ELECTRIC SENSING DEVICES

In a measuring chain or a measuring instrument, the sensor is the element that is directly affected by the measurand (1). Specifically, an electric sensing device converts the quantity to be measured into an electric output signal (generally a voltage) (2). Today electric measurement systems have replaced most nonelectric systems. Only in environments where ionizing radiation or explosive atmospheres are present, nonelectric (mechanical, hydraulic, pneumatic) or optical signals may be more suitable (3). The advantages of using electric sensing devices are numerous and are related above all to the current technology in electrical signal elaboration, recording, and transmission. There are, in fact, even sensors that incorporate integrated circuits for electric signal conditioning or modification in a single package and consequently provide outputs more suitable for the following elements of the measurement chain. Moreover, in the automatic control system where the sensor's outputs have to be elaborated by a numerical processor, it is very easy to convert an analog electric signal to a numerical form.

It is possible to design an electric sensor for measuring any nonelectric quantity. Because of the electronic structure of matter, by selecting appropriate materials, any variation in a nonelectric parameter yields a variation in the electric parameter (3).

Measurand quantities may be grouped on the basis of the form of energy in which the signal is received by the sensor: mechanical, thermal, electrical, magnetic, radiant (optics), or chemical. In Table 1 a limited number of significant examples belonging to each class are reported (4). Often more than one transformation step is required to generate an electric output signal. It is possible to (2) define *primary measurand* quantities directly sensed by electric sensor whereas *secondary measurands* include a combination of primary measurands (5). There are several physical effects that generate electric signals in response to nonelectric influences. It is very difficult to group the countless types of sensing devices. Table 2 gives an interesting summary of the most widely used physical principles of sensing with the electric output and the typical measured quantities (6).

MATERIALS USED FOR SENSING DEVICES

Metals

Metals are characterized by high electric and thermal conductivity, high optic reflectivity, high deformability, plasticity, mechanical tenacity, and high electronic extraction potential. Alloys or intermetallic compounds conserve these qualities to a high degree. Consequently, many sensors operate on the basis of the variation of physical proprieties of pure metals or alloys following variations of external quantities. In general, from the standpoint of sensor design, there are two classes of metals: nonferrous and ferrous. Ferrous metals, like steel, are often used in combination with a magnetic sensor to measure motion, distance, magnetic field strength, etc. Nonferrous metals offer a wide variety of mechanical and electric proprieties but are permeable to magnetic fields and used whenever these fields are not involved. The major use of nonferrous metals is to produce thermoresistances and thermocouples (5). Metals also exhibit piezoresistant effects, but because they are more sensitive to temperature, the production of

Table 1. Examples of Measurand Grouped by Their Domain

Type of Sensor	Physical Quantities
Mechanical	Displacement, length, strain, velocity, acceleration, mass flow, force, torque, pressure
Thermal	Temperature, heat, heat flow, entropy, humidity
Electrical	Voltage, current, power, charge, resistance, inductance, capacitance, dielectric constant, electric field
Magnetic	Field intensity, flux density, magnetic moment, permeability
Radiant	Intensity, phase, wavelength, polarization, reflectance, transmittance, refractive index
Chemical	Composition, concentration, reaction rate, pH, oxidation

