

MAGNETIC SENSORS

Magnetic sensors find many applications in everyday life and in industry. They provide convenient, noncontact, simple, rugged, and reliable operations compared to many other sensors. The technology to produce magnetic sensors involves many aspects of different disciplines such as physics, metallurgy, chemistry, and electronics.

Generally, magnetic sensors are based on sensing the properties of magnetic materials, which can be done in many ways. For example, magnetization, which is the magnetic moment per volume of materials, is used in many measurement systems by sensing force, induction, field methods, and superconductivity. However, the majority of industrial sensors make use of the relationship between magnetic and electric phenomenon. A typical application of the phenomenon is the computer memory requiring the reading of the contents of a disc without making any contact between the sensor and the device. In other applications, the position of objects sensitive to magnetic fields (e.g., the metals in the ground) can be sensed magnetically. Magnetic sensors find most sensitive applications in medicine to diagnose human illnesses, as in the case of superconducting quantum interference devices (SQUID) and nuclear resonance magnetic (NMR) imaging.

The magnetic elements in sensors are used in a wide range of forms: toroids, rods, films, substrates, and coatings. Some elements are essentially free standing, whereas others are an integral part of more complex devices. In order to obtain maximum material response in magnetic sensors, the relative orientation and coupling between input measurand and magnetic properties are very important, and they are optimized at the design stages.

Many different types of magnetic sensors are available. These sensors can broadly be classified as primary or secondary. In primary sensors, also known as the magnetometers, the parameter to be measured is the external magnetic field. The primary sensors are used in biological applications and

geophysical and extraterrestrial measurements. In secondary sensors, the external parameter is made from other physical variables such as force and displacement. In this article, both the primary and secondary sensors will be discussed. These sensors include inductive, eddy current, transformative, magnetoresistive, Hall-effect, metal-oxide-semiconductor (MOS) magnetic field, and magneto-optical sensors; magnetotransistor and magnetodiode sensors, magnetometers; superconductors; semiconductors; and magnetic thin films. They are offered by many manufacturers as listed in Table 1.

INDUCTIVE SENSORS

Inductive sensors make use of the principles of magnetic circuits. They can be classified as passive sensors and self-generating sensors. The passive sensors require an external power source; hence, the action of the sensor is restricted to the modulation of the excitation signal in relation to an external stimuli. On the other hand, the self-generating types generate signals by utilizing the electrical generator principle based on Faraday's Law of Induction. That is, when there is a relative motion between a conductor and a magnetic field, a voltage is induced in the conductor. Or a varying magnetic field linking a stationary conductor produces voltage in the conductor, which can be expressed as

$$e = -d\Phi/dt \text{ (V)} \quad (1)$$

where Φ is the magnetic flux.

In instrumentation applications, the magnetic field may be varying in time with some frequency, and the conductor may be moving at the same time. In many cases, the relative motion between field and conductor is supplied by changes in the measurand, usually by means of a mechanical motion.

In order to explain the operation of the basic principles of inductive sensors, a simple magnetic circuit is shown in Fig. 1. The magnetic circuit consists of a core, made from a ferromagnetic material, and a coil of n number of turns wound on it. The coil acts as a source of magnetomotive force (mmf), which drives the flux Φ through the magnetic circuit. If we assume that the air gap is zero, the equation for the magnetic circuit may be expressed as

$$\text{mmf} = \text{Flux} \times \text{Reluctance} = \Phi \times \mathcal{R} \text{ (A-turns)} \quad (2)$$

such that the reluctance \mathcal{R} limits the flux in a magnetic circuit just as resistance limits the current in an electric circuit. By writing the magnetomotive force in terms of current, the magnetic flux may be expressed as

$$\Phi = ni/\mathcal{R} \text{ (Wb)} \quad (3)$$

In Fig. 1, the flux linking a single turn is expressed by Eq. (3). But the total flux linking by the entire n number of the turns of the coil is

$$\Psi = n\Phi = n^2i/\mathcal{R} \text{ (Wb)} \quad (4)$$

Equation (4) leads to self-inductance L of the coil, which is described as the total flux per unit current for that particular coil. That is,

$$L = \Psi/I = n^2/\mathcal{R} \text{ (H)} \quad (5)$$

Table 1. List of Manufacturers

Adsen Tech, Inc. 18310 Bedford Circle La Puente, CA 91744 Fax: 818-854-2776	Motion Sensors, Inc. 786 Pitts Chapel Road Alizabath City, NC 27909 Tel: 919-331-2080 Fax: 919-331-1666
Analog Devices, Inc. 1 Technology Way P.O. Box 9106 Norwood, MA 02062-9102 Tel: 800-262-5663 Fax: 781-326-8703	Rechner Electronics Industries, Inc. 8651 Buffalo Avenue Niagara Falls, NY 14304 Tel: 800-544-4106 Fax: 716-283-2127
Dynalco Controls 3690 N. W. 53rd Street Ft. Lauderdale, FL 33309 Tel: 305-739-4300 & 800-368-6666 Fax: 305-484-3376	Reed Switch Developments Company, Inc. P. O. Drawer 085297 Racine, WI 53408 Tel: 414-637-8848 Fax: 414-637-8861
Electro Corporation 1845 57th Street Sarasota, FL 34243 Tel: 813-355-8411 & 800-446-5762 Fax: 813-355-3120	Smith Research and Technology, Inc. 205 Sutton Lane, Dept. TR-95 Colorado Springs, CO 80907 Tel: 719-634-2259 Fax: 719-634-2601
Honeywell Dept. 722 11 West Spring Street Freeport, IL 61032 Tel: 800-537-6945 Fax: 815-235-5988	Smith Systems, Inc. 6 Mill Creek Drive Box 667 Brevard, NC 28712 Tel: 704-884-3490 Fax: 704-877-3100
Kaman Instrument Company 1500 Garden of the Gods Road Colorado Springs, CO 80907 Tel: 719-599-1132 & 800-552-6267 Fax: 719-599-1823	Standex Electronics 4538 Camberwell Road Dept. 301L Cincinnati, OH 45209 Tel: 513-871-3777 Fax: 513-871-3779
Kavlico Corporation 14501 Los Angeles Avenue Moorpark, CA 93021 Tel: 805-523-2000 Fax: 805-523-7125	Turck, Inc. 3000 Campus Drive Minneapolis, MN 55441 Tel: 612-553-7300 & 800-544-7769 Fax: 612-553-0708
Lucas 1000 Lucas Way Hampton, VA 23666 Tel: 800-745-8008 Fax: 800-745-8004	Xolox Sensor Products 6932 Gettysburg Pike Ft. Wayne, IN 46804 Tel: 800-348-0744 Fax: 219-432-0828

This indicates that the self-inductance of an inductive element can be calculated by magnetic circuit properties. Expressing \mathcal{R} in terms of dimensions as

$$\mathcal{R} = l / \mu \mu_0 A \quad (\text{A-turns/Wb}) \quad (6)$$

where l is the total length of the flux path (meters), μ is the relative permeability of the magnetic circuit material, μ_0 is the permeability of free space ($= 4\pi \times 10^{-7}$ H/m), and A is the cross-sectional area of the flux path.

If the air gap is allowed to vary, the arrangement illustrated in Fig. 1 becomes a basic inductive sensor. In this case, the ferromagnetic core is separated in two parts by the air gap. The total reluctance of the circuit now is the addition of the reluctance of the core and the reluctance of the air gap. The relative permeability of air is close to unity, and the relative permeability of the ferromagnetic material is on the order

of a few thousand, indicating that the presence of the air gap causes a large increase in circuit reluctance and a corresponding decrease in the flux. Hence, a small variation in the air gap causes a measurable change in inductance. There are many different types of inductive sensors as will be discussed next.

Linear and Rotary Variable-Reluctance Sensors

The variable-reluctance transducers are based on change in the reluctance of a magnetic flux path. These types of devices find applications particularly in acceleration measurements. However, they can be constructed to be suitable for sensing displacements as well as velocities. They are constructed in many different forms, some of which will be described in this article.

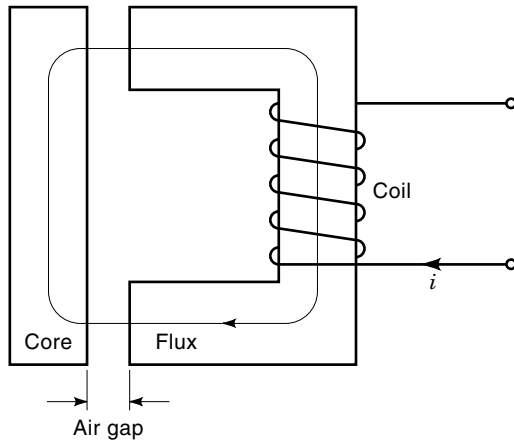


Figure 1. A basic inductive sensor consists of a magnetic circuit made up from a ferromagnetic core with a coil wound on it. The coil acts as a source of mmf, which drives the flux through the magnetic circuit and the air gap. The presence of the air gap causes a large increase in circuit reluctance and a corresponding decrease in the flux. Hence, a small variation in the air gap causes a measurable change in inductance.

