.com/products_sub.aspx?id = 45)
Endevco (B) (www.endevco.com/?search-class = DB_CustomSearch_Widget-db_customsearch_widget&widget_number = preset-1&active-1 = 1&all-2 = Products&cs-all-0 = Displacement+and+Position&search = Search)
Heidenhain (H) (www.heidenhain.com/en_US/products-and-applications/length-gauges/)
Honeywell (B, C) (sensing.honeywell.com/products/linear_position_sensors)
Kavlico (B) (www.kavlico.com/position-force/products/linear-position-sensors-lvdt)
LRT Sensors (C, G, H) (www.lrtsensors.com)
Macro Sensors (B) (www.macrosensors.com)
Melexis (F) (www.melexis.com/Products-By-Category/Hall-Effect-Sensor-ICs-1.aspx)
Midori (F) (www.midoriamerica.com/products_linear.php)
MTS Systems (D) (www.mtssensors.com)
Novotechnik (A) (www.novotechnik.com/Linear-In-Cylinder/linear-in-cylinder.html)
Penny & Giles (B, D) (www.pennyandgiles.com/Products/Linear-Position-Sensors/LVDT-Displacement-Transducer-AF111.aspx)
Positek (C) (www.positek.com/linear.htm)
RDP Electrosense (B) (www.rdpelectrosense.com)
Revolution Sensor Company (B, D, G) (www.rev.bz)
Sensitec (E) (http://www.sensitec.com/english/products/product-overview/produktprogramm.html)
Sentech (B) (www.sentechlvdt.com)
Sick-Stegmann (Pomux) (E, H)(www.sick.com/us/en-us/home/products/product_portfolio/encoders/pages/linear_noncontact_absolute.aspx)
Solartron Metrology (B) (www.solartron-metrology.com)

INTRODUCTION

Industrial applications of linear or angular position measurement include the detection of the position of valve stems/shafts, louvers, dampers, cylinders, etc.; inferential measurement of level, pressure, and bulk flow; injectors and clamps of molding machines; cutter position in woodworking, paper, web, etc.; weighing, brush wear in large motors; shape accuracy of formed glass; various inspection and test fixtures; and many more.

Applications

In a level measurement application, a wire may connect a float to a drum that is fixed to the shaft of a multiturn rotary position sensor. As the level changes, the wire winds or unwinds from the drum and turns it, while its position sensor detects the rotary position. Or, a permanent magnet may be mounted within a float and the float position measured by a magnetostrictive linear position sensor. In pressure devices, a position sensor can be used to detect the movement of a bourdon tube or bellows element as the pressure changes. In detecting the bulk flow on a conveyor, a pivot arm can skim the surface of the solids, and a position sensor can measure the height of the moving pile.

There is a difference between absolute position sensors and sensors that detect only displacement. An incremental or displacement sensor indicates the amount of movement and the direction of movement. The amount of movement and its direction is summed with a previously calculated position in order to infer the new position. But if the position information in memory is corrupted (such as by power loss or from electromagnetic interference), the position cannot be known until going through a homing or rezeroing procedure. Conversely, an absolute position sensor always indicates the position with reference to a fixed datum.

Position sensors may have a simple voltage, current, or other output, or they may be a “smart” sensor or transmitter, having additional communication capabilities. An LVDT (linear variable differential transformer) is often used because of its high-temperature capability (sometimes over 200°C), but the required signal conditioning electronics must be mounted in a lower-temperature environment. Some LVDTs have the signal conditioning electronics included within the LVDT housing, but then the temperature capability is somewhat lower.

Mounting

Mounting of position-sensing equipment often requires some mechanical fabrication work, because for many installations there are no applicable standards for mounting. An exception is the case of control valves for which standards do exist for the detection of both linear and rotary motion. The rotary actuators usually adhere to the applicable standard, but most linear actuators in today's market do not comply with the standard. Therefore, the mounting bracket in most linear actuator applications must be custom-made.

In some linear position measurement applications, a rotary sensor is used, and the rectilinear movement is converted into a quarter-turn motion using a lever. For this arrangement, special care must be taken when mounting and aligning the moving parts.

Some position-sensing technologies have a nonlinearity of as much as 1%, so this must be considered when choosing a technology and a model type. Some models are available with a standard error level, and for a slightly higher price, the same model may be available with a lower error level.

In many position measurement applications, repeatability matters more than nonlinearity. This is because, for example, the error in valve position detection may be corrected by the process control loop. In such a case, a lower amount of hysteresis and deadband may be more important than a low nonlinearity. Besides the sensor specifications, mounting the sensor and coupling the moving parts also require attention in order to avoid causing additional hysteresis or deadband.