Table 2. Physical Principles of Electric Sensing Devices

Physical Principle	Typical Application	Measurand	Output
Resistive The variation if the sensing element electric resistance depends on the measurand.	Thermistor or resistance thermometer	Temperature	Resistance
	Potentiometer	Displacement, force, pressure	Resistance
	Hot-wire anemometer	Flow	Resistance
	Resistive hygrometer	Humidity	Resistance
	Chemioresistor	Presence of gas	Resistance
Capacitive The sensing element capacitance depends on the measurand.	Parallel-plate capacitor sensor	Displacement, force, liquid level, pressure	Capacitance
	Rotary-plate capacitor sensor	Displacement, force, angular position, torque	Capacitance
	Differential capacitor	Small displacement	Capacitance
	Capacitance manometer	Very low pressure	Capacitance
	Humidity sensor	Moisture	Capacitance
	Capacitive diaphragm	Pressure	Capacitance
Inductive The sensing element inductance depends on the measurand.	Linear variable differential transformer	Displacement, torque	Inductance
	Self inductance sensor	Displacement, torque, liquid level	Inductance
	Eddy current sensor	Position, conductivity, thickness, cracks in materials	Inductance
Reluctive The variation in the reluctance path between two or more coils depends on the measurand.	Linear variable differential transformer	Linear displacement	Voltage
	Rotary variable differential transformer	Angular rotation	Voltage
	Microsyn	Angular displacement	Voltage
	Resolver	Position	Voltage
	Syncro	Position, torque	Voltage
	Reluctive diaphragm	Pressure	Reluctance
Piezoresistive effect Resistance of the sensing element depends on the strain.	Strain gauge	Stress, strain, fluid pressure, displacement, force	Resistance
Electromagnetic In any circuit capturing a magnetic flux, whenever the flux changes an electromotive force is induced (Faraday law).	Linear velocity sensor	Linear velocity	Voltage
	Flowmeter	Flow	Voltage
	Tachometer generator	Angular speed	Voltage
	Torque sensor	Torque	Voltage
Superconducting Josephson effect When a superconductor is placed inside a magnetic field, the field is completely expelled from the interior of the superconductor.	RF SQUID	Magnetic field	Voltage
	DC SQUID	Magnetic field	Voltage
Hall effect If the sensing element, carrying current, is put in a magnetic field, a difference in electric potential among its sides is generated.	Gaussmeter	Magnetic field, displacement	Voltage
	Wattmeter	Power	Voltage
Magnetoresistive effect Resistance of the sensing element depends on the strain.	Magnetoresistor	Magnetic field, linear and angular displacement, proximity, position	Resistance
Piezoelectric effect Subjecting the sensing element to stress there is a generation of electric charge.	Vibration cables	Vibration	Voltage or charge
	Active and passive force sensor	Force	Voltage or charge
	Piezoelectric microphone	Ultrasonic waves	Voltage or charge
	Piezoelectric temperature sensor	Temperature	Voltage or charge
Pyroelectric effect The sensing element generates an electric charge in response to heat flow.	Heat flowmeter	Change in the temperature	Voltage
	Pyroelectric sensor		
Thermoelectric effect When there is a difference in temperature between two junctions of different metals, a difference of electric potential is generated.	Thermocouples, thermopiles, infrared pyrometer	Difference of temperature	Voltage
Ionization effect The sensing element when exposed to the measurand becomes ionized.	Electrolytic sensor	Electrical conductivity, pH	Current
	Vacuum gauges	Pressure	Current
	Chemical ionizer	Atomic radiation	Current
Photoresistive The electric resistance of the sensing element is caused by the incidence of optical radiation.	Photoresistor, photodiode, phototransistor, photofet	Light, position, motion, sound flow, force	Resistance
Photovoltaic effect When the sensing element is subject to a radiation it generates an electric potential	Flame photometer	Light intensity	Voltage
	Light detector	Light, position, motion, sound flow, force	
	Pyrometers	Temperature	
Acoustooptic effect The interaction of an optical wave with an acoustic wave produces a new optical wave	Acoustic optic deflection, Bragg cell	Physical vibration	Phase modulated voltage
Doppler effect The apparent frequency of a wave train changes depending on the relative motion between the source of the train and the observer.	Remote sensor of linear velocity, Doppler radar, laser Doppler velocimeter	Relative velocity	Frequency
Thermal radiation An object emits thermal radiation, whose intensity is related to its temperature	Pyrometer	Temperature	Voltage

strain gauges by using metal alloys rather than pure metals is preferred.

When selecting a metal for a sensor design, one must consider its physical proprieties, and also the relative ease of mechanical processing. For example, copper has excellent thermal and electric proprieties, yet is difficult to work with. So in many cases aluminum is considered a compromise alternative (5).

Ceramics

Ceramic oxide materials play an important, steadily increasing role in almost all fields of electronics. In sensor technologies, ceramics are very useful because of their structural strength, thermal stability, light weight, resistance to many chemicals, ability to bond with other materials, and excellent electric properties (5). There are, moreover, abundant opportunities for optimizing performance and tailoring to specific demands by modifying their chemical composition and/or varying their microstructure by changing parameters in manufacturing. There are ceramic materials with piezoelectric, pyroelectric, and ferroelectric proprieties (4).

Glass

Glass is characterized by transparency, hardness, and resistance to most chemicals. The main type of glass used in sensor technologies is lead alkali, which is a good electric insulator and is used for manufacturing optical windows, prisms, and nuclear radiation shields. Furthermore, optical fibers can be realized from glass (5). Optical fiber sensors can be separated into extrinsic and intrinsic types. In extrinsic fiber-optic sensors, sensing process takes place externally to the fiber, and the fiber itself plays a passive role as a light conduit (characterized by a very low attenuation factor). In intrinsic transducers, however, the measurand interacts locally with the light in the fiber by changing a parameter of the fiber, such as the refractive index, and the fiber in turn modulates the light beam propagating through its core (4,7).

Plastics

The most widely used polymers in sensor-related applications are thermoplastic polymers, such as polyester, phenolic, alkyd, allyl, and epoxy (5). These are characterized by high flexibility and stability to mechanical stress and can be formed into any desirable shape. Because plastics are excellent electrical isolators, different methods are used to provide them with electrical conductive properties required for shielding: lamination with metal foil, painting with conductive paint, metallization, mixing plastics with conductive additives, and building composite plastic parts incorporating metal mesh. For example, piezoelectric plastics are realized by poling them either in high voltage or by corona discharge and depositing metal electrodes on both sides of the plastic film.

Furthermore, polymers are used together with glass or alone to produce optical fiber. The plastic fibers (plastic-plastic or plastic-glass) are more commonly used than glass because it is possible to realize fibers with any refractive index.