Single-Coil Linear Variable-Reluctance Sensor. A typical single-coil variable-reluctance displacement sensor is illustrated in Fig. 2. The sensor consists of three elements: a ferromagnetic core in the shape of a semicircular ring, a variable air gap, and a ferromagnetic plate. The total reluctance of the magnetic circuit is the sum of the individual reluctances:

$$\mathcal{R}_T = \mathcal{R}_C + \mathcal{R}_G + \mathcal{R}_A \quad (7)$$

where \mathcal{R}_C , \mathcal{R}_G , and \mathcal{R}_A are the reluctances of the core, air gap, and armature, respectively.

Each one of these reluctances can be determined by using the properties of materials involved as in Eq. (6). In this par-

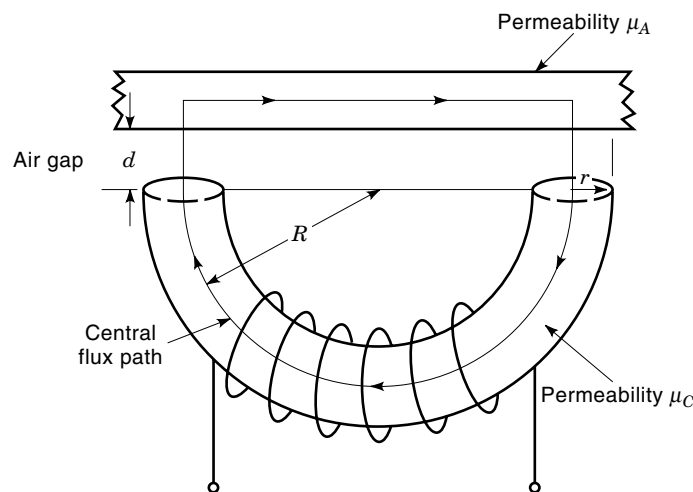


Figure 2. A typical single-coil variable-reluctance displacement sensor. The sensor consists of three elements: a ferromagnetic core in the shape of a semicircular ring, a variable air gap, and a ferromagnetic plate. The reluctance of the coil is dependent on the air gap. Air gap is the single variable, and the reluctance increases nonlinearly with the increasing gap.

ticular case, \mathcal{R}_T can be approximated as

$$\mathcal{R}_T = \frac{R}{\mu_C \mu_0 r^2} + \frac{2d}{\mu_0 \pi r^2} + \frac{R}{\mu_A \mu_0 r t} \quad (8)$$

In obtaining Eq. (8), the length of the flux path in the core is taken as πR , and the cross-sectional area is assumed to be uniform with a value of πr^2 . The total length of the flux path in air is $2d$, and it is assumed that there is no fringing or bending of the flux through the air gap, such that the cross-sectional area of the flux path in air will be close to that of the cross section of the core. The length of an average central flux path in the armature is $2R$. The calculation of an appropriate cross section of the armature is difficult, but it may be approximated to $2rt$, where t is the thickness of the armature.

In Eq. (8), all the parameters are fixed except the only one independent variable, the air gap. Hence, it can be simplified as

$$\mathcal{R}_T = \mathcal{R}_0 + kd \quad (9)$$

where $\mathcal{R}_0 = R/(\mu_0 r^2 [1/(\mu_C r) + 1/(\mu_A t)])$, and $k = 2/(\mu_0 \pi r^2)$.

By using Eqs. (5) and (9), the inductance can be written as

$$L = \frac{n^2}{\mathcal{R}_0 + kd} = \frac{L_0}{1 + \alpha d} \quad (10)$$

where L_0 represents the inductance at zero air gap and $\alpha = k/\mathcal{R}_0$.

The values of L_0 and α can be determined mathematically. They depend on the core geometry, permeability, and the like, as already explained. As it can be seen from Eq. (10), the relationship between L and α is nonlinear. Despite this nonlinearity, these types of single-coil sensors find applications in many areas, such as force measurements and telemetry. In force measurements, the resultant change in inductance can be made to be a measure of the magnitude of the applied force. The coil usually forms one of the components of an LC oscillator whose output frequency varies with the applied force. Hence, the coil modulates the frequency of the local oscillator.

Variable-Differential Reluctance Sensor. The problem of the nonlinearity may be overcome by modifying the single-coil system into variable-differential reluctance sensors (also known as push-pull sensors), as shown in Fig. 3. This sensor consists of an armature moving between two identical cores separated by a fixed distance of $2d$. Now, Eq. (10) can be written for both coils as

$$L_1 = \frac{L_{01}}{1 + \alpha(d - x)}, \quad L_2 = \frac{L_{02}}{1 + \alpha(d + x)} \quad (11)$$

Although the relationship between L_1 and L_2 is still nonlinear, the sensor can be incorporated into an ac bridge to give a linear output for small movements. The hysteresis error of these transducers is almost entirely limited to the mechanical components. These sensors respond to static and dynamic measurements. They have continuous resolution and high outputs, but they may give erratic performances in response to external magnetic fields. A typical sensor of this type has an input span of 1 cm, a coil inductance of 25 mH, and a coil

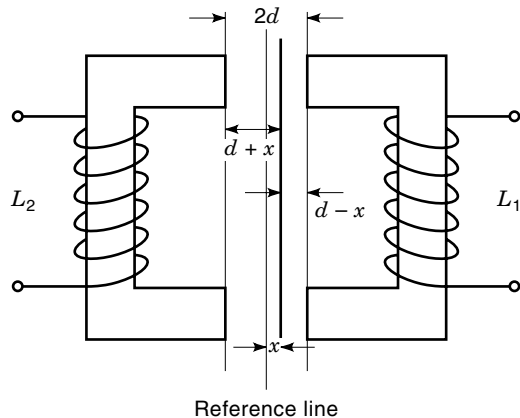


Figure 3. A variable-differential reluctance sensor consists of an armature moving between two identical cores separated by a fixed distance. The armature moves in the air gap in response to the mechanical input. This movement alters the reluctance of coils 1 and 2 thus altering their inductive properties. This arrangement overcomes the problem of nonlinearity inherent in single-coil sensors.

resistance of 75Ω . The resistance of the coil must be carefully considered when designing oscillator circuits. The maximum nonlinearity may be limited to 0.5%.

In typical commercially available variable-differential sensors, the iron core is located half way between the two E-shaped frames. The flux generated by primary coils depends on the reluctance of the magnetic path, the main reluctance being the air gap. Any motion of the core increases the air gap on one side and decreases it on the other side. Consequently, the reluctance changes in accordance with the principles explained previously, thus inducing more voltage on one of the coils than the other. Motion in the other direction reverses the action with a 180° phase shift occurring at null. The output voltage can be modified depending on the requirements in signal processing by means of rectification, demodulation, or filtering. In these instruments, full-scale motion may be extremely small, on the order of few thousandths of a centimeter.

In general, variable-reluctance transducers have small ranges and are used in specialized applications such as pressure transducers. Magnetic forces imposed on the armature are quite large, and this limits the application severely.

Variable-Reluctance Tachogenerators. Another example of the variable-reluctance sensor is shown in Fig. 4. These sensors are based on Faraday's Law of Electromagnetic Induction; therefore, they may also be referred as electromagnetic sensors. Basically, the induced electromagnetic force (emf) in the sensor depends on the linear or angular velocity of the motion.

The variable-reluctance tachogenerator consists of a ferromagnetic toothed wheel attached to the rotating shaft, and a coil wound onto a permanent magnet, extended by a soft iron pole piece. The wheel moves in close proximity to the pole piece, causing the flux linked by the coil to change, thus inducing an emf in the coil. The reluctance of the circuit depends on the width of the air gap between the rotating wheel and the pole piece. When the tooth is close to the pole piece, the reluctance is at a minimum, and it increases as the tooth

moves away from the pole. If the wheel rotates with a velocity ω , the flux may mathematically be expressed as

$$\Psi(\theta) = \Psi_m + \Psi_f \cos m\theta \quad (12)$$

where Ψ_m is the mean flux, Ψ_f is the amplitude of the flux variation, and m is the number of teeth.

The induced emf is given by

$$E = -\frac{d\Psi(\theta)}{dt} = -\frac{d\Psi(\theta)}{d\theta} \times \frac{d\theta}{dt} \quad (13)$$

or

$$E = \Psi_f m \omega \sin n\omega t \quad (14)$$

Both the amplitude and the frequency of the generated voltage at the coil are proportional to the angular velocity of the wheel. In principle, the angular velocity ω can be found from either the amplitude or the frequency of the signal. In practice, the amplitude measured may be influenced by loading effects and electrical interference. In signal processing, the frequency is the preferred option because it can be converted into digital signals easily.

The variable-reluctance tachogenerators are most suitable for measuring angular velocities. They are also used for volume flow rate measurements and the total volume flow determination of fluids.

Microsyn. Another commonly used example of variable-reluctance transducer is the microsyn, as illustrated in Fig. 5. In this arrangement, the coils are connected in such a manner that at the null position of the rotary element, the voltages induced in coils 1 and 3 are balanced by voltages induced in coils 2 and 4. The motion of the rotor in the clockwise direction increases the reluctance of coils 1 and 3 while decreasing the reluctance of coils 2 and 4, thus giving a net output voltage e_o . The movement in the counterclockwise direction causes a similar effect in coils 2 and 4 with a 180° phase shift. A direction-sensitive output can be obtained by using phase-sensitive demodulators.

