

21

Sensors

21.1	Introduction	21-1
21.2	Distance and Displacement Sensors	21-1
	Sensors for Large Distances • Sensors for Medium Distances • Sensors for Small Distances	
21.3	Pressure Sensors.....	21-5
	Piezoresistive Pressure Sensors • Capacitive Pressure Sensors • Piezoelectric Pressure Sensors	
21.4	Accelerometer.....	21-7
	Piezoelectric Accelerometer • Piezoresistive Accelerometer • Capacitance Accelerometer	
21.5	Temperature Sensors.....	21-9
	Thermistor • Thermocouple • IC Temperature Sensors	
21.6	Radiation Sensors	21-10
	Bolometer • Photon Detectors • Photoresistor • Photodiode • Photomultiplier	
21.7	Magnetic Field Sensors	21-14
	Induction Coil Sensors • Hall Effect Sensors • Fluxgate Sensors • Magnetoresistive Sensors	
21.8	Sensorless Control System.....	21-16
	References.....	21-17

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21.1 Introduction

A sensor is a device that provides an electrical output responding to a stimulation of a nonelectrical signal. It converts a physical parameter into a signal suitable for processing. Sensors are widely used in various places such as automobiles, airplanes, radios, and countless other applications. In this chapter, various types of sensors for measuring different physical parameters are described.

21.2 Distance and Displacement Sensors

In a control system, displacement or distance is an important parameter to be measured. Depending on the distance range, various types of sensors are used.

21.2.1 Sensors for Large Distances

The most popular sensors for large distance measurement are optical sensors [01ABLMR]. An optical sensor usually requires at least three essential components: a light source, a photodetector, and light guidance devices, which may include lenses, mirrors, optical fiber, etc. In a basic optical position sensor, light is guided toward a target by focusing lenses and it is diverted back to detectors by the reflector.

The time cost for the light traveling through the target and back to the receiver is proportional to the distance. These sensors are used for sensing distances from hundreds of meters to thousands of meters.

Laser triangulation sensors are specially designed optical sensors for more precision position measurements over short and long ranges. As shown in Figure 21.1, the position of the target is determined by measuring reflection from the target surface. A laser diode projects a spot of light to the target, and its reflection is focused via an optical lens on a light-sensitive array. If the target changes its position, the position of the reflected spot of light on the detector changes as well. The most critical element in this arrangement is the receiver/detector. It is commonly a charge-coupled device (CCD). The CCD is registering bright on pixel array and then reading it by transferring information across array. The intensity distribution of the imaged spot is viewed, and then image processing is incorporated for the linear triangulation measurement.

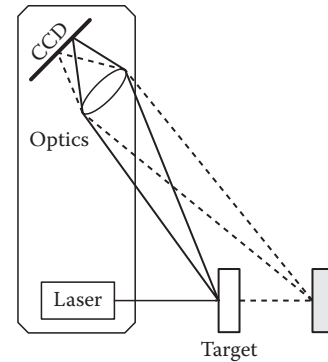


FIGURE 21.1 Laser distance sensor using triangulation principle.

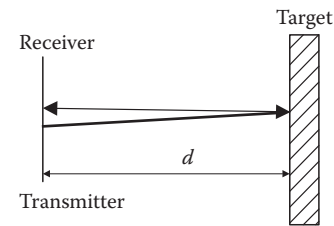


FIGURE 21.2 Schematic structure of ultrasonic distance sensor.

21.2.2 Sensors for Medium Distances

Ultrasonic distance sensors measure the traveling of ultrasonic pulse. The schematic structure of an ultrasonic distance sensor is shown in Figure 21.2. When the waves are incident on the target, part of their energy is reflected in a diffuse manner. A distance d to the target can be calculated though the speed v of the ultrasonic waves in the media:

$$d = \frac{vt}{2} \quad (21.1)$$

where t is the time cost for the ultrasonic waves traveling from the source to the target and back to the receiver. To generate the ultrasonic, piezoelectric materials are used. Ultrasonic sensors are used for distance ranging from several centimeters up to a few meters.

Another displacement sensor is linear variable differential transformer (LVDT). The transformer comprises three coils: a primary center coil and two outer secondary coils. The transfer of current between the primary and the secondary coils of the transducer depends on the position of a magnetic core shown in Figure 21.3. At the center of the position measurement stroke, the two secondary voltages of the displacement transducer are equal; since they are connected oppositely, the output from the sensor is zero. As the core moves away from the center, the result is an increase position sensor in one of the secondary coils and a decrease in the other, which results in an output from the measurement sensor. The LVDT is used to measure displacement ranging from fractions of a millimeter to several centimeters. They can be manufactured to meet stringent accuracy and resolution requirements, for example, accuracy better than 0.2%.

21.2.3 Sensors for Small Distances

Capacitive position sensors are based on the principle that the capacitance between two plates is proportional to the area A and inversely proportional to the distance d between them:

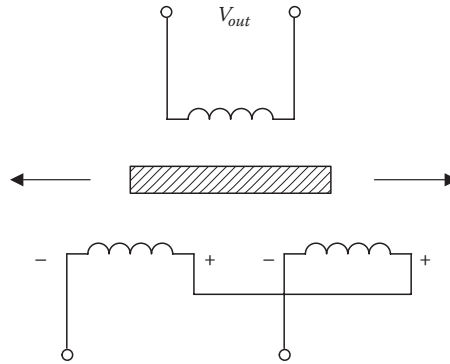


FIGURE 21.3 Structure of LVDT variation.

$$C = \frac{A\epsilon_0\epsilon_r}{d} \quad (21.2)$$

where

ϵ_r is the electric permittivity of the material

ϵ_0 is the electric permittivity of the vacuum

In capacitive position sensors, one plate of a capacitor is the base and fixed, while the other plate is movable [97B]. The capacitance position sensor can operate over a range of a few millimeters, but it is sensitive to temperature and humidity, especially if the dielectric is air.

There are two fundamental types of capacitive position sensors: spacing and area variations as shown in Figure 21.4.