Semiconductors

There are relatively few types of intrinsic semiconductors. Those made of germanium and gallium arsenide are the most widely used (8). Adding impurities to these materials, forms extrinsic semiconductors, also called doped semiconductors, which are characterized by an increased number of carriers (9). In sensor designs the semiconducting materials (intrinsic and extrinsic) are used both as active materials and as passive materials. In some cases, the sensing element is constituted by the semiconductor itself (active material). The semiconducting materials and, in particular, silicon actually exhibit a great number of physical effects which are quite useful for sensor application, for example, photovoltaic, photoelectric, photoconductive, piezoresistive, magnetoresistant, and ion sensitive. On the other hand, when a semiconducting material does not display the proper effect, it is possible to deposit layers of materials, that have the desired sensitivity on top of the silicon substrate, which provide either a mechanical structure or electrical connection to a sensing device. Silicon, in fact, exhibits very useful mechanical proprieties and is a relatively inert element. Most acids, except hydrofluoric acid, do not affect it, but it is affected by halogens and dilute alkali. The large use of semiconducting materials is also due to the fact that these materials are inexpensive and now are produced and processed in controlled conditions to unparalleled standards of purity and perfection.

SENSOR CHARACTERISTICS

Because sensors provide an interface between the measurement system and the outside world, the choice of a sensor involves evaluating its input-output relationship and also all links with external systems (6). In Fig. 1 the physical systems directly connected to the sensing device are reported, and the information path and interaction between the sensor and the other systems are indicated. Naturally, upstream there is the system to be measured and down stream is the user system. By user system we mean the system to which the sensor provides information. It may of course perform other elaborations on the sensor output. In the environment system all interfering sources are summarized, and an auxiliary system is required to operate the sensor (e.g., for the power supply) (6).

In the following, the most important characteristics of sensors are reported, organized on the basis of the systems to which they are related. The analysis and comparison of these characteristics among different sensors can help the user to choose the most suitable sensor for each particular applica-

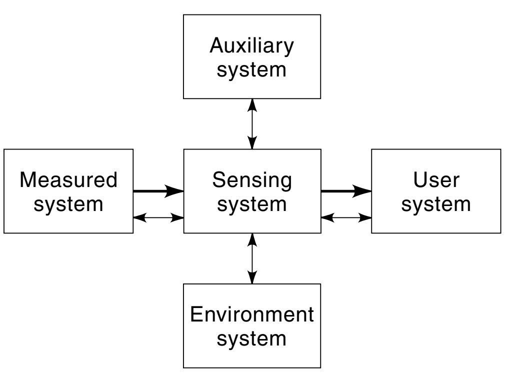

Figure 1. A sensing device and its interactions with the outside world.

tion. Naturally, depending on the application requirements, some characteristics may be more important than others.

Measured System

Input Range, Overload, Overrange. The sensor's nominal range indicates the lower limit and the upper limit values of the measurand between which the sensor is designed to operate. The span refers to the modulus of the difference between the two limits of the nominal range. In some fields, this is called input full scale (FS). (1,2). Often the overload values or the overrange value are also provided. The overload values are the extremes of the safety field of the measurand, whereas the overrange value is the maximum value safety field of the measurand, implying that the minimum coincides with the lower limit of the measured field.

Loading Effects. The introduction of any measuring device into a measured system always results in modifying the characteristics of the measurand, thereby changing its value from its undisturbed state, and thus making a perfect measure theoretically impossible (10). For example, introducing a temperature sensor into a vessel of liquid may change its temperature (7). Consequently, the sensor manufacturer has to indicate the sensor loading effects. In particular, the sensor input impedance indicates the electric loading. In general, to limit the electric loading effects, the input impedance of the sensor must be high compared to the output impedance of the system to which the sensor is connected (10).

Mechanical Coupling. From this viewpoint, sensors can be divided into two very broad categories: contacting sensors and noncontacting sensors (2). These categories indicate whether or not the sensor must be in direct contact with the measurand. Inability to connect suitably may depend on physical requirements (the fingers cannot reach the point of interest or it is impossible to see inside the container holding the measurand) or on safety considerations (the measurand or its environment may be hazardous) (7).

Sensing System

Sensor performance characteristics are generally categorized as static and dynamic. The first describe performance at room conditions with very slow changes in the measurand and without any shock, vibration, or acceleration. The latter are related to the response of the sensor to variations of the measurand with time (11). In most measurement systems the quantity to be measured changes so slowly that it is only necessary to know the static characteristics of sensors. But the same sensor in the same operating conditions can be defined in a static or a dynamic regime according to the accuracy required (3).

Finally it is necessary to emphasize that we regard the sensor as a black box and that we are only concerned with the relationship existing between input and output quantities, even if more than one conversion step is involved from the input to the output.

Static Characteristic

Accuracy, Uncertainty, Bias, Repeatability, Reproducibility. Accuracy indicates the closeness of agreement between the result of a measurement and the value of the measurand (1).

Uncertainty characterizes the dispersion of values that could reasonably be attributed to the measurand. Thus, it expresses the fact that, for a given measurand and a given response to it, there is not one value but an infinite number of values dispersed around the result that are consistent. Even if the uncertainties are small, there is no guarantee that accuracy is high. Thus the uncertainty does not necessarily indicate the likelihood that the sensor response is close to the value of the measurand (12).

The bias of a sensor is the constant error that exists for the full range of its measurements (6).

Repeatability indicates the closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement. These conditions are called repeatability conditions and include the same measurement procedure; the same observer; the same location; and repetition over a short period of time. Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results (1).