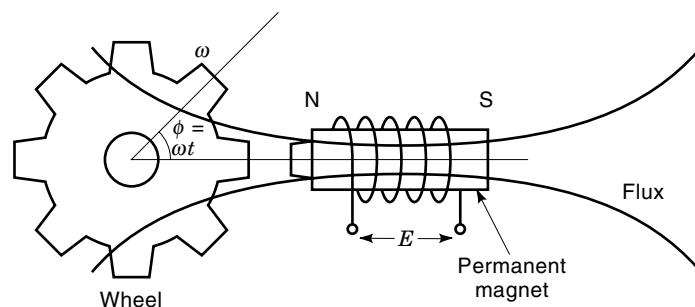


Figure 4. A variable-reluctance tachogenerator is a sensor based on Faraday's Law of Electromagnetic Induction. It consists of a ferromagnetic toothed wheel attached to the rotating shaft and a coil wound onto a permanent magnet extended by a soft iron pole piece. The wheel moves in close proximity to the pole piece, thus causing the flux linked by the coil to change. The change in flux causes an output in the coil similar to a square waveform whose frequency depends on the speed of the rotation of the wheel and the number of teeth.

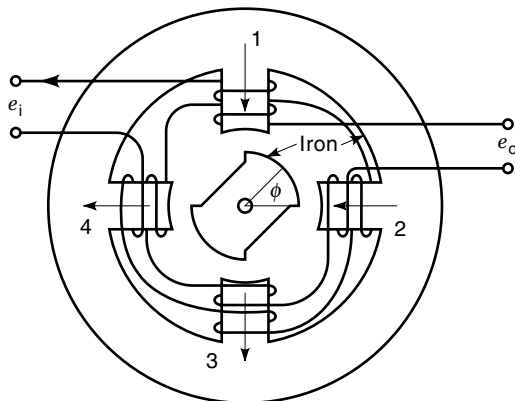


Figure 5. A microsyn is a variable-reluctance transducer that consists of a ferromagnetic rotor and a stator carrying four coils. The stator coils are connected such that at the null position, the voltages induced in coils 1 and 2 are balanced by voltages induced in coils 3 and 4. The motion of the rotor in one direction increases the reluctance of two opposite coils while decreasing the reluctance in others resulting in a net output voltage e_o . The movement in the opposite direction reverses this effect with a 180° phase shift.

Microsyn transducers are extensively used in applications involving gyroscopes. By using microsins, very small motions can be detected giving an output signal as low as 0.01° of changes in angles. The sensitivity of the device can be made as high as 5 V per degree of rotation. The nonlinearity may vary from 0.5% to 1.0% full scale. The main advantage of these transducers is that the rotor does not have windings and slip rings. The magnetic reaction torque is also negligible.

Synchros

The term *synchro* is associated with a family of electromechanical devices. They are primarily used in angle measurements and are commonly applied in control engineering as parts of servomechanisms, machine tools, antennas, and the like.

The construction of synchros is similar to that of wound-rotor induction motors, as shown in Fig. 6. The rotation of the motor changes the mutual inductance between the rotor coil and the three stator coils. The three voltage signals from these coils define the angular position of the rotor. Synchros are used in connection with a variety of devices, such as control transformers, Scott T transformers, resolvers, phase-sensitive demodulators, and analog-to-digital (AD) converters.

In some cases, a control transformer is attached to the outputs of the stator coils such that the output of the control transformer produces a resultant mmf aligned in the same direction as that of the rotor of the synchro. In other words, the synchro rotor acts as a search coil in detecting the direction of the stator field of the control transformer. When the axis of this coil is aligned with the field, the maximum voltage is supplied to the transformer.

In other cases, ac signals from the synchros are first applied to a Scott T transformer, which produces ac voltages with amplitudes proportional to the sine and cosine of the synchro shaft angle. It is also possible to use phase-sensitive demodulations to convert the output signals to make them suitable for digital signal processing.

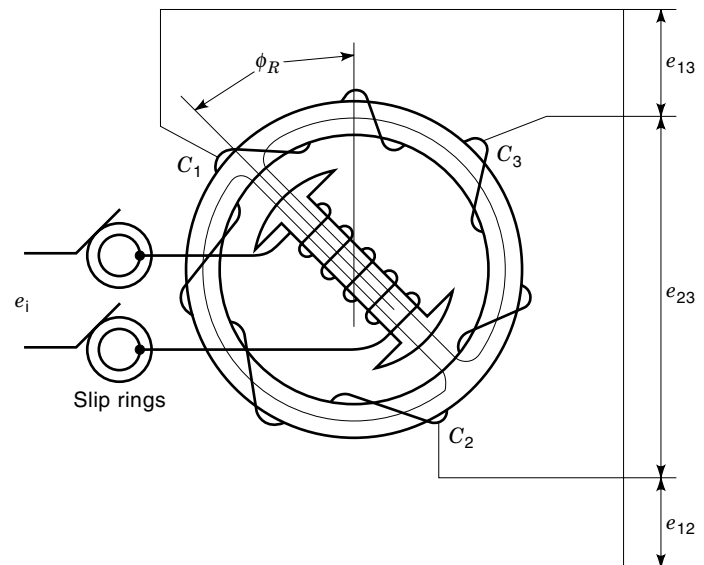


Figure 6. A synchro is similar to a wound-rotor induction motor. The rotation of the rotor changes the mutual inductance between the rotor coil and the three stator coils. The voltages from these coils define the angular position of the rotor. They are primarily used in angle measurements and are commonly applied in control engineering as parts of servomechanisms, machine tools, antennas, and the like.

Linear Variable Inductor

There is very little distinction between variable-reluctance and variable-inductance transducers. Mathematically, the principles of linear variable transducers are very similar to the variable-reluctance type of transducers. The distinction is mainly in the sensing rather than principles of operations. A typical linear variable inductor consists of a movable iron core to provide the mechanical input and the two coils forming two legs of bridge network. A typical example of such a transducer is the variable coupling transducer.

The variable-coupling transducers consist of a former holding a center-tapped coil and a ferromagnetic plunger, as shown in Fig. 7. The plunger and the two coils have the same length l . As the plunger moves, the inductances of the coils change. The two inductances are usually placed to form two arms of a bridge circuit with two equal balancing resistors. The bridge is then excited with ac of 5 V to 25 V with a frequency of 50 Hz to 5 kHz. At the selected excitation frequency, the total transducer impedance at null conditions is

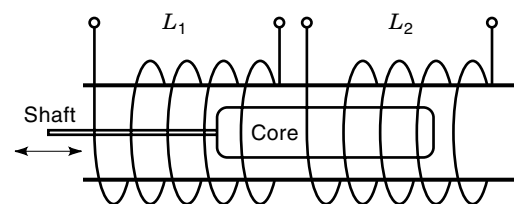


Figure 7. A typical linear variable inductor consists of a movable iron core inside a former holding a center-tapped coil. The core and both coils have the same length l . When the core is in the reference position, each coil will have equal inductances of value L . As the core moves by δl , changes in inductances $+\delta L$ and $-\delta L$ create voltage outputs from the coils.

set in the $100\ \Omega$ to $1000\ \Omega$ range. The resistors are set to have about the same value as transducer impedances. The load for the bridge output must be at least ten times the resistance R value. When the plunger is in the reference position, each coil will have equal inductances of value L . As the plunger moves by δl , changes in inductances $+\delta L$ and $-\delta L$ create a voltage output from the bridge. By constructing the bridge carefully, the output voltage may be made as a linear function displacement of the moving plunger within a rated range.

In some transducers, in order to reduce power losses resulting from the heating of resistors, center-tapped transformers may be used as a part of the bridge network. In this case, the circuit becomes more inductive, and extra care must be taken to avoid the mutual coupling between the transformer and the transducer.

It is particularly easy to construct transducers of this type, by simply winding a center-tapped coil on a suitable former. The variable-inductance transducers are commercially available in strokes from about 2 mm to 500 cm. The sensitivity ranges between 1% full scale to 0.02% in long-stroke special constructions. These devices are also known as linear displacement transducers or LDTs, and they are available in various shapes and sizes.

Apart from linear variable inductors, rotary types are also available. Their cores are specially shaped for rotational applications. Their nonlinearity can vary between 0.5% and 1% full scale over a range of 90° rotation. Their sensitivity can be up to 100 mV per degree of rotation.

Induction Potentiometer

A version of rotary-type linear inductors is the induction potentiometer, as shown in Fig. 8. Two concentrated windings are wound on stator and rotor. The rotor winding is excited with an ac, thus inducing voltage in the stator windings. The

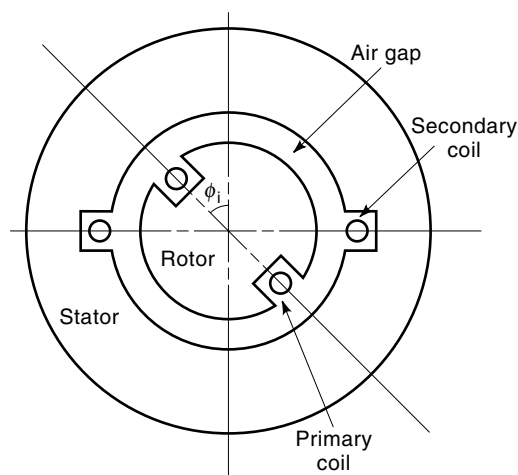


Figure 8. An induction potentiometer is a linear variable inductor with two concentrated windings wound on the stator and rotor. The rotor winding is excited with ac, inducing voltage in the stator windings. The amplitude of the output voltage is dependent on the relative positions of the coils determined by the angle of rotation. For concentrated coils, the variation of the amplitude is sinusoidal, but linearity is restricted in the region of the null position. Different types of induction potentiometers are available with distributed coils, which give linear voltages over an angle of 180° of rotation.