In the first type of sensor (Figure 21.4a), distance between two plates are being measured. The capacitance is inversely proportional to the distance between plates. This relationship is nonlinear. However, if the circuit in Figure 21.5 is used for measurement, the nonlinear relationship can be eliminated. In this circuit, the output voltage is calculated by

$$V_{out} = -\frac{1/sC_2}{1/sC_1} V_{in} = -\frac{C_1}{C_2} V_{in} = -C_1 V_{in} \frac{d}{A\epsilon_r\epsilon_0} \quad (21.3)$$

The nonlinear dependence on d (see Equation 21.2) can be transferred to linear sensor using this method.

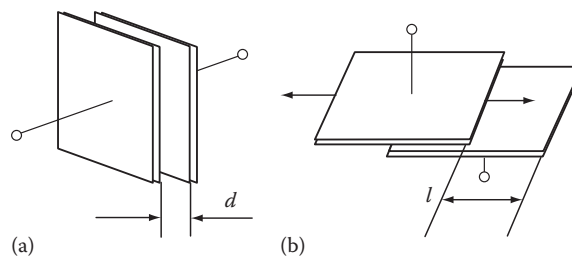


FIGURE 21.4 Two types of capacitive position sensors: (a) spacing variation and (b) area.

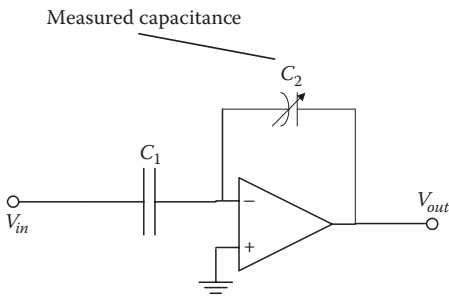


FIGURE 21.5 Circuit of linear spacing variation capacitive distance sensor.

For larger distances, the area variation (Figure 21.4b) is preferred. As the plates slide transversely, the capacitance of the area variation changes as a linear function of sliding length.

For small and medium distances, the grating displacement sensor can be used as shown in Figure 21.6. Grating capacitive displacement sensor, which is based on the principle resembling that of caliper, is used for precision displacement measurement [96PST]. The sensor is fabricated with two overlapping gratings with slightly different pitch, which serve as a capacitive modulator. One grating is fixed while the other is movable. When the opaque sector of the moving grating is maximum aligned with the transmitting sector, the overlapping area is the least (Figure 21.6a). The overlapping area is periodic variable as shown in Figure 21.7, which induces the capacitive modulated. The displacement of the moving grating can be obtained by calculating the number of hanging periods of the capacitive. For high

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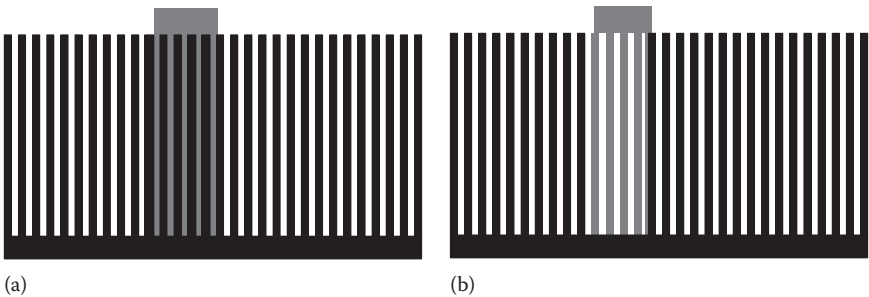


FIGURE 21.6 Grating type displacement sensor: (a) minimum capacitance area and (b) maximum capacitance area.

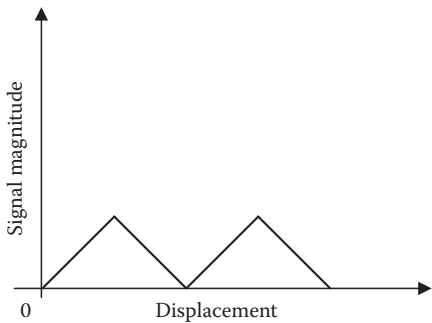


FIGURE 21.7 Transfer function of grating type displacement sensor.

sensitivity, the grating pitch can be made very small, so that very short movements of the grating will result in a large output signal.

21.3 Pressure Sensors

Pressure sensors are the devices used to measure pressure. They can be used to measure the flow of liquid, the weight or force exerted by one object on another, atmospheric pressure, and anything else involving force [97N]. Many modern pressure sensors are much more sensitive than scales, and give an accurate output that can be measured electronically.

21.3.1 Piezoresistive Pressure Sensors

Piezoresistivity is a material property where bulk resistivity is influenced by mechanical stress applied to material. The common piezoresistors can be silicon, poly silicon, silicon dioxide, zinc oxide, etc.

A piezoresistive pressure sensor consists of a thin silicon membrane supported by a thick silicon rim as shown in Figure 21.8a and b. The diaphragm acts as a mechanical stress amplifier. When a pressure difference is applied across the device, the thin diaphragm will bend downward or upward, indicating traction or compression on the piezoresistors. The resistance change caused by this stress can be measured by Wheatstone bridge (Figure 21.8c).

Figure 21.8c shows the four piezoresistors connected in the Wheatstone bridge configuration. By placing one piezoresistor parallel to two edges of the diaphragm and the other perpendicular to the other two edges, the resistance change of the two piezoresistors will always be opposite. When the diaphragm is bent downward, causing the tensile stress on the diaphragm surface at the edges, the parallel resistors are under lateral stress and show a decrease in resistance while the perpendicular ones are under longitudinal stress and show an increase in resistance. The applied stress is proportional to the change of resistance, which is precisely measured.