SENSOR TYPES

Modern position sensors convert the position into an electrically measurable signal such as resistance, voltage, current, inductance, pulses, capacitance, or digital signal. Position sensors comprise at least one fixed and one moving part. The degree of separation between the two parts makes a big difference for the life and reliability of the sensor. If the two parts are in contact with each other, there is friction that causes wear and tear, reducing the life of the sensor. Also, when the parts are in contact, vibrations and shock are transmitted from the moving part to the stationary part of the sensor, which may cause premature failure.

Conversely, if the parts are not in contact, wear and tear are eliminated. This results in longer life and an operation that is more reliable. Although some sensing principles are noncontacting, the mechanical design of the sensor often integrates the two parts together such that friction can still occur and vibration can still be transmitted.

Potentiometric Sensors

The simplest and most widely used position sensor is the potentiometer. Potentiometers are often built into the device being measured, particularly for rotary motion.

In such rotary potentiometers, the moving part, of which the position is being detected, turns the potentiometer shaft. As the shaft is turned, a brush/wiper slides along a resistive element that can be made of a wound wire, conductive plastic, a hybrid of these, or other special materials. A simple potentiometer has three terminals, one for each end of the resistive element and one for the wiper/brush. As the wiper moves, the resistance between the wiper and each end terminal changes (Figure 7.9a).

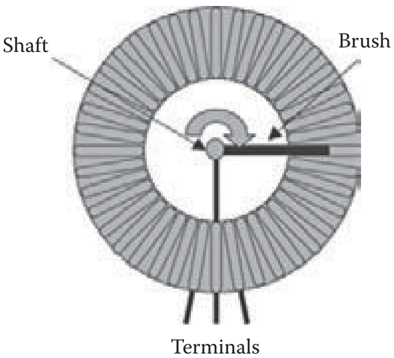


FIG. 7.9a
Wire-wound potentiometer.

With a linear potentiometer, the arrangement is essentially the same, the resistance element is laid out in a straight line, and the wiper rides on a track that is parallel with the resistive element.

Voltage Divider and Rheostat Methods A potentiometer can be wired as a rheostat or as a voltage divider. When wired as a rheostat (as on the left in Figure 7.9b), current passes through the wiper and so any variations in wiper resistance will affect the measurement. This problem is minimized when the wiper contact resistance is much lower than the element resistance. The preferred circuit for a potentiometer is that of a voltage divider (as on the right in Figure 7.9b). The voltage at the wiper should be connected with a relatively high-impedance circuit, such as the noninverting input of an operational amplifier, and then any variations in the wiper contact resistance over its lifetime will not affect the measurement.

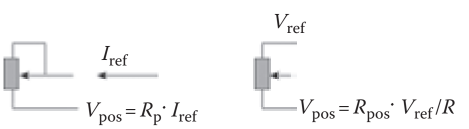


FIG. 7.9b
A potentiometer can be wired as a rheostat (left) or as a voltage divider (right).

When used as a rheostat, and if the resistance of the wires between the sensor and the transmitter is significant in comparison with the resistance of the potentiometer, lead wire compensation should be used. If the rheostat method is implemented while using a temperature transmitter, lead wire resistance compensation is typically included.

The life span of potentiometers is reduced by the wear and tear due to contact with the resistive material. The moving shaft of the potentiometer is connected to the fixed assembly, which transmits the vibration to cause wear between the two parts.

Advantages and Limitations Rotary potentiometers are best suited for angular position measurement. Quarter-turn

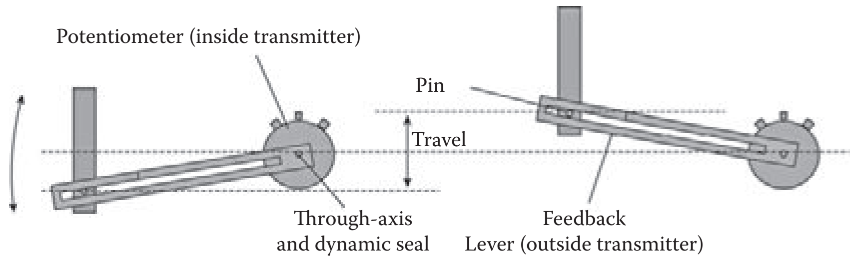


FIG. 7.9c
Lever converting rectilinear to rotary motion.

actuators require only a gear to convert the motion for a full-turn potentiometer. Care must be taken to ensure that gears do not jam, gall, or cause excessive hysteresis. For linear motion, a lever is required when used with a rotary potentiometer (Figure 7.9c). This configuration can introduce some hysteresis and deadband due to mechanical defects. So, for linear motion, it is often preferable to use a linear potentiometer rather than a rotary one.