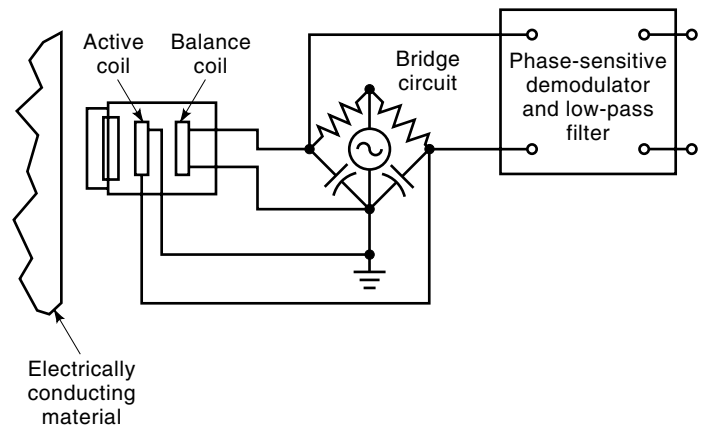


Figure 9. Eddy current transducers are inductive transducers using probes. The probes contain one active and one balance coil. The active coil responds to the presence of a conducting target, whereas the balance coil completes a bridge circuit and provides temperature compensation. When the probe is brought close to the target, the flux from the probe links with the target producing eddy currents within the target, which alter the inductance of the active coil. This change in inductance is detected by a bridge circuit.

amplitude of the output voltage is dependent on the mutual inductance between the two coils, where mutual inductance itself is dependent on the angle of rotation. For concentrated coil-type induction potentiometers, the variation of the amplitude is sinusoidal, but linearity is restricted in the region of the null position. A linear distribution over an angle of 180° may be obtained by carefully designed distributed coils.

Standard commercial induction pots operate in a 50 Hz to 400 Hz frequency range. They are small in size from 1 cm to 6 cm, and their sensitivity can be in the order of $1\ \text{V}/1^\circ$ of rotation. Although the ranges of induction pots are limited to less than 60° of rotation, it is possible to measure displacements in angles from 0° to full rotation by suitable arrangements of a number of induction pots. As in the case of most inductive sensors, the output of the induction pots may need phase-sensitive demodulators and suitable filters. In many inductive pots, additional dummy coils are used to improve linearity and accuracy.

EDDY CURRENT SENSORS

Inductive transducers based on eddy currents are mainly probe types containing two coils, as shown in Fig. 9. One of the coils, known as the active coil, is influenced by the presence of the conducting target. The second coil, known as the balance coil, serves to complete the bridge circuit and provides temperature compensation. The magnetic flux from the active coil passes into the conductive target by means of a probe. When the probe is brought close to the target, the flux from the probe links with the target, producing eddy currents within the target.

The eddy current density is greatest at the target surface and become negligibly small about three skin depths below the surface. The skin depth depends on the type of material used and the excitation frequency. Even though thinner targets can be used, a minimum of three skin depths may often be necessary to minimize the temperature effects. As the tar-

get comes closer to the probe, the eddy currents become stronger, causing the impedance of the active coil to change and altering the balance of the bridge in relation to the target position. This unbalance voltage of the bridge may be demodulated, filtered, and linearized to produce a dc output proportional to target displacement. The bridge oscillation may be as high as 1 MHz. High frequencies allow the use of thin targets and provide a good system frequency response.

Probes are commercially available with full-scale ranges from 0.25 mm to 30 mm with a nonlinearity of 0.5% and a maximum resolution of 0.0001 mm. Targets are usually supplied by the clients, involving noncontact measurements of machine parts. For nonconductive targets, conductive materials of sufficient thickness must be attached onto the surface by means of commercially available adhesives. Because the target material, shape, and the like influence the output, it is necessary to calibrate the system statistically for a specific target. The recommended measuring range of a given probe begins at a standoff distance equal to about 20% of the stated range of the probe. In some cases, a standoff distance of 10% of the stated range for which the system is calibrated is recommended as standard. A distance greater than 10% of the measuring range can be used as long as the calibrated measuring range is reduced by the same amount.

Flat targets must be the same diameter as the probe or larger. If the target diameter is smaller than the probe diameter, the output drops considerably, thus becoming unreliable. Curved-surface targets may behave similar to flat surfaces if the diameter exceeds about three or four diameter of the probe. In this case, the target essentially becomes an infinite plane. This also allows some cross-axis movement without affecting the system output. Target diameter comparable to the sensor could result in detrimental affects from cross-axis movements.

For curved or irregularly shaped targets, the system needs to be calibrated using an exact target that may be seen in the operation. This tends to eliminate any errors caused by the curved surfaces during the applications. However, special multiprobe systems are available for orbital motions of rotating shafts. If the curved (shaft) target is about ten times greater than the sensor diameter, it acts as an infinite plane and does not need special calibrations. Special care must be exercised to deal with electrical runout resulting from factors such as inhomogeneities in hardness, particularly valid for ferrous targets. However, nonferrous targets are free from electrical runout concerns.

TRANSFORMATIVE SENSORS

Transformative sensors make use of the principles of transformer action, that is magnetic flux created by one coil links with the other coil to induce voltages. There are many different types, such as linear variable transformers, rotary variable differential transformers, and flux-gate magnetometers.

Linear Variable-Differential Transformer

The linear variable-differential transformer (LVDT) is a passive inductive transducer that has found many applications. It consists of a single primary winding positioned between two identical secondary windings wound on a tubular ferro-

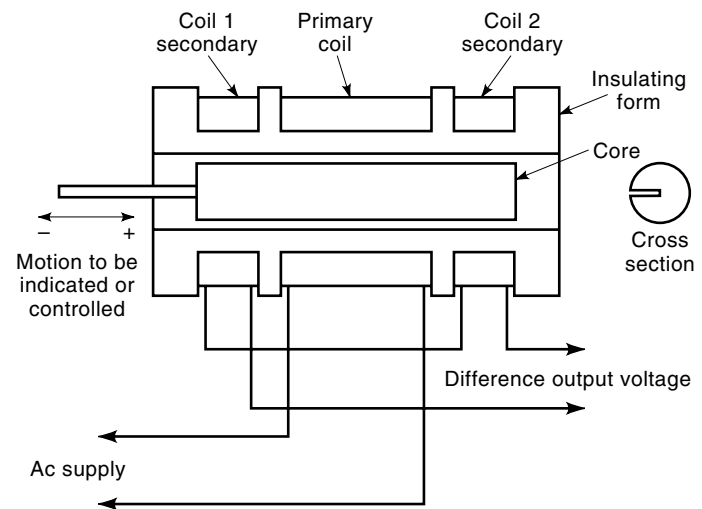


Figure 10. A linear variable-differential transformer is a passive inductive transducer consisting of a single primary winding positioned between two identical secondary windings wound on a tubular ferromagnetic former. As the core inside the former moves, the magnetic paths between primary and secondaries alter, thus giving secondary outputs proportional to the movement. The two secondaries are made as similar as possible by having equal sizes, shapes, and number of turns.

magnetic former, as shown in Fig. 10. The primary winding is energized by a high-frequency 50 Hz to 20 kHz ac voltage. The two secondaries are made identical by having an equal number of turns. They are connected in series opposition so that the induced output voltages oppose each other.

In many applications, the outputs are connected in opposing form, as shown in Fig. 11(a). The output voltages of individual secondaries v_1 and v_2 at null position are illustrated in Fig. 11(b). However, in opposing connection, any displacement in the core position x from the null point causes amplitude of the voltage output v_o and the phase difference α to change. The output waveform v_o in relation to core position is shown in Fig. 11(c). When the core is positioned in the middle, there is an equal coupling between primary and secondaries, thus giving a null point or reference point of the sensor. As long as the core remains near the center of the coil arrangement, output is very linear. The linear ranges of commercial differential transformers are clearly specified, and the devices are seldom used outside this linear range.

The ferromagnetic core or plunger moves freely inside the former; thus altering the mutual inductance between the primary and secondaries. With the core in the center, or at the reference position, the induced emfs in the secondaries are equal, and because they oppose each other, the output voltage is zero. When the core moves, say to the left, from the center, more magnetic flux links with the left-hand coil than with the right-hand coil. The voltage induced in the left-hand coil is therefore larger than the induced emf on the right-hand coil. The magnitude of the output voltage is then larger than at the null position and is equal to the difference between the two secondary voltages. The net output voltage is in phase with the voltage of the left-hand coil. The output of the device is then an indication of displacement of the core. Similarly, movement in the opposite direction to the right from the cen-