Reproducibility is the sensor's ability to indicate identical values of the measurand each time a measurement is made, assuming that all environmental conditions are the same for each measurement. It is defined as the closeness of agreement between the results of measurements of the same measurand carried out under changed conditions of measurement. Changes in conditions may include the principle of measurement; the method of measurement; the observer; and the same location, time, and condition of use. Reproducibility may be expressed quantitatively in terms of the dispersion characteristics of the results, and it is necessary to specify the conditions changed (1).

Response Characteristic, Static Calibration. The response characteristic for a sensing device is the relationship between the input quantity (also called stimulus) and the corresponding output value (also called response) for defined conditions. This relationship may be expressed in the form of a mathematical equation, a numerical table, or a graph. An ideal or theoretical response characteristic exists for every sensor, and if the sensor follows this ideal behavior, its output always represents the value of the stimulus. But because of variations of materials, design errors, manufacturing tolerances, workmanship and other limitations, the real response characteristic rarely coincides with the ideal. Consequently, it is necessary to establish a relationship between the sensor response and the value, with its uncertainty, to be assigned to the measurand. A calibration process helps determine this relationship. This is a test during which known values of the measurand, also called calibration points, are applied to the sensor, and the corresponding output values are recorded. The input is changed very slowly over the entire range, first increasing and then decreasing the measurand and keeping all other influential quantities constant. A single performance of this test is called a calibration cycle. A complete calibration process usually comprises two or more calibration cycles. The choice of the number and location of the calibration points and of the number of calibration cycles is very important because they may affect the achievable accuracy for a given total number of measurements. The sensor responses are suitably fitted against the input values to form the calibration curve (or calibration diagram). On the basis of all of the gath-

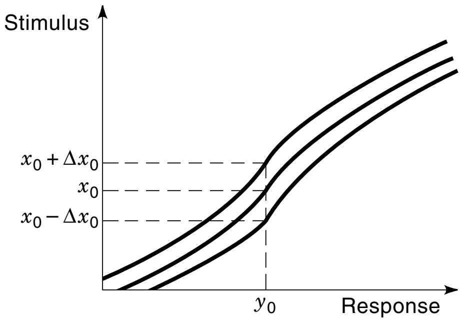

Figure 2. An example of a calibration diagram.

ered calibration points an uncertainty band, which can vary along with any variation of the measurand, can also be added to the calibration curve. The value of measurand (y_0) corresponding to a sensor response (x_0) is obtained as the ordinate of the point of intersection between the calibration curve and the straight line parallel to the ordinate axis passing through x_0. The uncertainty given to the input (Δy_0) is determined by the width of the segment obtained by the intersection of the same line with the uncertainty band (see Fig. 2) (1–4,9,11).

In the calibration process the value of the measurand can be determined by using two different methods: direct comparison and indirect comparison (see Fig. 3). In the first case, a standard generator furnishes a known stimulus to the sensor being calibrated. The values of these stimuli should be at least ten times more accurate than the sensor. In the indirect comparison, the calibration test consists of comparing the calibrating sensor outputs to the outputs of a standard sensor. In this case an approximate level of stimulus source is required, but the time stability and the spatial uniformity of the source must be guaranteed (7).

Sensitivity, Offset, Resolution, Dead Band, Threshold, Saturation

Sensor sensitivity refers to the sensor's ability to generate an output response to a given change in the measurand (1). It is expressed as the change in the response divided by the corresponding change in the stimulus ($\Delta y/\Delta x$). If the response characteristic of the sensor is not a straight line, the sensitivity varies with the value of the stimulus (1,2,10).

Offset is the deviation of the output signal from zero when the input is zero (6).

Resolution is defined as the smallest difference between sensor readings that can be clearly distinguished. In other words it is the minimal change of the input necessary to produce a detectable change at the output. When the output signal is digital, the resolution represents the smallest change in analog input that generates a change of one bit. The resolution is sometimes expressed as a fraction of the maximum input value (1,3,6).

The dead band describes the insensitivity of a sensor in a specific range of the input signal. It is defined as the maximum interval through which a stimulus changes in both directions without producing a change in response. It may depend on the rate of the change. The dead band is sometimes deliberately widened to prevent any change in response for small changes in the stimulus (1,9).

The sensor threshold is the largest change in a null-stimulus that produces no detectable change in the response of the sensor. The threshold may depend, for example, on noise, friction, and also on the value of the stimulus (1).

Almost any sensor has its operating limits. Further increase of the stimulus does not produce an increase (or decrease) of the output, and the sensor goes into a saturation zone.

Linearity. Sometimes, rather than expressing the calibration curve as a numerical table or a graph, its linear approximation is furnished. There are different methods for constructing the line (2,3,11) (see Fig. 4):

Least-Square Linearity. The straight line is defined by the least square criterion. Consequently the sum of the squares of the residuals is minimized. This is the method that usually gives the lowest value of nonlinearity error.

Zero-Based Linearity. The straight line is also defined by the least square but with the additional restriction that it passes through zero.

Theoretical-Slope Linearity. The straight line is referenced to the theoretical line defined in the sensor design phase.