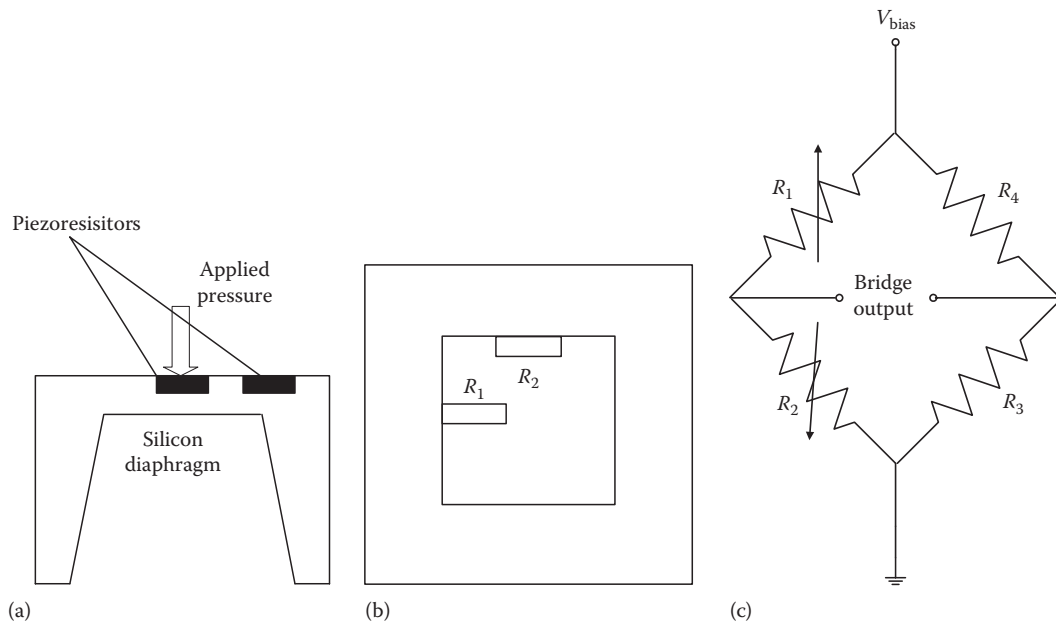


FIGURE 21.8 Piezoresistive pressure sensors: (a) cross section, (b) top view, and (c) Wheatstone bridge.

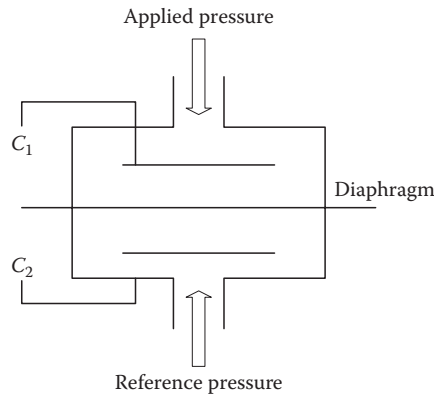


FIGURE 21.9 Schematic of a capacitive pressure sensor.

21.3.2 Capacitive Pressure Sensors

The capacitive pressure sensors use capacitance sensitive components to transform the pressures to electrical signals. The structure of a capacitive pressure sensor is shown in Figure 21.9. A diaphragm is suspended between two parallel metallic plates so as to form two capacitances C_1 and C_2 . The capacitances of C_1 and C_2 will be changed if the diaphragm is deflected due to a pressure difference between its two sides. This type of sensor is mostly used to measure small changes of a fairly low static pressure. The capacitive pressure sensor is more sensitive and less temperature dependent than piezoresistive sensor.

21.3.3 Piezoelectric Pressure Sensors

A piezoelectric pressure sensor is a device that uses the piezoelectric effect to measure force by converting it to an electrical signal [00SC]. The scheme of piezoelectric pressure sensor is shown in Figure 21.10. The pressure is applied on the piezoelectric material and makes it deformed, so as to generate charge. The circuit part in Figure 21.10 converts the input current into voltage. Therefore, the pressure can be calculated by measuring output voltage. The electrical signal generated by the piezoelectric material decays rapidly after the application of force. This makes these devices unsuitable for the detection of static force. Depending on the application requirements, dynamic force can be measured as either compression, tensile, or torque force.

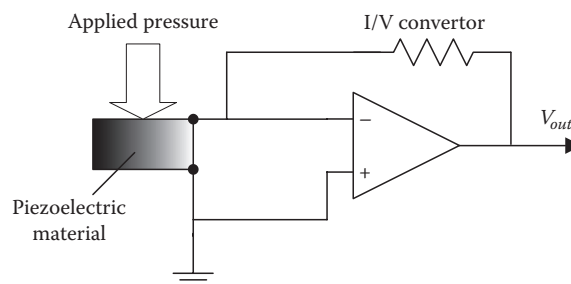


FIGURE 21.10 Scheme of piezoelectric pressure sensor.

21.4 Accelerometer

An accelerometer is an electromechanical device that will measure acceleration forces. These forces may be static or dynamic. The accelerometer has been used in engineering, building and structural monitoring, medical application, etc. An accelerometer requires a component whose movement lags behind that of the accelerometer's housing, which is coupled to the object under study. This component is usually called inertial mass. No matter how the sensors are designed or what is the conversion technique, an ultimate goal of the measurement is the detection of the mass displacement with respect to the housing. Hence, any suitable displacement sensor capable of measuring microscopic movements under strong vibrations or linear acceleration can be used as an accelerometer.

21.4.1 Piezoelectric Accelerometer

Piezoelectric accelerometer utilizes the piezoelectric effect of materials to measure dynamic changes in mechanical variables. The structure of piezoelectric accelerometer is shown in Figure 21.11. When a physical force is exerted on the accelerometer, the seismic mass loads the piezoelectric element according to Newton's second law of motion ($F = ma$). The force exerted on the piezoelectric material can be observed corresponding to the change of the voltage generated by the piezoelectric material. Therefore, the acceleration can be obtained. Single crystal, like quartz, and ceramic piezoelectric materials, such as barium titanate and lead-zirconate-lead-titanate, can be used for the purposes of accelerometer. These sensors are suitable from frequency as low as 2 Hz and up to about 5 kHz. They possess high linearity and a wide operating temperature range.