Many potentiometers have very fine resolution. Nonlinearity for a precision rotary potentiometer can be as good as 0.25%. However, due to linkages and gears, the nonlinearity for the entire assembly is often 0.5% to 1%. Many linear potentiometers have a nonlinearity of 0.1% or 0.25%. The advantages of potentiometric sensors include being simple and well understood. Troubleshooting can be done using a simple multimeter. It is possible to use a temperature transmitter with resistance input for the position measurement; thus, a special signal conditioner is not required (Figure 7.9d). Many position-related devices already are shipped with built-in potentiometers. A typical 50 kΩ potentiometer operated at 24 V DC has a current draw of 0.5 mA and a power dissipation of 12 mW, while a 10 kΩ potentiometer operated at 5 V DC draws 0.5 mA and dissipates only 2.5 mW.

FIG. 7.9d
Industrial transmitter with resistance input.

Linear Variable Differential Transformers

An LVDT is mostly used in linear motion applications and inside some pressure transmitters. A rotary version is also available, called an RVDT (rotary variable differential transformer). A typical LVDT is essentially a transformer having a primary coil and two secondary coils. The three coils each have a hollow bore and are arranged within a metal alloy case so that the primary coil is at the center (see Figure 7.9e). A rod-shaped nickel–iron alloy core is movable within the bore of the coils. The core is moved by the part or component of which the position is being measured.

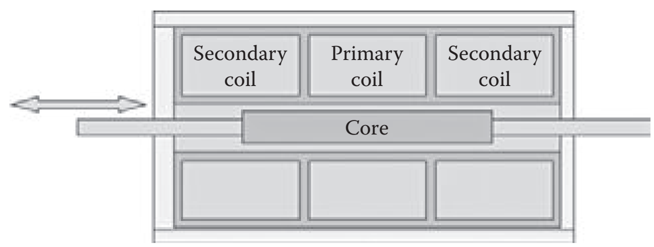


FIG. 7.9e
The three coils and core of an LVDT.

An excitation signal (usually sinusoidal) is applied to the primary coil. Voltage is coupled from the primary coil to the secondary coils in amounts relative to the core position. With the core centered, the two secondaries have the same voltage as each other, and this is called the null position. A demodulation circuit is normally used to convert the AC voltages of the secondaries to a DC voltage having zero volts at null and a positive or negative output voltage depending on the direction and amount of core travel from the null position.

An “AC-LVDT” has the excitation, demodulation, and signal conditioning functions performed by a module that is external to the LVDT. A “DC-LVDT” is one that includes all of the required electronics within the same housing as the LVDT.

Because the LVDT operates through inductive coupling between the core and the coils, there need not be any mechanical contact between the moving core and the coil structure. This eliminates friction and wear and also provides virtually infinite life if the core is mounted in such a way that it does not touch the coil assembly.

Hermetic sealing of the coil assembly is important for reliable operation, often accomplished by welding endplates to a bore liner and outer shell. The inside sealing of the coil structure to the core must be done using nonmagnetic materials. LVDTs are available in lengths of up to 45 cm. Near-infinite resolution is possible and has a nonlinearity of 0.1%–0.5%, depending on type, model, and length.

The DC-LVDT versions are available with voltage outputs, such as 0–5 V DC, and current outputs, such as two-wire 4–20 mA.

Inductive Linear Position Sensors

An inductive linear position sensor (not to be confused with a proximity sensor, some of which are also inductive) utilizes a relatively long coil and typically has a magnetically permeable core that is movable within the coil, as shown in Figure 7.9f. Some models may be very similar to an LVDT in appearance. But with an inductive sensor, the signal is derived from the change of the coil inductance as the core is inserted more or less into the coil. Usually, the inductance increases as the core is inserted further into the coil. Alternatively, the coil may be wound on a nonmagnetic rod, and a tubular target is moved over the coil rod (such as with a Positek model P100). Generally, operating at a higher excitation frequency than an LVDT (an inductive sensor often operates at 50–100 kHz vs. 1–20 kHz for an LVDT), an inductive linear position sensor can have a longer stroke length than an LVDT for a given diameter.