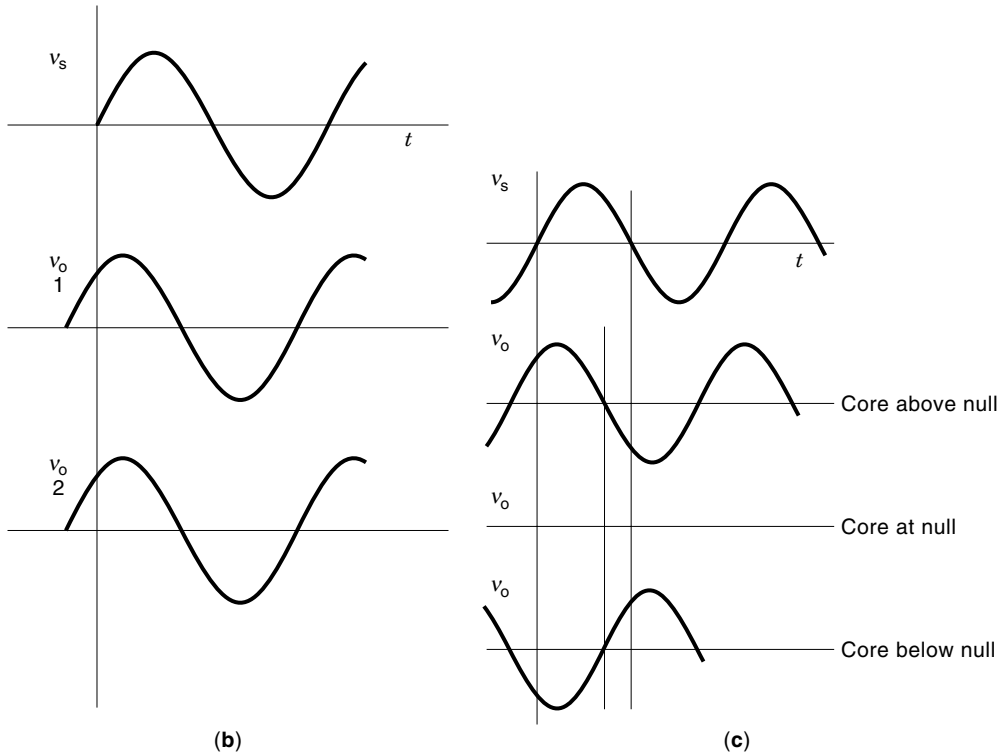
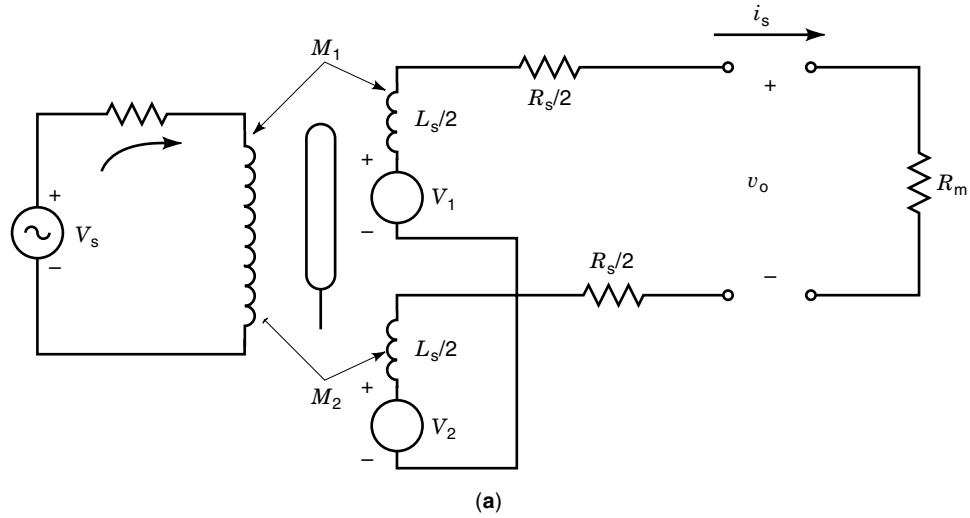


Figure 11. The voltages induced in the secondaries of a linear variable-differential transformer (a) may be processed in a number of ways. The output voltages of individual secondaries v_1 and v_2 at null position are illustrated in (b). In this case, the voltages of individual coils are equal and in phase with each other. Sometimes the outputs are connected opposing each other, and the output waveform v_o becomes a function of core position x and phase angle α as in (c). Note the phase shift of 180° as the core position changes above and below the null position.

ter reverses this effect, and the output voltage is now in phase with the emf of the right-hand coil.

For mathematical analysis of the operation of LVDTs Fig. 11(a) may be used. The voltages induced in the secondary coils are dependent on the mutual inductance between the primary and individual secondary coils. Assuming that there is no cross coupling between the secondaries, the induced voltages may be written as

$$v_1 = M_1 s i_p \quad \text{and} \quad v_2 = M_2 s i_p \quad (15)$$

where M_1 and M_2 are the mutual inductances between primary and secondary coils for a fixed core position, s is the Laplace operator, and i_p is the primary current.

In the case of opposing connection, no load output voltage v_o without any secondary current may be written as

$$v_o = v_1 - v_2 = (M_1 - M_2) s i_p \quad (16)$$

writing

$$v_s = i_p (R + sL_p) \quad (17)$$

Substituting i_p in Eq. (16) gives the transfer function of the transducer as

$$\frac{v_o}{v_s} = \frac{(M_1 - M_2)s}{R + sL_p} \quad (18)$$

However, If there is a current resulting from output signal processing, then describing equations may be modified as

$$v_o = R_m i_s \quad (19)$$

where $i_s = (M_1 - M_2)si_p / (R_s + R_m + sL_s)$ and

$$v_s = i_p(R + sL_p) - (M_1 - M_2)si_s \quad (20)$$

Eliminating i_p and i_s from Eqs. (19) and (20) results in a transfer function

$$\frac{v_o}{v_s} = \frac{R_m(M_1 - M_2)s}{[(M_1 - M_2)^2 + L_s L_p]s^2 + [L_p(R + R_m) + RL_s]s + (R_s + R_m) + R} \quad (21)$$

This is a second-order system, which indicates that with the effect of the numerator the frequency of the system changes from $+90^\circ$ at low frequencies to -90° at high frequencies. In practical applications, the supply frequency is selected such that at null position of the core the phase angle of the system is 0° .

The amplitudes of the output voltages of secondary coils are dependent on the position of the core. These outputs may directly be processed from each individual secondary coils for slow movements of the core, if the direction of the movement of the core does not bear any importance. However, for fast movements of the core, the signals may be converted to dc, and the direction of the movement from the null position may be detected. There are many options to do this; however, a *phase-sensitive demodulator* and filter are commonly used as shown in Fig. 12(a). A typical output of the phase-sensitive demodulator is illustrated in Fig. 12(b), for core positions as in Fig. 12(c), in relation to output voltage v_o , displacement x , and phase angle α .

The phase-sensitive demodulators are extensively used in differential-type inductive sensors. They basically convert the ac outputs to dc values and also indicate the direction of movement of the core from the null position. A typical phase-sensitive demodulation circuit may be constructed, based on diodes shown in Fig. 13(a). This arrangement is useful for very slow displacements, usually less than 1 or 2 Hz. In Fig. 13(a), bridge 1 acts as a rectification circuit for secondary 1, and bridge 2 acts as a rectifier for secondary 2. The net output voltage is the difference between the outputs of two bridges as in Fig. 13(b). The position of the core can be worked out from the amplitude of the dc output and the direction of the movement of the core can be determined from the polarity of the dc voltage. For rapid movements of the core, the output of the diode bridges need to be filtered, and this passes only the frequencies of the movement of the core and filters all the other frequencies produced by the modulation process. For this purpose, a suitably designed simple *RC* filter may be sufficient.

In the marketplace, there are phase-sensitive demodulator chips available, such as AD598 offered by Analog Devices,

Inc. These chips are highly versatile and flexible to suit particular application requirements. They offer many advantages over conventional phase-sensitive demodulation devices; for example, frequency of excitation may be adjusted to any value between 20 Hz and 20 kHz by connecting an external capacitor between two pins. The amplitude of the excitation voltage can be set up to 24 V. The internal filters may be set to required values by external capacitors. Connections to analog-to-digital converters are made easy by converting the bipolar output to a unipolar scale.

The frequency response of LVDTs is primarily limited by the inertia characteristics of the device. In general, the frequency of the applied voltage should be ten times the desired frequency response. Commercial LVDTs are available in a broad range of sizes, and they are widely used for displacement measurements in a variety of applications. The displacement sensors are available to cover ranges from ± 0.25 mm to ± 7.5 cm. They are sensitive enough to be used to respond to displacements well below 0.0005 mm. They can have operational temperature range from -265° to 600°C . They are also available in radiation-resistant designs for operation in nuclear reactors. For a typical sensor of range ± 25 mm, the recommended supply voltage is 4 V to 6 V, with a nominal frequency of 5 kHz and a maximum nonlinearity of 1% full scale. Several commercial models, which can produce a voltage output of 300 mV for 1 mm displacement of the core, are available.

One important advantage of the LVDTs is that there is no physical contact between the core and the coil form; hence there is no friction or wear. Nevertheless, there are radial and longitudinal magnetic forces on the core at all times. These magnetic forces may be regarded as magnetic springs that try to displace the core from its null position. This may be a critical factor in some applications.

One problem with LVDTs is that it may not be easy to make the two halves of the secondary identical; their inductance, resistance, and capacitance may be different, causing a large unwanted quadrature output in the balance position. Precision coil-winding equipment may be required to reduce this problem to an acceptable value.

Another problem is associated with null position adjustments. The harmonics in the supply voltage and stray capacitances result in small null voltages. The null voltage may be reduced by proper grounding, which reduces the capacitive effects and the center-tapped voltage source arrangements. In center-tapped supplies, a potentiometer may be used to obtain a minimum null reading.

The LVDTs find a variety of applications, which include jet engines controls that are in close proximity to exhaust gases, and controls that measure roll positions in the thickness of materials in hot-slab steel mills. After some mechanical conversions, LVDTs may also make force and pressure measurements.