21.4.2 Piezoresistive Accelerometer

The structure of piezoresistive accelerometer is the same as piezoelectric accelerometer. The piezoelectric material is substituted by a Wheatstone bridge of resistors incorporating one or more legs that change value when strained. The piezoresistive material's resistance value decreases when it is subjected to a compressive force and increases when a tensile force is applied. A seismic mass is fabricated at the center of the sensor die. This mass behaves like a pendulum, responding to acceleration and causing deflection of the diaphragm.

21.4.3 Capacitance Accelerometer

Capacitance accelerometers are usually designed as parallel-plate air-gap capacitors in which motion is perpendicular to the plates. The sensor of a typical capacitance accelerometer is constructed of three silicon elements bonded together to form a hermetically sealed assembly shown in Figure 21.12a. Two of

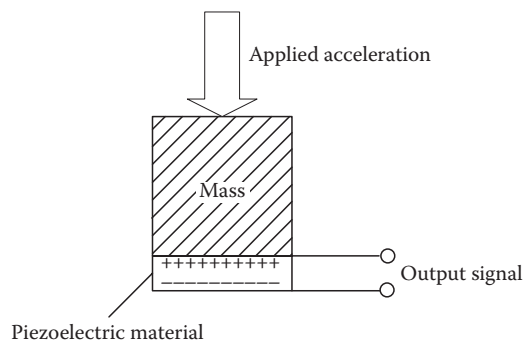


FIGURE 21.11 Structure of piezoelectric accelerometer.

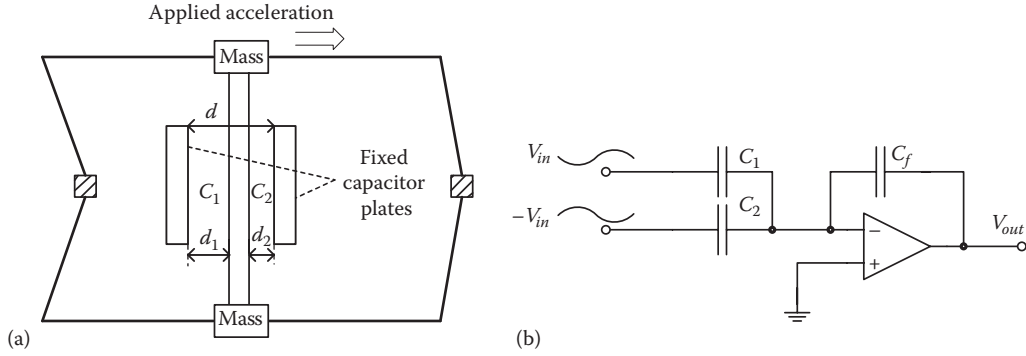


FIGURE 21.12 Capacitance accelerometer: (a) structure and (b) circuit.

the elements are the electrodes of an air dielectric, parallel-plate capacitor. The middle element is a rigid central mass. Changes in capacitance due to acceleration are sensed by a pair of current detectors that convert the changes into voltage output.

Using the circuit in Figure 21.12b, the relationship between output voltage and capacitance change can be described as

$$V_{out} = \frac{C_2 - C_1}{C_f} V_{in} \quad (21.4)$$

By combining Equations 21.2 and 21.4,

$$V_{out} = \frac{A\epsilon_0\epsilon_r}{C_f} V_m \left(\frac{1}{d_2} - \frac{1}{d_1} \right) \quad (21.5)$$

With the Newton's second law, it can be obtained that

$$\frac{d_1 - d_2}{2} = \frac{at^2}{2} \quad (21.6)$$

where

t is the time cost for changing

a is the accelerator

Since

$$d_1 + d_2 = d \quad (21.7)$$

where d is the distance between the two fixed capacitor plates.

By combining Equations 21.6 and 21.7, the accelerator can be calculated as

$$a = \frac{\sqrt{4 + \left(V_{out}/V_{in} \right)^2 \left(C_f^2 d^2 / A^2 \epsilon_r^2 \epsilon_0^2 \right)} - 2}{(V_{out}/V_{in})(C_f/A\epsilon_r\epsilon_0)t^2} \quad (21.8)$$

21.5 Temperature Sensors

The temperature of electronic systems needs to be measured at regular intervals. The temperature testing must be interpreted and processed properly, so that actions can be taken to counteract the unwanted temperature change. There are an abundance of applications where temperature must be monitored and controlled. Many devices have been developed to match the widely varying technical and economic requirements, including thermistor, thermocouple, and integrated circuit (IC) temperature sensors.

21.5.1 Thermistor

Thermistors are special solid temperature sensors that behave like temperature-sensitive electrical resistors that are fabricated in forms of droplets, bars, cylinders, rectangular flakes, and thick films. There are basically two types: negative temperature coefficient (NTC) thermistors, used mostly in temperature sensing; and positive temperature coefficient (PTC) thermistors, used mostly in electrical current control.

The resistances of the NTC thermistors decrease with the increase of temperature. They are composed of metal oxides. The most commonly used oxides are those of manganese, nickel, cobalt, iron, copper, and titanium. The relationship between the resistance and temperature is highly nonlinear. The most popular equation is the exponential form

$$R_t = R_{t_0} \exp \left(\beta \left(\frac{1}{T} - \frac{1}{T_0} \right) \right) \quad (21.9)$$

where

T_0 is the calibrating temperature

R_{t_0} is the resistance at calibrating temperature

β is a material's characteristic temperature

The NTC α can be found by

$$\alpha = \frac{1}{R} \frac{\partial R}{\partial T} = -\frac{\beta}{T^2} \quad (21.10)$$

One may notice that NTC thermistors depend on both β and T . An NTC thermistor is much more sensitive at lower temperatures and its sensitivity drops fast with a temperature increase. In the reality, β is not constant and depends on temperature. The sensitivity α varies over the temperature range from 2% to 8%/°C, which implies that this is a very sensitive device.

PTC thermistors are generally made by introducing small quantities of semiconducting material into a polycrystalline ceramic, usually barium titanate or solid solutions of barium and strontium titanate. These ceramic PTC materials in a certain temperature range are characterized by very large temperature dependence. Above the Curie temperature of a composite material, the ferroelectric properties change rapidly, resulting in a rise in resistance. The coefficient changes vary significantly with temperature and may be as large as 2/°C.