Terminal-Based Linearity. The straight line is defined as the line that passes through the output corresponding to the lower input and the theoretical output when the higher input is applied.

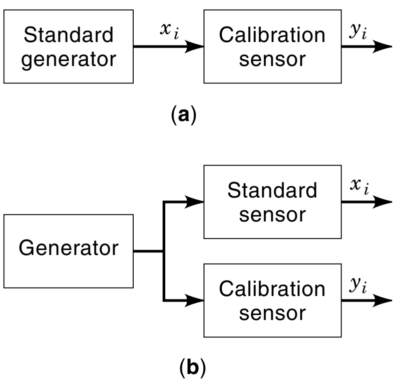

Figure 3. Techniques for calibration: (a) direct comparison; (b) indirect comparison.

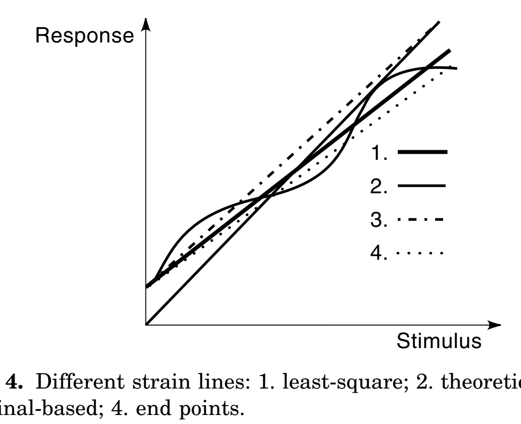

Figure 4. Different strain lines: 1. least-square; 2. theoretical slope; 3. terminal-based; 4. end points.

End-Point Linearity. The straight line is defined by the real output when the upper and lower input range are applied.

The nonlinearity error is defined as the maximum deviation of any calibration point from the corresponding point on a specified straight line. Normally it is defined as a percentage of the output range.

Another term sometimes used is conformance (or conformity), which indicates the closeness of a calibration curve to a specific curve (normally the theoretical curve) for a nonlinear sensor (4,5).

Hysteresis. Hysteresis is the difference between two output values that correspond to the same stimulus depending on the direction (increasing or decreasing) and whether that value is reached. There is a chance that the output corresponding to a given input depends on whether the previous input was higher or lower than the present one. That is similar to the magnetization of ferromagnetic materials (3). Typical causes for hysteresis are friction and structural change in the material of the sensing element. Hysteretic error is defined as the difference between the measured values obtained when the measured quantity is increasing and when decreasing to that value. Hysteresis is usually quantified in terms of the maximum hysteretic error as a percentage of the full-scale output (6,9).

Stability, Creep, Drift, Zero-Shift, Sensitivity Shift. Stability indicates the sensor's ability to maintain constant metrological characteristics in time (1). Short-term stability is manifested as changes in the sensor performance within minutes, hours, or even days. The long-term stability may be related to aging of the sensor materials, which causes an irreversible change in its material proprieties. Aging depends greatly on environmental storage and operating conditions and how well the sensor components are isolated from the environment. Stability may be quantified in several ways, for example, in terms of the time over which a metrological characteristic changes by a stated amount or in terms of the change in a characteristic over a stated time (5).

A sensing device shows drift if there is a gradual change in output over a period of time which is unrelated to any change in input (6).

Zero-shift is a change in the zero measurand over a specific time interval at room conditions. The zero-measurand output is the output of the sensor under room conditions with nominal excitation and zero measurand applied (1).

Sensitivity shift is a change in the sensor's sensitivity over a specific period at room conditions (1).

Dynamic Characteristics. When an input stimulus varies suddenly, the sensor response does not follow this variation with perfect fidelity. The sensor does not respond instantly to the stimulus change. The sensor's dynamic characteristics can be stated in term of speed of response, velocity limit, slew rate, and recovery time (2,5,11). Speed of response indicates how fast the sensor reacts to changes in the output variable. Slew rate is the maximum rate of change with time of the input for which the output can keep up with the change. Recovery time is the time interval necessary after a specified event for the sensor to resume functioning as specified.

For linear sensors other parameters are used to describe the sensor behavior in dynamic conditions. They refer to the time and frequency domains.

Time Domain. The most commonly used dynamic characteristics in the time domain are the step response and the natural response. In response to a step in a measurand, the sensor may have different damping characteristics (see Fig. 5):

- An underdamped sensor oscillates around its final value (y_∞) before coming to rest at that value.
- An overdamped system comes to a final value without overshoot.
- A critically damped system is at the point of change between underdamped and overdamped conditions.

The ratio of the actual damping to the degree of damping required for critical damping is the damping factor. A damping ratio of 1.0 indicates critical damping. Damping ratios larger than 1.0 signify overdamping. Finally, underdamping is indicated by a damping ratio of less than 1.0 (11).

The parameters of an overdamped or critically damped sensor are defined as follows:

Dead time is the time interval between the instant of step application (t_0) and the instant (t_1) in which the response exceeds a threshold value (y_1), usually defined as a percentage of (y_∞).

Response time describes the time that has to elapse before the sensor fully responds to the change. It is defined as the length of time required for the output to rise to a specified percentage of (y_∞) (the percentage is typically 95% or 98%).