Rotary Variable-Differential Transformer

A variation from the linear variable-differential transformer is the rotary core differential transformer, as shown in Fig. 14. Here the primary winding is wound on the center leg of an E core; the secondary windings are wound on the outer legs of the E core. The armature is rotated by an externally applied force about a pivot point above the center leg of the

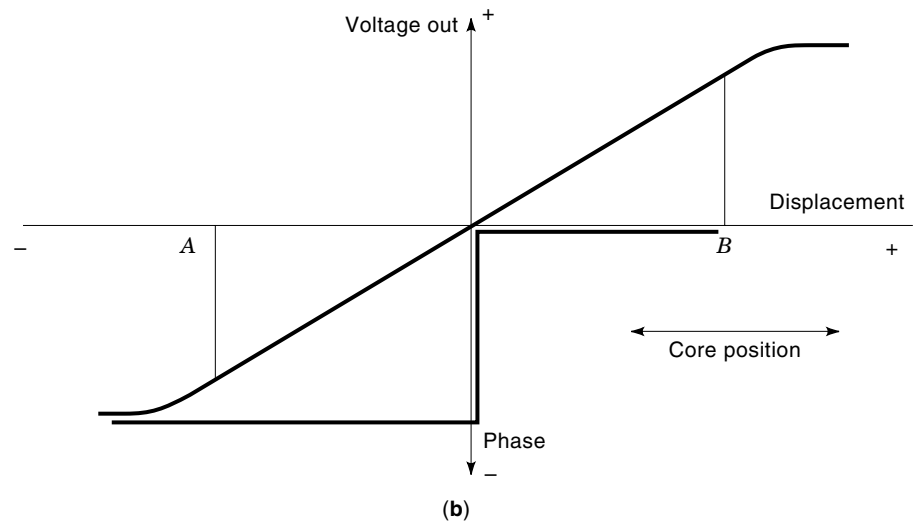
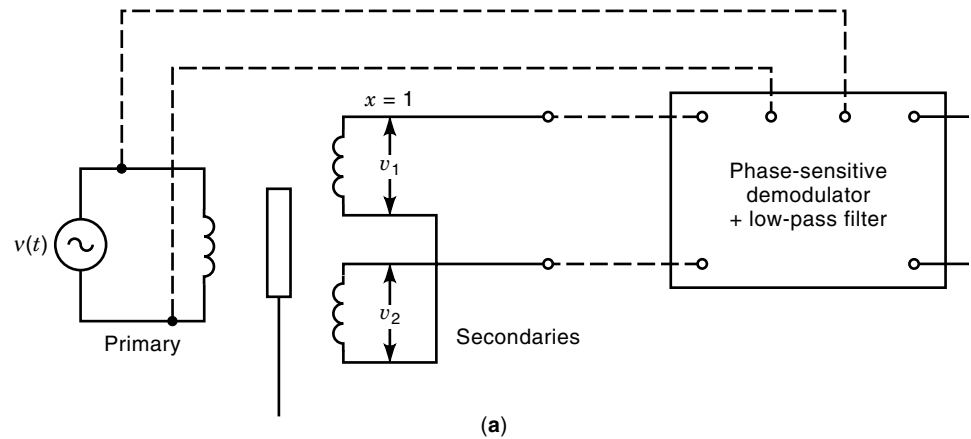
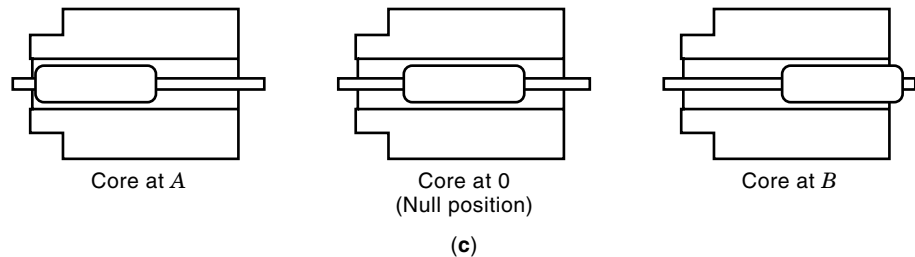


Figure 12. Phase-sensitive demodulator and filter (a) are commonly used to obtain displacement-proportional signals from LVDTs and other differential-type inductive sensors. They convert the ac outputs from the sensors into dc values and also indicate the direction of movement of the core from the null position. A typical output of the phase-sensitive demodulator is shown in (b). The relationship between output voltage v_o and phase angle α is also shown against core position x as sketched in (c).



core. When the armature is displaced from its reference or balance position, the reluctance of the magnetic circuit through one secondary coil is decreased; simultaneously the reluctance through the other coil is increased. The induced emfs in the secondary windings, which are equal in the reference position of the armature, are now different in magnitude and phase as a result of the applied displacement. The induced emfs in the secondary coils are made to oppose each other, and the transformer operates in the same manner as LVDTs. The rotating variable transformers may be sensitive to vibrations. If a dc output is required, a demodulator network may be used, as in the case of LVDTs.

In most rotary linear-variable differential transformers, the rotor mass is very small, usually less than 5 g. The non-linearity in the output ranges between $\pm 1\%$ and $\pm 3\%$, depending on the angle of rotation. The motion in the radial direction produces a small output signal that can affect the

overall sensitivity. But this transverse sensitivity is usually kept less than 1% of the longitudinal sensitivity.

MOS MAGNETIC FIELD SENSORS

The technology of integrated magnetic field sensors, also called semiconductor magnetic microsensors, is well developed. This technology uses either high-permeability (e.g., ferromagnetic) or low-permeability (e.g., paramagnetic) materials. The integrated circuit magnetic techniques support many sensors, such as magnetometers, optoelectronics, Hall-effect sensors, magnetic semiconductor sensors, and superconductive sensors.

At the present, silicon offers an advantage of inexpensive batch fabrication for magnetic sensors. Most of the integrated circuit magnetic sensors are manufactured by following the

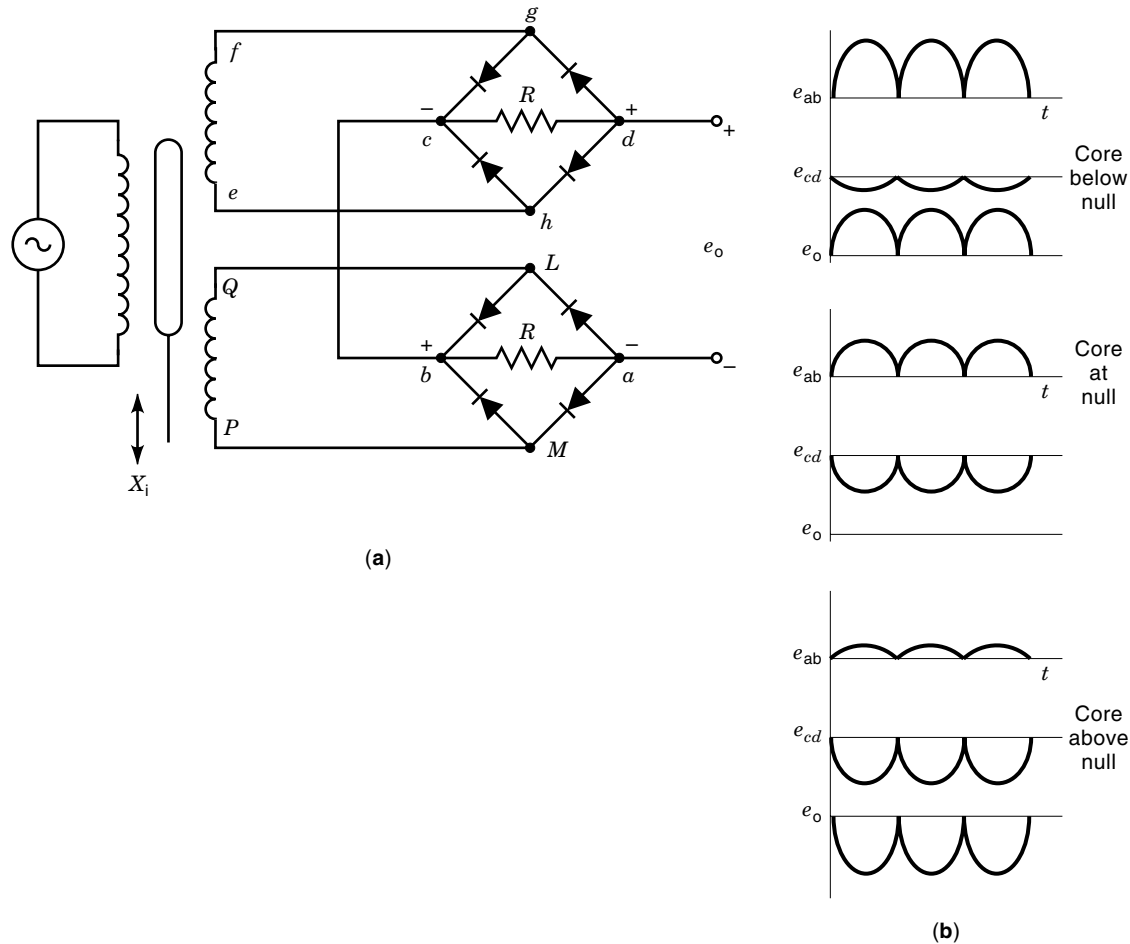


Figure 13. A typical phase-sensitive demodulation circuit based on diode bridges as in (a). The bridge 1 acts as a rectification circuit for secondary 1, and bridge 2 acts as a rectifier for secondary 2 where the net output voltage is the difference between the two bridges as in (b). The position of the core can be worked out from the amplitude of the dc output, and the direction of the movement of the core can be determined from the polarity of the voltage. For rapid movements of the core, the output of the diode bridges need to be filtered. For filters, a suitably designed simple RC filter may be sufficient.