Inductive position sensors are also available on the market for measuring rotary motion, such as with the Positek model RIPS 500 (in which RIPS is for rotary inductive position sensor).

Magnetostrictive Sensors

The magnetostrictive (sometimes erroneously called magnetorestrictive) principle utilizes a property of ferromagnetic materials called magnetostriction. This should not be confused with the magnetoresistive (MR) sensor or giant magnetoresistance (GMR).

When a ferromagnetic material is exposed to a strong magnetic field, such as from a current flow or from a permanent magnet, its physical dimensions change. It may, for example, become longer or shorter. This is due to the alignment of the magnetic domains of the ferromagnetic material with the applied magnetic field. A special case is called the Wiedemann effect. In this effect, a current is applied to a tubular or wire-shaped ferromagnetic material (called the waveguide), while a permanent magnet (called the position magnet, or sometimes called the marker) is located somewhere along the length of the waveguide, with the magnet's field axially facing the waveguide (see Figure 7.9g). Interaction of the two fields forms a torsional force on the waveguide at the location of the position magnet. In a position sensor, the current is applied as a short pulse of approximately 1–5 μs at 0.5–4.0 A and is called the interrogation pulse. Then the torsional force is very abrupt, causing a torsional sonic wave to be formed in the waveguide at the location of the position magnet. This wave travels in the waveguide at about 3000 m/sec, until it is detected near one end of the waveguide by a coil, piezo pickup, or other device. A timer is started upon application

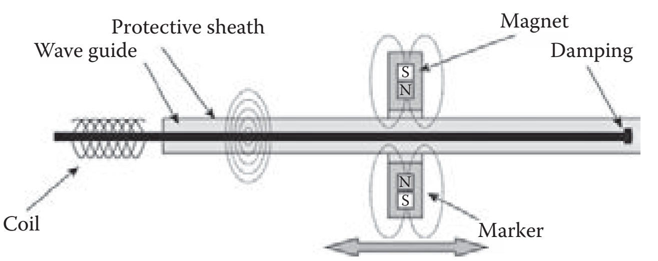


FIG. 7.9g
The operation of a magnetostrictive position sensor.

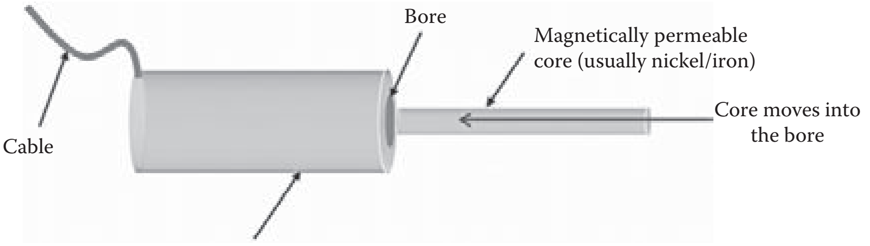


FIG. 7.9f
An inductive linear position sensor: insertion of a magnetically permeable core increases the coil inductance.

of the interrogation pulse, and the timer is stopped when the torsional pulse is detected. The elapsed time is an indication of the distance between the position magnet and the pickup. Torsional waves traveling away from the pickup are damped near the other end of the waveguide. It is often explained that a torsion wave is sent one way and then reflected at the position magnet, but this is incorrect. The torsion wave is generated at the location of the position magnet upon application of the interrogation pulse. The wave travels each way in the waveguide from that point. The wave traveling toward the pickup is detected by the pickup when it arrives. The wave traveling the other way is eliminated by the damping device.

Although the figure shows a coil as the torsion wave pickup device, other types are also in use, including a welded tape having a bias magnet and coil and piezoelectric transducers.

The output signals available from a magnetostrictive sensor can be start–stop, PWM (pulse width modulation), voltage or current, or various digital formats. With start–stop, a start logic pulse is sent to the sensor and causes the sensor to interrogate the waveguide. When the pickup detects the torsional pulse, a stop logic pulse is sent from the sensor. The time between the start and stop pulses indicates the measured position, as shown in Figure 7.9h. For PWM, the start pulses are internally generated within the sensor at a fixed rate. The internal start and stop pulses operate a flip–flop circuit, forming the PWM signal in which the output is high during the measured elapsed time and then low until the start of the next interrogation.

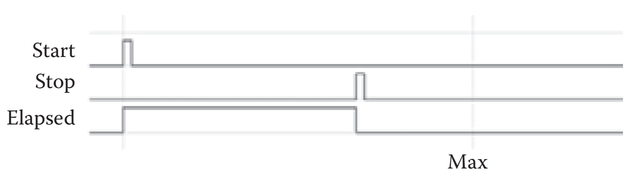


FIG. 7.9h
Start and stop pulses of a magnetostrictive sensor.