Thermistors have high sensitivity and accuracy, and fast response. However, they have limited temperature range and a nonlinear resistance–temperature relationship. Errors may also be generated from self excitation currents being dissipated by the thermistors.

21.5.2 Thermocouple

Thermocouples operate under the principle of Seebeck. Thermocouples for practical measurement of temperature are junctions of specific alloys that have a predictable and repeatable relationship between

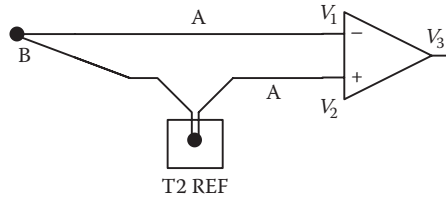


FIGURE 21.13 The structure of thermocouple.

temperature and voltage. The typical structure of thermocouple is shown in Figure 21.13. The Seebeck voltage developed by the two junctions is $V_1 - V_2$. Absolute temperature measurements can be made once one of the junctions is held at a known temperature, or an electronic reference junction is used. The three most common thermocouple materials for moderate temperatures are Iron-Constantan (Type J), Copper-Constantan (Type T), and Chromel-Alumel (Type K).

Thermocouple can be made in very tough designs; they are very simple in operation and measure temperature at a point. Over different types, they cover from -250°C to $+2500^\circ\text{C}$.

21.5.3 IC Temperature Sensors

IC temperature sensors employ the principle that a bipolar junction transistor (BJT)'s base-emitter voltage to collector current varies with temperature:

$$V_{BE} = \frac{kT}{q} \ln \left(\frac{I_{CE}}{I_S} \right) \quad (21.11)$$

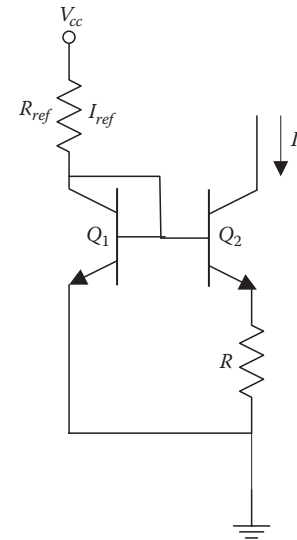


FIGURE 21.14 Circuit of silicon temperature sensor.

Figure 21.14 shows an example of a circuit utilizing this principle. If currents in a fixed ratio or equal currents flow through one transistor and a set of N identical paralleled transistors, the current change can be calculated by

$$I = \frac{\Delta V_{BE}}{R} = \frac{(kT/q) \ln(I_{ref}/I_S) - (kT/q) \ln(I/I_S)}{R} = \frac{kT}{qR} \ln \left(\frac{I_{ref}}{I} \right) \quad (21.12)$$

One may notice that the current change I is proportional to absolute temperature.

The fundamental design of IC temperature sensor results from the diode and silicon temperature sensor [02FL]. The use of IC temperature sensors is limited to applications where the temperature is within a -55°C – 150°C range. The measurement range of IC temperature sensors is small compared to that of thermocouples, but they have several advantages: they are small, accurate, and inexpensive, and are easy to interface with other devices such as amplifiers, regulators, DSPs, and microcontrollers.

21.6 Radiation Sensors

Radiation sensors convert incident radiant signals into standard electrical output signals. Radiation, which can be classified by their frequency from low to high, is microwave, infrared, visible, and ultraviolet radiation, respectively. The common source of radiation can be thermal radiation, which includes

the solar, earth, atmosphere, human body, incandescent, gas-discharge light source, solid-state laser, and semiconductor light source. There are mainly two fundamental detectors for radiation detecting: bolometer and photon detector.

21.6.1 Bolometer

A bolometer is a device that heats up by absorbing radiation. The change in temperature is sensed in some way, resulting in the signal. It can be used to measure the energy of incident electromagnetic radiation. There are two fundamental components in the bolometer: a sensitive thermometer and high cross-section absorber. Both thermometer and absorber are connected by a weak thermal link to a heat sink. The incoming energy is converted to heat in the absorber. Then, the temperature increase decays as power in absorber flows out to the heat sink. The temperature increase is proportional to the incoming energy.

There are several types of bolometer due to different sensitive thermometer, such as bulk resistor, diode, and pyroelectric material.

The bolometer uses high thermo-resistance material such as a suitable metal, VO_x , amorphous silicon, and semiconductors. In order to determine the amount of absorbed radiation, the resistor has to be biased by a pulse with its duration limited to tens of microseconds. Otherwise, the bolometer would be damaged by excessive Joule heat dissipated within the bolometer membrane.

A semiconductor diode made of single-crystal silicon has been applied to replace resistive temperature sensor due to its excellent stability and low noise. Diodes as temperature sensors can be operated in various modes, such as constant current or constant voltage either forward biased or reverse biased. The major problem is thermal isolation of a silicon island containing the diode from the substrate required for the bolometer operation. However, the problem could be solved by electrochemical etch stop technique or utilizing silicon-on insulator wafers.

Pyroelectric bolometer is based on a pyroelectric crystal covered by absorbing layer (silver or silver blackened with carbon). Once the radiation is absorbed by pyroelectric bolometer and its temperature rises, the polarization of dipolar domains inside the crystal changes to more chaotic, which results in an electric current flowing across the crystal. The current can be amplified by current-to-voltage converter based on operational amplifier. The amplifier should be placed as close as possible to the detector to reduce the noise. Pyroelectric sensors have a flat response over wide spectral range.

21.6.2 Photon Detectors

In photon detectors, light energy quantum produces free electrons and causes the change of electric signal. The photon must have sufficient energy to exceed some thresholds. The wavelength must be shorter than the cutoff wavelength. Photodiode, photoresistor, and photomultiplier are three typical photon detectors that utilize photoelectric effect.

21.6.3 Photoresistor

Photoresistor is a photoconductive device. It requires a power source as it does not generate resistance because the photoconductive effect is manifested in change in the material's resistance. Figure 21.15 shows a schematic diagram of a photoresistor. In darkness, the resistance of the material is high. Hence, applied voltage V results in small dark current due to temperature effect. When light is incident on the surface, current flows.