A special term has been assigned to 63.2% response time: the time constant (τ).

Having fixed two percentages of the final output value, the rise time is the interval necessary for the output to rise from the smaller percentage to the larger. Unless otherwise specified, the percentages should be assumed to be 10% and 90% of the final value, respectively.

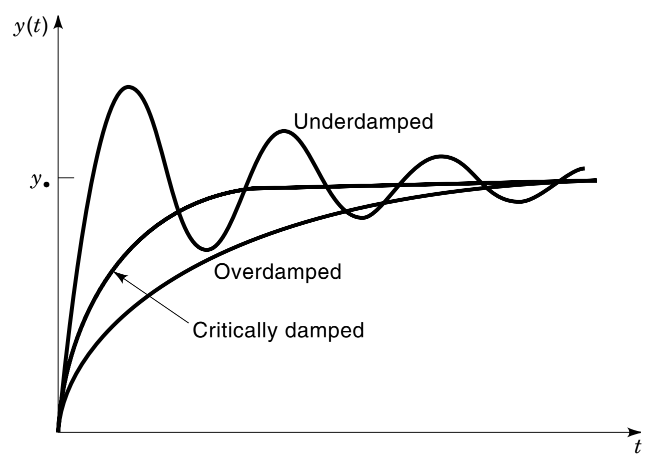

Figure 5. Different damping characteristics.

For underdamped systems other parameters are also used:

The overshoot is the difference between the maximum output value (y_{max}) and y_∞.

After having fixed a value band at around y_∞ (normally it is equal to 5% of y_∞), the settling time is the time interval between t_0 and the instant in which the output remains limited to the previously mentioned band;

The ringing frequency is the damping oscillation frequency.

With reference to natural response, which is the evolution of the sensor output starting from a not null initial value and without measurand, two parameters are defined, the natural frequency and the natural undamped frequency. The natural frequency is the fundamental sinusoidal component of the natural response (14).

Frequency Domain. In the frequency domain a very important dynamic characteristic is the frequency response. It is the change of the amplitude and phase of the output as a function of the frequency of a unit amplitude sinusoidal input. These two curves are, respectively, the module and the phase of the so-called Fourier transfer function [$G(\omega)$] (4). The frequency response is displayed graphically (see Fig. 6) as the plot as a function of the frequency of the sensor amplitude output (amplitude diagram), normally using a logarithmic scale, and of the phase displacement between the input sinusoid and the output sinusoid (phase diagram). Many synthetic parameters describe the frequency response of a system. The bandwidth, also called frequency range, indicates the range of frequencies over which the sensor can be used. It is defined as the range of frequencies for which the transfer function is within a fixed band (normally 3 dB, 70.7%) of its peak value and is defined by the lower and upper cutoff frequencies. The resonant frequency is the frequency corresponding to which the module of the frequency response has a maximum value (6).

Static and Dynamic Compensation Technique. Generally, the sensor calibration curve is nonlinear, but it may be corrected by a suitable static compensation technique. One of the most common methods consists of introducing a compensating nonlinear element in cascade connection to the sensing device.

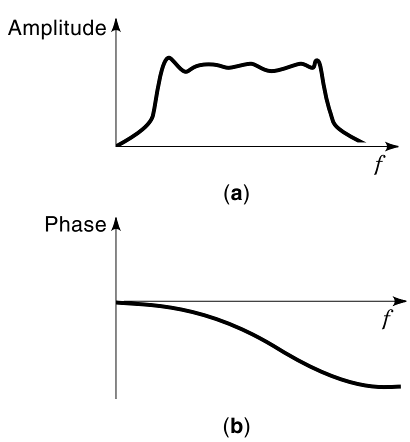

Figure 6. An example of the (a) amplitude and (b) phase frequency response of a sensor.

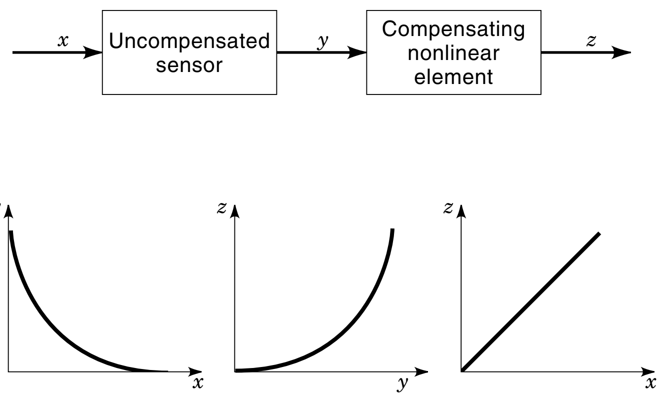

Figure 7. A static compensation technique.

This method is illustrated in Fig. 7, which also shows the response characteristic of the single blocks and the whole compensated system (13). As a consequence the relationships between response y and stimulus x can be expressed as: $y = ax + b$. Sometimes, to obtain a proportional relationship $y = kx$, another compensation stage is added, which allows compensating the sensor's sensitivity (a) and the shift from zero (b).