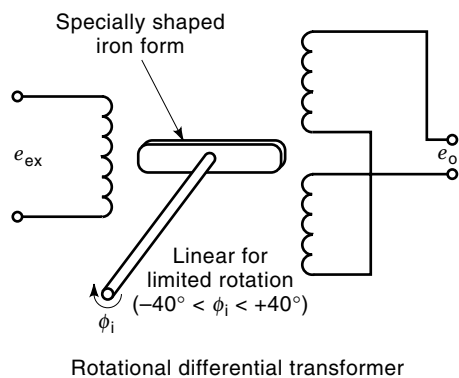


Figure 14. A rotary core differential transformer has an armature rotated by an externally applied force about a pivot point above the center leg of the core. When the armature is displaced from its reference or balance position, the reluctance of the magnetic circuit through one secondary coil is decreased; simultaneously the reluctance through the other coil is increased. The induced emfs in the secondary windings are different in magnitude and phase as a result of the applied displacement.

design rules of standard chip manufacturing. For example, MOS and complementary metal oxide semiconductor (CMOS) technologies are used to manufacture highly sensitive Hall-effect sensors, magnetotransistors, and other semiconductor sensors. Some of the magnetic semiconductor sensors are discussed in detail in the following sections.

MAGNETOMETERS

Magnetometers are devices that are produced to sense external magnetic fields mainly based on Faraday's Law of Induction. There are many different types of magnetometers including search coil magnetometers, SQUIDS, flux-gates, nuclear, and optical magnetometers. The two most commonly used types are the flux-gate and the search coil magnetometers.

Flux-Gate Magnetometers

Flux-gate magnetometers are made from two coils wound on a ferromagnetic material, as illustrated in Fig. 15. One of the coils is excited with a sinusoidal current, which drives the

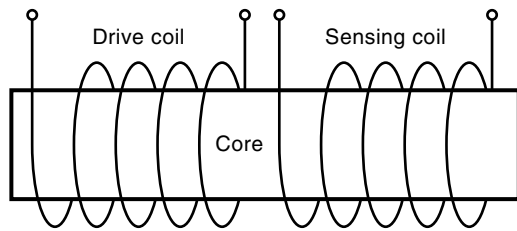


Figure 15. A flux-gate magnetometer consists of two coils wound on a ferromagnetic core. The driving coil is excited with a sinusoidal current, which drives the core into a saturation state. When saturated, the reluctance of the core to external magnetic field increases, thus repelling the external flux and hence reducing the effect of the external field on the second coil. The harmonics of the induced voltage in the sensing coil is an indication of the magnitude of the external magnetic field.

core into a saturation state. At this stage, the reluctance of the core to external magnetic field increases, thus repelling the external flux and so reducing the effect of the external field on the second coil. As the core becomes unsaturated, the effect of the external field increases. The increase and reduction of the effect of the external field on the second coil is sensed as the harmonics of the induced voltage. These harmonics are then directly related to the strength and variations in the external field. The sensitivity of these devices is dependent on the magnetic properties and the shape of the saturation curve of the core material. The measurement range can vary from 100 pT to 10 mT operating in the 0 kHz to 10 kHz frequency range.

Search Coil Magnetometers

Search coil magnetometers operate on the principle of Faraday's Law of Induction. A typical search coil magnetometer is shown in Fig. 16. The flux through the coil changes if the magnetic field varies in time or the coil is moved through the field. The sensitivity depends on the properties of the core material, dimensions of the coil, number of turns, and rate of change of flux through the coil.

Search coil magnetometers are manufactured from 4 cm in dimensions to 100 cm. They can sense weak fields as low as 100 pT within the frequency range of 1 Hz to 1 MHz. The upper limit is dependent on the relative magnitudes of resistance and inductance of the coil. During the signal processing, they can be used as part of a bridge or resonant circuits.

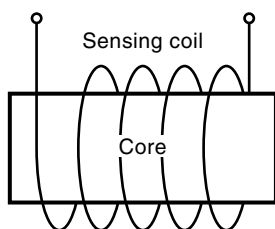


Figure 16. A search coil magnetometer uses Faraday's Law of Induction. The changing magnetic flux induces an emf in the coil. The sensitivity of the magnetometer depends on the properties of the core material, dimensions of the coil, number of turns, and rate of change of flux through the coil. They can sense weak fields as low as 100 pT within the frequency range of 1 Hz to 1 MHz.

SQUID Magnetometers

Superconducting quantum interference device sensors are used in many diverse applications from medicine, geophysics, and nuclear magnetic resonance to nondestructive testing of solid materials. The SQUID offers high sensitivity for the detection of weak magnetic fields and field gradients. They are made from conventional superconductors such as niobium operating at liquid helium temperatures. They are manufactured by using integrated circuit technology, as illustrated in Fig. 17.

The principle of operation is the Josephson effect. If a magnetic flux links to a ring-shaped superconducting material, a current is induced in the ring. This current flows forever due to the lack of any resistance. The intensity of current is proportional to the intensity of the field. The current in the ring is measured by using the Josephson effect wherein a weak link in the superconducting ring causes the superconducting current to oscillate as a function of magnetic field intensity. These oscillations can be sensed by many techniques such as coupling to a radio-frequency circuit and other resonance techniques.

The SQUIDs are extremely sensitive devices, with sensitivities ranging from 10 fT to 10 nT. The SQUID sensors can be arranged to measure magnetic fields in three dimensions in x , y , and z directions of Cartesian coordinates, as in the case of high-sensitivity gradiometers. One disadvantage of SQUIDs is that they need supercooling at very low temperatures. Much research is concentrated on materials exhibiting superconductivity properties at high temperatures. SQUIDs are used in gradiometers, voltmeters and amplifiers, displacement sensors, geophysics, gravity wave detection, and nondestructive testing, to name a few.

MAGNETORESISTIVE SENSORS

In magnetoresistive sensors, the magnetic field causes a change in resistance of some materials such as permalloys. In these materials, current passing through the material magnetizes the material in a particular magnetic orientation. An

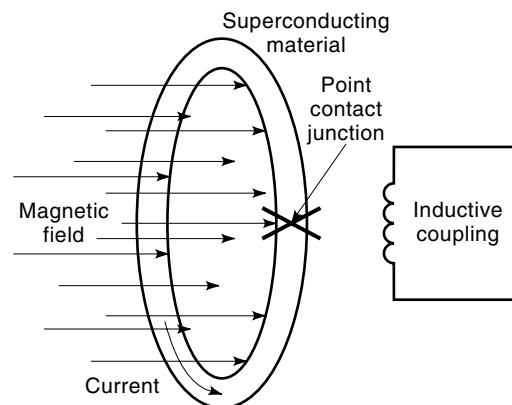


Figure 17. A SQUID consists of a superconducting ring. When subjected to an external field, the current is induced in the ring, which flows forever. The current in the ring is measured by using the Josephson effect and by creating a weak link in the ring. This weak link makes the superconducting current oscillate as a function of the external magnetic field intensity.

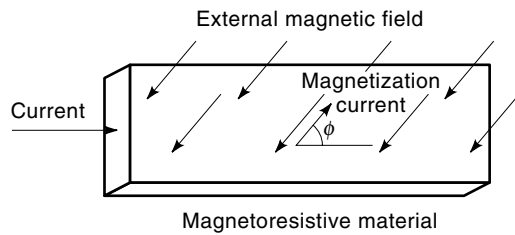


Figure 18. A magnetoresistive sensor's resistance changes in response to an external magnetic field. Magnetic domain orientation of the material is a function of external field and current flowing through it. The resistance is highest when the magnetization is parallel to the current and lowest when it is perpendicular to the current. These sensors are manufactured as thin films, and they have good linearity.

external field perpendicular to the current, as illustrated in Fig. 18, causes the magnetic orientation to be disturbed. The resistance is highest when the magnetization is parallel to the current and lowest when it is perpendicular to the current. Hence, depending on the intensity of the external magnetic field, the resistance of the permalloy changes in proportion.

Magnetoresistive sensors are manufactured as thin films and usually integrated to be part of an appropriate bridge circuit. They have good linearity and low temperature coefficients. These devices have a sensitivity ranging from $1 \mu\text{T}$ to 50 mT . By improved electronics with suitable feedback circuits, the sensitivity can be as low as 100 pT . They can operate from dc to several gigahertz.

Magnetotransistor and Magnetodiode Sensors

Magnetotransistor and magnetodiode sensors are integrated silicon devices. They contain n -doped and p -doped regions forming pn , nnp , or pnp junctions. In the case of magnetotransistors, there are two collectors, as shown in Fig. 19. Depending on the direction, an external magnetic field deflects electron flow between emitter and collector in favor of one of the collectors. The two collector voltages are sensed and related to the applied magnetic field. These devices are more sensitive than Hall-effect sensors.