Consider an optical beam of power P and frequency ν , which is incident on a photoconductive detector. Taking the probability for excitation of a carrier by an incident photon—the quantum efficiency η , the carrier generation rate is

$$G = \frac{P\eta}{h\nu} \quad (21.13)$$

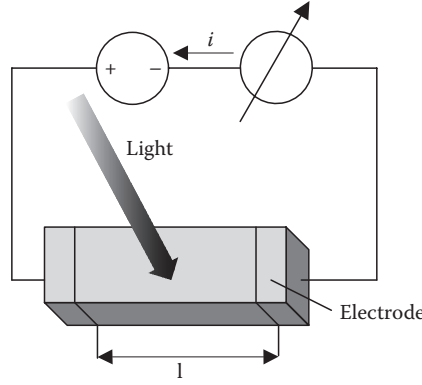


FIGURE 21.15 Schematic diagram of a photoresistor.

If the carriers last on the average seconds τ_0 before recombining, the average number of carriers N_c is found by equating the generation rate to the recombination rate:

$$N_c = G\tau_0 = \frac{P\eta\tau_0}{h\nu} \quad (21.14)$$

To a current in the external circuit,

$$i_e = \frac{e\bar{v}}{l} \quad (21.15)$$

where l is the length of semiconductor.

The total current

$$\bar{i} = N_c i_e = \frac{P\eta\tau_0 e\bar{v}}{h\nu l} = \frac{e\eta}{h\nu} \left(\frac{\tau_0}{\tau_l} \right) P \quad (21.16)$$

where $\tau_l = l/\bar{v}$ is the drift time for a carrier across the length l .

The resistor is obtained by

$$R = \frac{V}{i} = \frac{Vh\nu\tau_l}{e\eta\tau_0 P}$$

where V is the bias voltage. This equation describes the response of a photoconductive detector to a constancy optical flux. It can be seen that

$$R \propto \frac{1}{P} \quad (21.17)$$

It can be shown that for large sensitivity, the carrier life time τ_0 should be larger. Photoresistor has nonlinear responsibility and cannot be used to detect short pulse. In addition, it is very sensitive to temperature variation.

Depending on their spectral responsivity function, photoresistors are divided into photoconductive detectors for the visible wavelength range (such as cadmium sulfide or CdS photoconductive detectors), the near infrared wavelength range (such as lead sulfide or PbS photoconductive detectors), and the

infrared wavelength range (such as silicon doped with arsenide or Si:As photoconductive detectors and the mercury-cadmium-telluride or HgCdTe photoconductive detector).

21.6.4 Photodiode

Photodiode is a type of photodetector device converting light into either current or voltage depending on the mode of operation. When a photon of sufficient energy strikes the diode, it excites an electron, thereby creating a mobile electron and a positively charged electron hole. If the absorption occurs in the junction's depletion region, or one diffusion length away from it, these carriers are swept from the junction by the built-in field of the depletion region. Thus, holes move toward the anode, and electrons toward the cathode, and a photocurrent is produced.

If a p-n junction is forward biased and exposed to light of proper frequency, the current increase will be very small with respect to a dark current. If the junction is reversely biased, the current will increase quite noticeably. Because the increase of the reverse bias can widen the depletion layer, decrease the capacitance, and increase the drift velocity, the efficiency of the direct conversion of optical power into electric power becomes quite low. The p-n photodiode possess 1–3 μm wide depletion layer and is usable for visible light with Si and near infrared light with Ge.

There are two general operating modes for a photodiode: the photoconductive and the photovoltaic.

For photovoltaic mode, no bias voltage is applied. The result is that there is no dark current, so there is only thermal noise present. This allows much better sensitivities at low light levels; however, the speed response is worse due to an increase in internal capacitance. For photoconductive operating mode, a reverse bias voltage is applied to the photodiode. The result is a wider depletion region, lower junction capacitance, lower series resistance, shorter rise time and linear response in photocurrent over a wider range of light intensities. However, as the reverse bias is increased, shot noise increases as well due to increase in a dark current.

In the sensor technologies, an additional high resistivity intrinsic layer is present between p and n types of the material, which is called PIN photodiode. PIN has wider depletion region due to very lightly doped region between a p-type semiconductor and n-type semiconductor. The wide intrinsic region makes the PIN diode largely improve the response time and thus enhance sensitivity for longer wavelengths.

The photodiode directly converts photons into charge carriers. The phototransistors can do the same and provide additional current again, resulting in a much higher sensitivity but slow response. The collector-base junction is a reverse biased diode that functions as described above. If the transistor is connected into a circuit containing a battery, a photoinduced current flows through the loop, which includes the base-emitter region. This current is amplified by the transistor as in a conventional transistor, resulting in a significant increase in the collector current.

21.6.5 Photomultiplier

Photomultiplier tube is a typical photoemissive detector whose structure is shown in Figure 21.16. Photomultipliers are constructed from a glass envelope with a high vacuum inside, which houses a photocathode, several dynodes, and an anode. Incident photons strike the photocathode material with electrons being produced as a consequence of the photoelectric effect. The electron multiplier consists of a number of dynodes. Each dynode is held at a more positive voltage than the previous one. The electrons leave the photocathode, having enough incoming energy. As the electrons move toward the first dynode, they are accelerated by the electric field and arrive with much greater energy. Upon striking the first dynode, more low-energy electrons are emitted, and these electrons in turn are accelerated toward the second dynode. The number of the electrons is multiplied. When the electrons reach the anode, the accumulation of charge results in a sharp current pulse. This current pulse indicates the arrival of a photon at the photocathode.