For other types of outputs, the start–stop or PWM signal is gated into a microcontroller, and a digital-to-analog (D/A) converter is used to form voltage or current outputs, or suitable interface hardware implements the various digital communication protocols.

Magnetostrictive linear position sensors are available with measurement ranges from 1 cm to over 20 m. Rotary magnetostrictive sensors are possible (the author is inventor on several such U.S. and international patents), but not yet commonly available.

Magnetoresistive Position Sensors

The electrical resistance of most nonmagnetic conductors increases when a magnetic field is applied. This property is called magnetoresistance and is due to the Lorentz force, which causes the charge carriers to align with the magnetic field, leaving fewer charge carriers available to carry electrical current in a portion of the magnetoresistor and increasing its resistance. This is explained in further detail in reference 1.

Specialized materials have been developed, which have optimized MR properties, including, so far, those called AMR (anisotropic magnetoresistance), GMR, and CMR (colossal magnetoresistance).

A single MR element and one or two magnets can be used to implement a linear position sensor, having a very short linear range of less than 1 cm. A longer-range linear sensor, such as the Pomux model KH53 from Sick-Stegmann, requires the use of an array of MR elements arranged in a line, has electronics that can determine which (MR) elements are the closest to the position magnet, and interpolates the reading. A pictorial of such an arrangement is shown in Figure 7.9i.

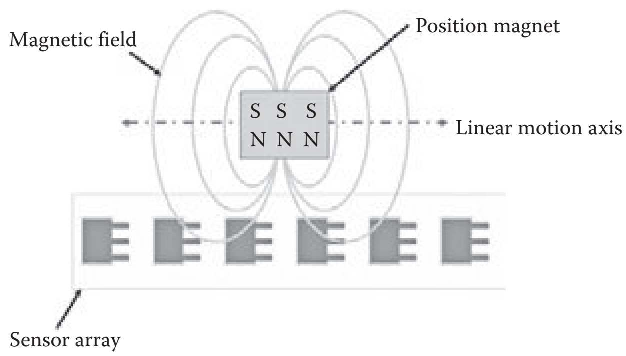


FIG. 7.9i
A long MR linear position sensor having multiple MR sensing elements.

A set of four MR sensors and a permanent magnet or target assembly can be arranged to provide a 360-degree rotary position sensor. The sensing element assemblies are available from several manufacturers (such as Sensitec, Honeywell, and others), with some of them including the associated electronics to drive the sensing elements and interpret the readings to provide a standard output. A complete rotary position sensor is available from several manufacturers, including the model Blade 360, from Gill.

Hall Effect Sensors

In a Hall device, an electrically conductive material has an electric current passed through it, while a magnetic field is also present, and electrodes pick up a voltage developed across the material. The current, magnetic field, and measured voltage are mutually other.* A Hall effect sensor

* Nyce, D.S., *Linear and Position Sensors, Theory and Application*, New York: John Wiley & Sons, 2004.

utilizes one or more Hall device(s), fixed in a reference position, while one or more permanent magnet(s) are movable in proximity with the Hall device(s).

The magnet and sensing assemblies can be constructed for either linear or rotary motion. Longer linear motions can be measured by sensors that utilize multiple Hall effect sensing elements arranged in a line, thereby interpolating the results (similar to MR sensors as shown in Figure 7.9l).

A linear magnet assembly may comprise two opposing magnets side by side. The strength of the magnetic field along the magnet assembly varies at every point (Figure 7.9j). The Hall effect sensor is positioned between the two magnets roughly at the center when movement is at half the travel. For linear movement, the length of the magnet must exceed the expected travel.

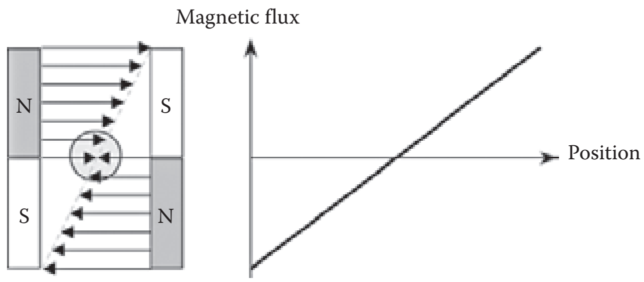


FIG. 7.9j
Magnet assembly for linear motion.