In the case of magnetodiodes, p and n regions are separated by an area of undoped silicon containing the sensor. An external magnetic field perpendicular to the flow of charges deflects the holes and electrons in the opposite directions, re-

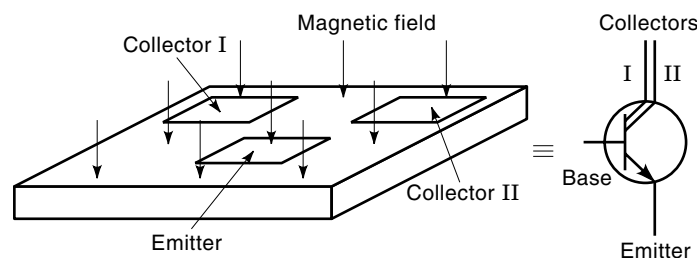


Figure 19. A magnetotransistor is an integrated silicon device that contains nnp or pnp junctions. The electron flow between emitter and collector is influenced by the external magnetic field in favor of one of the collectors. The two collector voltages are sensed and related to the applied magnetic field.

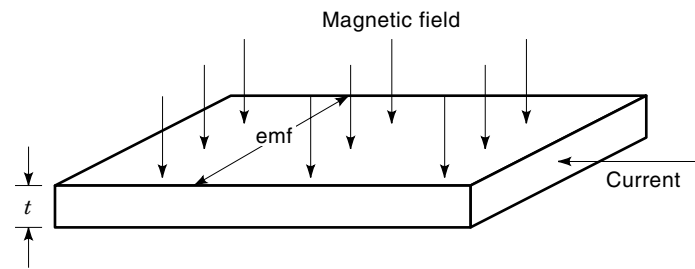


Figure 20. A Hall-effect sensor makes use of Lorentz force. The response of electrons to Lorentz force creates the Hall voltage, which is perpendicular to both the external magnetic field and the direction of current flow. If the current is dc, the voltage has the same frequency as magnetic flux.

sulting effectively in a change in the resistance of the undoped silicon layer.

HALL-EFFECT SENSORS

In Hall-effect sensors, the voltage difference across a thin conductor carrying current depends on the intensity of the magnetic field applied perpendicular to the direction of current flow, as shown in Fig. 20. An electron moving through a magnetic field experiences Lorentz force perpendicular to the direction of motion and to the direction of the field. The response of electrons to Lorentz force creates a voltage known as the Hall voltage. If a current I flows through the sensor, the Hall voltage can mathematically be found by

$$V = R_H IB/t \quad (22)$$

where R_H is the Hall coefficient (cubic meters per degree Celsius), B is the flux density (tesla), and t is the thickness of the sensor (meters).

Therefore, for a specified current and temperature, the voltage is proportional to B . If the current is dc, the voltage has the same frequency as magnetic flux.

Hall-effect sensors can be made by using metals or silicon, but they are generally made from semiconductors with high electron mobility such as indium antimonide. They are usually manufactured in the form of probes with a sensitivity down to $100 \mu\text{T}$. Silicon Hall-effect sensors can measure constant or varying magnetic flux having an operational frequency from dc to 1 MHz , within the range of 1 mT to 100 mT . They have good temperature characteristics from 200°C to near absolute zero.

MAGNETO-OPTICAL SENSORS

In recent years, highly sensitive magneto-optical sensors have been developed. These sensors are based on fiber-optics, polarization of light, Moire effect, and Zeeman effect, among others. This type of sensors leads to highly sensitive devices and is used in applications requiring high resolution such as human brain function mapping and magnetic anomaly detection. Here, because of the availability of space, only the polarization effect will be discussed briefly. Interested readers can find further information in the Refs. 1–6.

In the polarization effect, a plane of polarized light in a strong magnetic field rotates its plane of vibration. The per-unit angular rotation is related to the per-unit magnetic field in a given length of material by the Verdet constant. For example, terbium gallium demonstrates a Verdet constant of 50 $\text{min}/\mu\text{T}\cdot\text{cm}$, whereas bismuth-substituted iron garnet can have up to 0.04 $\text{min}/\text{T}\cdot\text{cm}$. This polarization effect was first noticed by Faraday in 1845; hence, it is generally known as the Faraday effect. Recently, this principle was applied to semiconductors and crystals, which have different physical properties such as interband effects, intraband free carrier effects, and absorption of magnetism by impurities.

MAGNETIC THIN FILMS

Magnetic thin films are an important part of superconducting instrumentation, sensors and electronics in which active devices are made from deposited films. The thin films are usually made from amorphous alloys, amorphous gallium, and the like. As an example of this use of thin-film technology, a thin-film Josephson junction is given in Fig. 21. The deposition of thin films can be done by thermal evaporation, electroplating, sputter deposition, or chemical methods. The choice of technology depends on the characteristics of the sensors. For example, thin-film superconductors require low-temperature operations, whereas common semiconductors operate at room temperature.

The magnetic thin films find extensive applications in memory devices where high density and good sensitivities are required. In such applications, the magnetic properties of the coating are determined by the magnetic properties of the particles that can be controlled before coating. The choice of available materials for this purpose is extremely large. Thin-film technology is also developed in magneto-optics applications where erasable optical media for high-density magnetic storage is possible. The miniature magnetoresistive sensors for magnetic recording and pick-up heads, the Hall-effect sensors, and other magnetic semiconductors make use of thin-film technology extensively.

AMORPHOUS MAGNETIC MATERIALS

The amorphous magnetic materials can be classified as amorphous alloys (Fe, Co, Ni), amorphous rare earths, and amor-

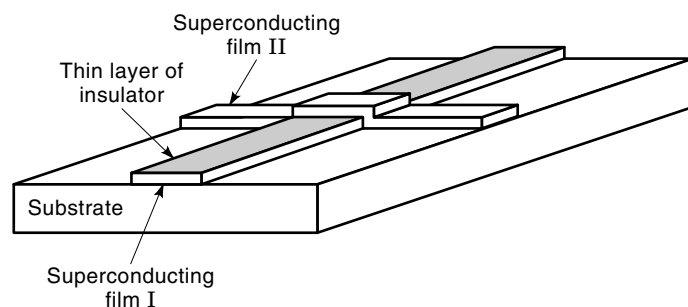


Figure 21. The magnetic thin films are made from deposited thin films from amorphous alloys such as gallium. This figure illustrates thin-film technology to form a Josephson. The deposition of thin films can be done by thermal evaporation, electroplating, sputter deposition, or chemical methods.

phous superconductors. Amorphous alloys have good soft magnetic materials and are extensively used in magnetic heads. They have high-saturation magnetization, high permeability, and flat high-frequency dependence. Amorphous alloys are produced in the form of 20 μm to 50 μm thick ribbons using rapid solidification methods. Nevertheless, thermal stability of these alloys is the major drawback preventing the wider applications of these materials. Many of the amorphous metallic films are based on rare earth 3D transition metal alloys, such as Gd_xCo_x . They are used in bubble domain devices.

On the other hand, the amorphous superconductors are a class of superconducting materials such as bismuth and gallium. They are manufactured in the form of powders, ribbons, or flakes by using evaporation methods, ion mixing or ion implantation, or liquid quenching. The vapor deposition technique is used in semiconductor-type sensors. These materials are used in high field magnets, memory devices, and other computer applications.

SHIELDING AND SENSITIVITY TO ELECTROMAGNETIC INTERFERENCE

Magnetic fields are produced by currents in wires and more strongly by the coils. The fields produced by coils are important as a result of magnetic coupling, particularly when there are two or more coils in the circuit. The magnetic coupling between coils may be controlled by large spacing between coils, the orientation of coils, the shape of the coils, and shielding.

Inductive sensors come in different shapes and sizes. Even though some sensors have closed cores such as toroidal shapes, others have open cores and air gaps between cores and coils. Closed cores may have practically zero external fields, except small leakage fluxes. Even if the sensors do not have closed cores, most variable-inductor sensors have a rather limited external field, as a result of two neighboring sets of coils connected in opposite directions, thus minimizing the external fields. Because the inductive sensors are made from closed conductors, a current will flow, if the conductor moves in a magnetic field. Alternatively, a magnetic change produces current in stationary closed conductor. Unless adequate measures are taken, there may be external magnetic fields linking (interference) with the sensor coils, thus producing currents and unwanted responses.

Because of inherent operations, inductive sensors are designed to have a high sensitivity to magnetic flux changes. External electromagnetic interference and external fields can affect the performance of the sensors seriously. It is known that moderate magnetic fields are found near power transformers, electrical motors, and power lines. These small fields produce current in the inductive sensors elements. One way of eliminating external effects is accomplished by magnetic shielding of the sensors and by grounding appropriately. In magnetic shielding, one or more shells of high-permeability magnetic materials surround the part to be shielded. Multiple shells may be used to obtain a very complete shielding. Ends of each individual shell are separated by insulation so that the shell does not act as a single shorted turn, thus accommodating high current flows. Similarly, in the case of multiple shielding, shells are isolated from each other by proper insulation.

Alternating magnetic fields are also screened by interposing highly conductive metal sheets such as copper or aluminium on the path of the magnetic flux. The eddy currents induced in the shield give a counter mmf that tends to cancel the interfering magnetic field. This type of shielding is particularly effective at high frequencies. Nevertheless, appropriate grounding must be observed.

In many inductive sensors, stray capacitances may be a problem, especially at null position of the moving core. If the capacitive effect is greater than a certain value, say 1% of the full-scale output, this effect may be reduced by the use of a center-tapped supply and appropriate grounding.

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