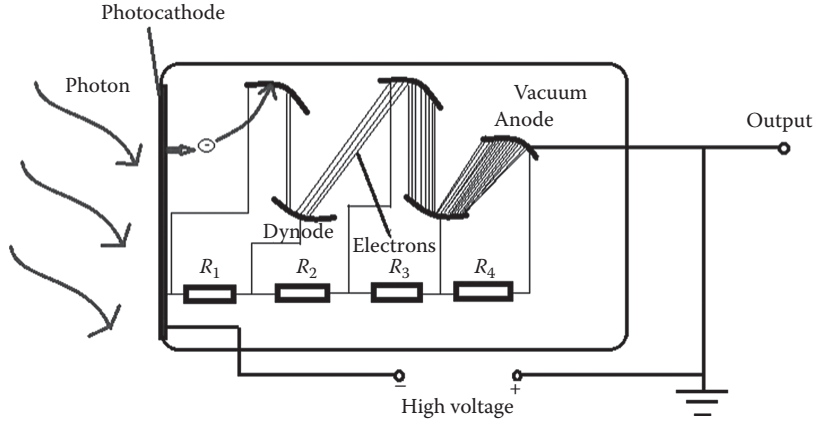


FIGURE 21.16 Structure of photomultiplier tube.

21.7 Magnetic Field Sensors

Magnetic field sensors are used for detecting magnetic field or other physical parameter via magnetic field. Based on their principle, there are four fundamental types of magnetic field sensors: induction coil sensor, Hall effect sensor, fluxgate sensor, and magnetoresistive sensor.

21.7.1 Induction Coil Sensors

The induction coil sensor is one of the oldest and well-known magnetic sensors. Its transfer function results from the fundamental Faraday's law of induction:

$$V = -n \frac{d\Phi}{dt} = -nA \frac{dB}{dt} = -\mu_0 nA \frac{dH}{dt} \quad (21.18)$$

where

- Φ is the magnetic flux passing through a coil with an area A
- n is a number of turns

The output signal V of a coil sensor depends on the rate of change of flux density dB/dt .

In order to improve the sensitivity, the coil should have large number of turns and large active area. The coil sensors are widely used in detecting displacement, magnetic field, etc.

21.7.2 Hall Effect Sensors

The Hall element is another basic magnetic field sensor. When a current-carrying conductor is placed into a magnetic field, a voltage will be generated perpendicular to both the current and the field. This voltage is the Hall voltage and is given by

$$V_{out} = \frac{IB}{qnd} \quad (21.19)$$

where

- d is the thickness of the Hall plate
- n is the carrier density
- q is the charge of the electron

From the above equation, in order to increase the sensitivity of the Hall device, small thickness d and low carrier concentration n are needed.

This principle is known as the Hall effect, which is shown in Figure 21.17. If the current changes direction or the magnetic field changes direction, the polarity of the Hall voltage flips. The Hall effect sensor can be used to measure magnitude and direction of a field. The Hall voltage is a low-level signal on the order of 30 mV/T. Hall effect can also be used for measuring angular displacement, power, etc.

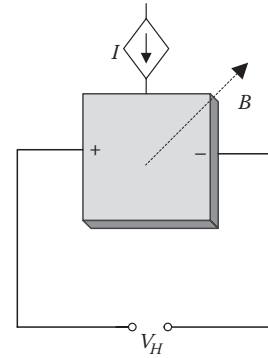


FIGURE 21.17 Principle of Hall effect.

21.7.3 Fluxgate Sensors

Fluxgate sensor is a device measuring the magnitude and direction of the DC or low-frequency AC magnetic field in the range 10^{-10} – 10^{-4} T with 10 pT resolution [92R].

Fluxgate sensor exploits the hysteresis of soft magnetic materials. The basic ring-core fluxgate sensor configuration is shown in Figure 21.18. The core is made of soft magnetic material. Two coils are wrapped around these cores: the drive coil and pick-up coil. The drive coil is thought to be two separate half cores. As the current flows through the drive coil, one half of the core will generate a field in the same direction as external magnetic field and the other will generate a field in the opposite direction. When the external measured magnetic field is present, the hysteresis loop of half of the core is distorted. For some critical value of magnetic field, half of the core in which the excitation and measured fields have the same direction is saturated. At this moment, the magnetic resistance of the circuit rapidly increases and the effective permeability of the other half core decreases. As a result, the other half core comes out in saturation later. There is a net change in flux in the pick-up coil. According to Faraday's law, this net change in flux induces a voltage in the same direction as external magnetic field. Consequently, there are two spikes in voltage for each transition in the drive and the induced voltage is at twice the drive frequency.

21.7.4 Magnetoresistive Sensors

The magnetoresistive effect is the change of the resistivity of a material due to a magnetic field. There are two basic principles of magnetoresistive effect [97M]. The first which is similar to Hall elements is

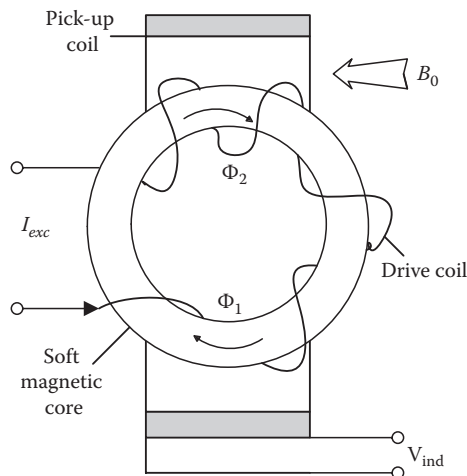


FIGURE 21.18 Ring core fluxgate sensor.

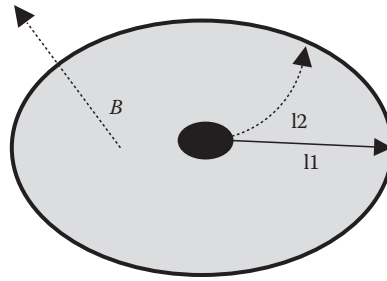


FIGURE 21.19 Scheme of a Corbino ring.

known as the geometrical magnetoresistive effect. The magnetic field forces electrons to take a longer path and thus the resistance of the material increases. A relationship between magnetic field and current is established. The resistance of the device becomes a measure of the field. The relation between field and current is proportional to B^2 for most configurations. It is dependent on carrier mobility in the material used. The Corbino ring shown in Figure 21.19 is a particularly useful configuration for magnetoresistor. Without the magnetic field, the radial current flows in the conducting annulus due to the battery connected between the conductivity rims. When a magnetic field along the axis is turned on, the Lorentz force drives a circular component of current and the resistance between the inner and outer rims goes up. Geometrical magnetoresistor is used in a manner similar to Hall elements or magnetoresistive read heads where Hall elements cannot be used. It is much more sensitive than Hall elements.