When the sensing fails to meet the dynamic specifications, that is, the dead time is too long or equally the frequency range is too small, it is necessary compensate for it (15). Having identified the dominant element in the system, the most obvious method of improving the dynamic response is that of the inherent design, that is, the design parameters are varied to improve the dynamic response of such an element. Two other methods are normally used: open-loop and closed-loop dynamic compensation. In the open-loop technique a linear element, with a transfer function in the Laplace domain $H_c(s)$, is introduced into the sensor system, such that the overall Laplace transfer function $H(s) = G(s)H_c(s)$ fulfils the required condition [Fig. 8(a)]. In the closed-loop, the compensation is obtained by using a high negative feedback [Fig. 8(b)]. The output of the sensing device is amplified by a high-gain amplifier [$H_g(s)$]. The amplifier output is fed back to an element [$H_c(s)$] which provides a balancing force to oppose the input force. In this case the compensated transfer function is given by

$$H(s) = \frac{G(s)}{1 + H_c(s) \cdot G(s)}$$

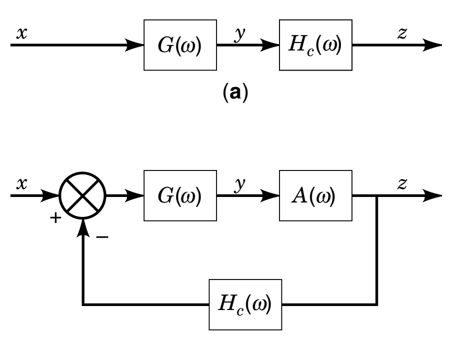

Figure 8. Sensor dynamic compensation, using (a) an open-loop technique; (b) a closed-loop with high negative feedback.

If the amplifier gain is rendered large such that the condition $G(s)H_c(s)H_g(s) \gg 1$ is satisfied, then $H(s) \sim 1/H_c(s)$. This means that, providing the previous condition is respected, changes in $G(s)$ due to nonlinear effects have a negligible effect on the compensated output (13) (Fig. 9).

Today, compensation is often realized by numerical microprocessors. In static compensation, using a look-up table based on the results of the calibration or using an interpolation technique, the microprocessor gives the corresponding input value for each measured value. Consequently, there is more interest in repeatability than in linearity. As for dynamic compensation, the transfer function of the sensor is stored in the processor memory, and using a deconvolution technique and the previous output values, the processor gives the corresponding input value for each output value. The sensor transfer function is obtained by an identification procedure realized in a preliminary dynamic calibration. Naturally, it is necessary that the dynamic behavior of the sensor not vary in time (10).

Reliability Characteristics. Reliability characteristics are those characteristics relating to the useful life of a sensor. These characteristics can be specified in different ways depending on the sensor type and, for a sensor, depending on what aspect has to be highlighted. In particular, the following parameters can be of interest:

Operating Life: it is the minimum length of time over which the sensor will operate, either continuously or over a number of on-off cycles, whose duration is specified, without changing its performance beyond specified tolerances.

Cycling Life: it is the minimum number of measurand full-range excursions (or specified partial range excursions) over whish a sensor will operate without changing its performance beyond specified tolerances.

In some cases it may also be necessary to specify or be concerned about a sensor's storage life, the length of time over which it can be exposed to specified storage conditions without changing its performance beyond specified tolerances.

The evaluation of the operating life, also of great interest in the field of industrial applications, is hardly ever performed, because specification for operating life tends to be in terms of years, typically between three and ten years. Sometimes, field experience can be substituted for performing an operating life test, when it can be documented that at least one sensor of the same design, taken randomly from a production lot, has operated maintenance free and within specified tolerances but in its end-use application for a certain number of years. In order to reduce the testing time and consequently the cost, suitable accelerated life tests (tests performed under environmental conditions more severe than normal) can be set up for some kind of sensors. Of course, the results of these kind of tests have to be considered as indicative and have to be verified by a life test under nominal environmental conditions.

Cycling life tests are usually performed as part of a qualification test when a sensor specification call for full-range or partial range cycling life. Equipment has been designed for rapid and automatic cycling of many categories of sensors.