As the magnet moves along the fixed sensor, the Hall device responds to the change in the field strength of the magnet (Figure 7.9k). The magnet assembly is designed to strengthen the magnetic field between the magnets within the assembly and reduce external influence.

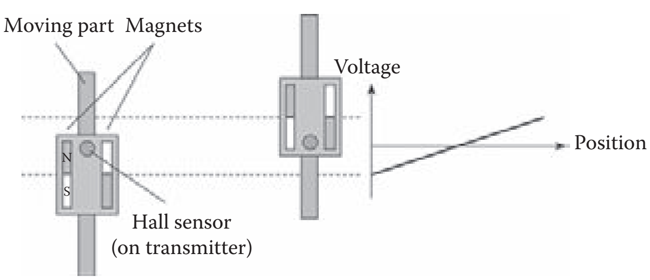


FIG. 7.9k
Operation of the Hall effect sensor.

Rotary Sensor For rotary, quarter-turn motion, a round magnet assembly with the two magnets arranged in-line is used. The magnetic flux sensed by the Hall device is a sinusoidal function of the angle (Figure 7.9l). The nearly linear

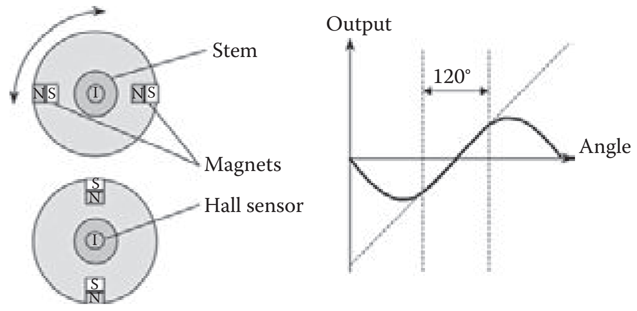


FIG. 7.9l
Rotary magnet assembly for a Hall effect sensor.

part of the function (about 120°) is used for sensing, and then linearization is applied in software.

The Hall device is typically fabricated of a semiconductor material and mounted in a rugged housing. A constant current is applied to the Hall device. As the electrons move through the magnetic field, they experience a force that pushes the electrons toward one side, creating a voltage differential across the semiconductor material. The voltage potential, in turn, creates an electric field, which subsequently causes an opposing force (Figure 7.9m). At equilibrium, the forces balance. The potential is thus proportional to the strength of the magnetic field. Complete rotary sensors are available on the market, such as the model CP-3HABS from Midori. Sensing elements are available from Austria Microsystems, Melexis, and others.

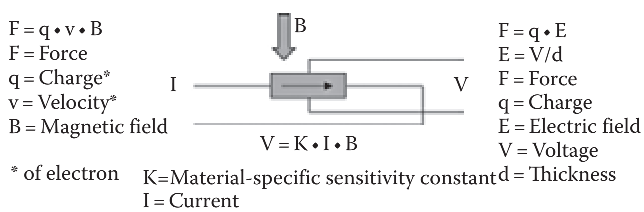


FIG. 7.9m
The Hall effect principle.

Hall Effect Position Transmitters The manufacture of long magnets is difficult. Therefore, the Hall effect is most commonly used for rotary motion and for linear travel of up to 100 mm, which is suitable for most valves. The Hall effect sensor has low power consumption and is ideal for two-wire transmitters. The sensor has a nearly infinite resolution. This principle is noncontacting, and the sensor does not cause any friction, allowing for long life. It also has low sensitivity to vibration.

Since the magnet assembly can be arranged for either linear or rotary sensing, the same transmitter can be used for both angular and linear movement without leaver linkages, etc. This is done simply by the selection of the magnet assembly. Since magnetic coupling is used, the Hall effect sensor can be completely encapsulated within a static seal. This is effective in harsh environments where both moisture and dirt

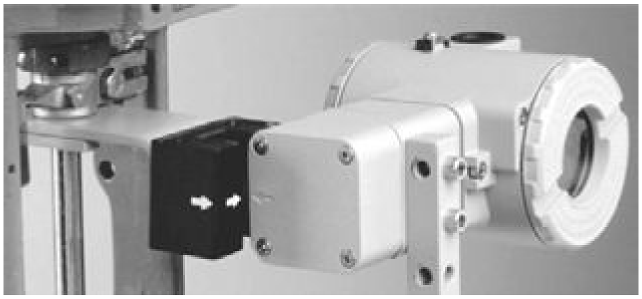


FIG. 7.9n
Hall effect industrial position transmitter.

may be present (Figure 7.9n). Nonlinearity, including that of the magnet, is about 1%, and the repeatability is about 0.1%.