The second principle is based on those materials with highly anisotropic properties, such as ferromagnetics, whose resistances are changed in the presence of a magnetic field when a current flows through them. Unlike geometrical magnetoresistor, the effect is due to change of their magnetization direction due to application of the field, thus called anisotropic magnetoresistor. A magnetoresistive material is exposed to the magnetic field to be sensed. A current passes through the magnetoresistive material at the same time. Magnetic field is applied perpendicular to the current. The sample has an internal magnetization vector parallel to the flow of current. When the magnetic field is applied, the internal magnetization changes direction by an angle α . Magnetoresistor offers several advantages as compared with other magnetic sensors. First, their mathematical model is a zero-order system. This differs from inductive sensors in which response depends on the time derivative of magnetic flux density. When compared with Hall effect sensors, which also have a first-order model, magnetoresistor shows increased sensitivity, temperature range, and frequency passband. Magnetoresistor can be used for position sensor, pressure sensor and accelerometer, etc.

21.8 Sensorless Control System

Instead of measuring a parameter that is difficult to measure, other parameters are being measured and the value of this differs to measuring parameters that are evaluated by countless physical effects. The sensorless control system estimates the parameters without using a detector. For example, inductive motor utilizes the sensorless control system to estimate torque, speed, and flux without sensor.

Permanent-magnet synchronous (PMS) motor with high energy permanent magnet materials provides fast dynamics, efficient operation, and very good compatibility. The electric windings of PMS motors are spaced on the armature at regular angles. When excited with current, they each produce magnetic fluxes that add vectorially in space to produce the stator flux vector. By controlling the proportions of currents in the windings, flux magnitude and orientation are determined.

There are two competing control strategies for PMS motors: vector control (VC) and direct torque control (DTC) technology. Sensorless VC is a variable frequency drive (VFD) control strategy that improves motor performance by regulating the VFD output based on a mathematical determination of motor characteristics and operating conditions. Operating conditions are estimated from measurements of

electrical parameters. Both types of VC provide improved performance over the basic control strategy called “V/Hz control.” With the simplest type of V/Hz, control, the drive simply acts as a power supply that provides an adjustable output frequency with output voltage proportional to frequency. To provide the maximum possible motor torque with the minimum possible current, the motor voltage needs to be “fine tuned” to suit the exact motor characteristics and to compensate for changes in those characteristics due to load changes and motor temperature changes.

For DTC, the required measurements for this control technique are only the input currents. The input of the motor controller is the reference speed, which is directly applied by the pedal of the vehicle. The DTC technique is based on the direct stator flux and torque control. The input voltage (v_s) and current (i_s) of the motor on the stationary reference frame can be expressed as

$$v_s = v_{s\alpha} + jv_{s\beta}$$

$$i_s = i_{s\alpha} + ji_{s\beta}$$

The actual stator flux can be estimated from the equivalent circuit of the motor as follows:

$$\Psi_s = \int (v_s - R_s i_s) dt + \Psi_{s0}$$

$$\phi_s = \sqrt{\Psi_{s\alpha}^2 + \Psi_{s\beta}^2}$$

where

Ψ_s is flux vector

Ψ_{s0} is the initial flux vector

ϕ_s is the flux vector rms value

R_s is the stator resistance

The electromagnetic torque of the motor is

$$T_e = \phi_{s\alpha} i_{s\beta} - \phi_{s\beta} i_{s\alpha}$$

The control command for the system is speed. The flux reference can be calculated based on the speed. Below the rated speed, rated flux is used as a reference (constant torque region). Above the rated speed, a relatively large rated flux may imply the need to exceed the supply voltage limits to maintain speed. Therefore, a flux-weakening method generates the flux reference for higher-than-rated speed. The reference flux is selected, proportional to the inverse of the reference speed. The reference torque can be calculated using the difference between reference speed and instantaneous speed.

These inductive motors can be widely used in industries such as oil well diagnosis [00B]. The information from the terminal characteristics of the induction motor could be combined with the fault identification of electrical motors by neural networks. With this approach, the quality of the oil well could be monitored continuously and proper adjustments could be made.

References

- [01ABLMR] M. C. Amann, T. Bosch, M. Lescure, R. Myllylä, M. Rioux, Laser ranging: A critical review of usual techniques for distance measurement. *Optical Engineering*, 40, 10–19, 2001.
- [96PST] O. Parriaux, V. A. Sychugov, A. T. V. Tishchenko, Coupling gratings as waveguide functional elements. *Pure and Applied Optics*, 5, 453–469, 1996.
- [97B] L. K. Baxter, *Capacitive Sensors: Design and Applications*. Institute of Electrical & Electronics Engineering, New York, pp. 61–80, 1997.

- [97M] D. J. Mapps, Magnetoresistive Sensors. *Sensors and Actuators A*, 59, 9–19, 1997.
- [00SC] J. Sirohi, I. Chopra, Fundamental understanding of piezoelectric strain sensors. *Journal of Intelligent Material Systems and Structures*, 11, 246–257, 2000.
- [92R] P. Ripka, Review of fluxgate sensors. *Sensors and Actuators A*, 33, 129–141, 1992.
- [02FL] I. M. Filanovsky, Su Tam Lim, Temperature sensor application of diode-connected MOS transistors. *IEEE International Symposium on Circuits and Systems*, 2, 149–152, 2002.
- [97N] N. T. Nguyen, Micromachined flow sensors—A review. *Flow Measurement and Instrumentation*, 8, 7–16, 1997.
- [00B] B. M. Wilamowski, O. Kaynak, Oil well diagnosis by sensing terminal characteristics of the induction motor, *IEEE Transactions on Industrial Electronics*, 47, 1100–1107, 2000.