Distributed Impedance Position Sensors

A relatively new type of electromagnetic noncontact sensing technology is called distributed impedance. It also has the trade name NyceWave™ and can be used for measuring linear or rotary position as well as for measuring liquid level. In a distributed impedance linear position sensor, a probe is typically constructed as a dual-helix coil that is wound onto a low-permittivity substrate. An electrically conductive target tube is movable over the sensing probe. The target tube does not have to be magnetically permeable. See Figure 7.9o.

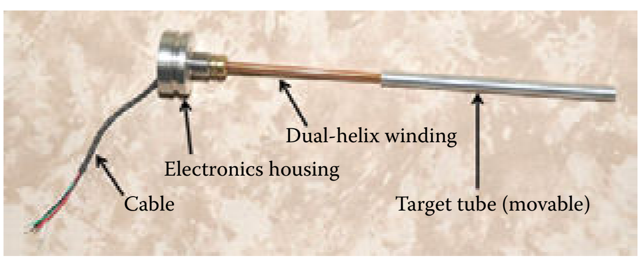


FIG. 7.9o
A distributed impedance linear position sensor (a.k.a. NyceWave). (Photo by the author.)

The construction, configuration, pitch of the coils, and operating frequency are selected so that both inductance and capacitance are distributed along the length of the sensing element. In some designs, the capacitance is variable, but in most linear position designs, the inductance is the variable quantity. The distributed inductance and capacitance can be considered as a transmission line and has a delay time associated with its length. The sensing element has a resonant frequency that is inversely proportional to the delay time and can therefore be used as the frequency controlling element in an oscillating circuit. In this case, the frequency of oscillation is dependent upon the position of the target tube.

Rather than having a lump inductance (and a lump parasitic capacitance), as with a typical inductive position sensor, the distributed impedance technique allows the electromagnetic field to be split into its component parts of an electric field and a magnetic field. The electric field and the magnetic field can each be shaped by the geometry of the sensing conductor pattern. Shaping of the fields provides an ability to retain optimum sensitivity to the target position, while limiting the field dimensions in order to reduce sensitivity to interference and nearby conductors.

Distributed impedance sensors are presently manufactured by LRT Sensors (the DIST model series) and Alliance Sensors (models MR-7, ME-7).

Encoders

Encoders can be either absolute or incremental. Incremental encoders measure the distance and direction moved and not the position; thus, they are not really position sensors and are not covered here. But even with incremental encoders, it is possible to home the device (i.e., returned to the zero or home position) every time power is applied.

Absolute encoders can have either a linear or a rotary configuration. In the rotary configuration, the encoder shaft is turned by the member of which the position is being measured. The shaft then turns a disk that has a radial pattern with a unique code provided for each of a finite number of distinct positions, such as in the optical encoder of Figure 7.9p.

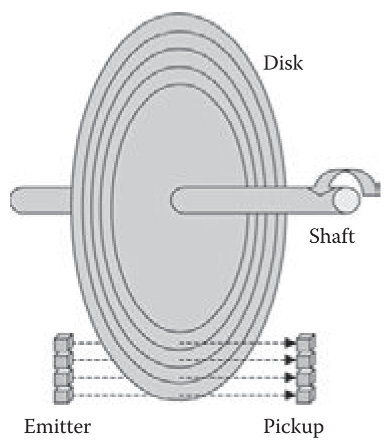


FIG. 7.9p
Rotary optical encoder principle of operation.

For each bit, or increment of resolution, there is one track of code pattern. For example, for 12 bits of resolution, there are 12 tracks. The number of distinct positions is determined as 2^N, so for 12 bits/tracks there are 4096 distinct positions (i.e., bits 0 through 4095), which results in a resolution of better than 0.025% of scale. With an optical absolute encoder, there is a light-emitting diode for each track. Phototransistors are mounted on the opposite side of the disk to read the pattern of holes or slots in the disk. The disk track patterns are usually not in natural binary code but

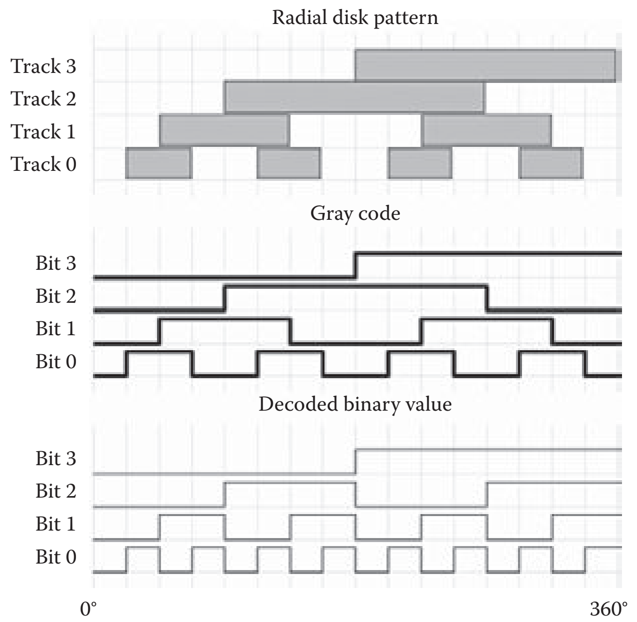


FIG. 7.9q
Gray encoding.

in Gray code (Figure 7.9q). The advantage of the Gray code is that only 1 bit changes at a time for each increment of disk rotation. Whereas for straight binary, many bits may change at once, such as going from 15 to 16 changes 4 bits at once: 01111–10000. So with straight binary, the slightest imperfection may cause some of those bits to change before others, causing an instantaneous grossly incorrect reading. But with Gray code, the analogous incorrect reading can only be off by one increment of resolution.

The conversion from Gray code to natural binary code or vice versa is a simple logical operation that can be performed in software.

The encoder is a true digital sensor theoretically having no drift at all, unless dimensional changes can be induced by temperature changes, mechanical strain, or warping. It has a finite resolution depending on the number of bits represented on the disk. Long linear motion measurement may use a wire on drum connected to a multiturn rotary encoder, or an actual linear sensor may be used if the measuring range is less than 2 m. Changing from linear to rotary application requires a change in the sensor.

TRANSMITTER TECHNOLOGIES

To integrate a position measurement into a control system, a raw signal from a position sensor must be converted into a standardized analog or digital signal. This is often accomplished within the electronics of a transmitter. The sensor may be an integral part of the transmitter, or a separate transmitter can be provided for the sensor. A temperature transmitter can be substituted to provide conditioning for some position sensors by converting their low-level signals, such as resistance or millivolts from a potentiometer or preconditioned LVDT into 4–20 mA. Most distributed control system/programmable logic controller packages are provided with low-level signal capability in their temperature-input module.

Other functions performed by a transmitter include range scaling, signal reversal (forward/backward, clockwise/counterclockwise), and calibration of sensor end points. Many transmitters are of a two-wire type, meaning that they are connected as part of the system using only two wires. Power is provided, and the signal is transmitted over this one pair of wires. Many smart transmitters communicate by digital means, including CANbus, HART, SSI, PROFIbus, MODbus, and others. Such smart transmitters usually cost about $100 or more above the cost of a transmitter that only communicates by 4–20 mA. Smart transmitters may also measure a second variable. This can often be temperature, using a thermocouple, resistance temperature detector (RTD), thermistor, or solid-state temperature sensor. Smart transmitters may also allow remote ranging of a transmitter, including turndown, zero suppression, or zero elevation. Wireless communication has also been gaining in popularity in recent years. This adds greater expense but is sometimes preferred due to the difficulty of running cables in some applications.

Analog Transmitters

In a 4–20 mA DC transmitter, the output is typically 4 mA when the position is 0% of the set range, and the output is 20 mA when the position is 100% of the range. This range must be configured, and it is important not to confuse range setting with calibration.

If the sensor is low power, the 4–20 mA transmitter can operate on a two-wire current loop. Two-wire operation means that the transmitter changes its current consumption proportional to the measurement, and the amount of current drawn is then the output signal. Since the signal never goes below 4 mA (or 3.6 mA during failure, to be precise), there is always some current flow to power the device. This means that such a device must be able to operate while drawing no more than 3.6 mA.

Many position sensors require large quantities of power and therefore need a third and possibly fourth wire to provide them with separate power supplies. Similarly, a 0–20 mA output requires a separate power supply. On the other hand, two-wire operation reduces the amount of wiring required in a plant. A second advantage of current output is that the signal is not as easily distorted as a voltage signal.

Commonly used ranges for voltage output include 0–10, 1–5, and 0–5 V. For voltage output devices, the power supply must be provided separately over a third wire or by a separate pair of wires. A concern with a voltage output is that the signal may be attenuated along the wire if the load impedance is relatively low, resulting in a reduced signal level at the