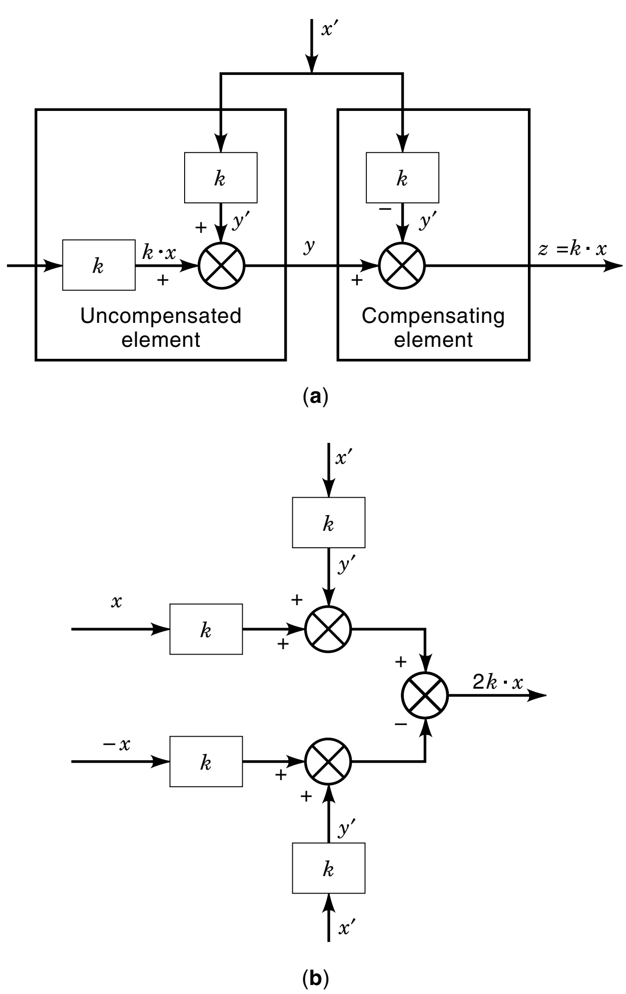

Figure 9. Compensation for interfering inputs (x') using (a) opposing environmental inputs or (b) a differential system for a linear sensor.

User System

Output Signal. There are three major categories of data signal forms: analog, carrier, and digital or pulse. In the analog sensor the output signal level is directly correlated to the value of the measurand. In the so-called carrier form the measured value modulates the characteristics of a carrier sinusoid. The amplitude (amplitude modulation AM), the frequency (frequency modulation FM) or the phase relationship with a reference signal (phase modulation PM) of the sensor output signal depends on the measurand. The most widely used modulation is frequency modulation, because the analog signal frequency has great advantages for signal transmission, for example, fail-safeness and easy galvanic separation. Furthermore it is very easy to obtain a digital output from FM (2). A digital signal consists of a series of pulses containing the encoded information corresponding to the input data. The information may be encoded into the amplitude, width, position or frequency of the pulses. Only a few sensors with direct digital output are available (e.g., incremental or coded displacement and angle sensors) because it is mostly necessary to convert the output signals into digital form to interface them with digital system. Many sensing devices also incorporate an analog-to-digital converter.

Output Range. To indicate the output range, the most commonly used parameter is the full-scale output (FSO). This is the algebraic difference between the electric output signal measured, respectively, with the maximum and the minimum input in the input range. The output overload values are the sensor outputs that correspond to input overload values (9).

Output Noise. This is a random fluctuation of the output signal not correlated to any information. Noise at the sensor output is caused by internal and external sources, but when a sensor has to be characterized, only internal noise is considered. Noise is usually furnished in terms of rms value, and its considered bandwidth is also indicated. Sometimes the signal-to-noise ratio is indicated. This is the ratio of the signal level to the internally generated noise level usually expressed in decibels (4,14).

Output Impedance. The sensor output impedance is the impedance between the output terminals of the instrument (6). It may be connected in parallel or in series with the input impedance of the interface circuit. Output impedance generally should be represented in a complex form and may include active and reactive components. When the reactive part is negligible, it is called output resistance. It is important to know its value to better interface a sensor with the user system (5).

Output Power. This is the maximum value of the power that the sensor can supply to the user system without decreasing its own performance. Sometimes, if the sensor output is in voltage, the maximum deliverable current is indicated, whereas, for a current output signal, the maximum deliverable voltage or the maximum load impedance values are specified.

Grounding. Sometimes the sensing device is grounded to establish a common mode among different parts of the system with the requirement that no potential variation may occur along this common node with respect to any point inside the node (4). It is important to know the possible grounding circuit to avoid grounding some user system floating points unintentionally.

Auxiliary System

In considering the need for a power supply, sensors can be classified as modulating (passive) or self-generating (active). Modulating sensors require excitative power from an external source. To produce the output signal, the excitative signal is modified by the sensing element as a function of the measurand. In self-generating sensors, instead, output power comes from the input, that is they produce an electric output signal from their input quantity. For example, a thermocouple is a self-generating thermal sensor. It produces an electromagnetic force from the difference in junction temperatures, whereas the resistance of a thermistor changes with temperature. To measure its value, it is necessary to pass a current through the thermistor. By using the power supply voltage, it is possible to control overall sensitivity. In fact, normally self-generating sensors produce very low output power, whereas modulating sensors produce much higher output energies. The presence of an auxiliary power source increases the danger of explosion in explosive atmospheres. (2,3,5,9).

Environment System

The static and dynamic performance characteristics of sensors are those which the sensor exhibits at room conditions and in the absence of any external conditions such as temperature, humidity, vibrations, that may affect the sensor's performance (11). The definition of influential quantity includes values associated with measurement standards, reference materials, and reference data, upon which the result of a measurement may depend, and phenomena, such as room temperature, barometric pressure, and humidity (11).

When a sensor is reasonably expected to operate under conditions, called operating environmental conditions, other than those under which it was calibrated, the environmental effects must be known, and the resulting deviations from static performance (environmental errors) must be determined by tests. Such environmental tests may have to be performed on each sensor used. Usually they are performed on a sampling basis (test one of every N sensors of each model and range) but sometimes only on a qualification basis (a test on a representative sensor). In linear sensors, the effect of a particular parameter can be studied in terms of its effect on static and dynamic sensor behavior, keeping the remainder of the parameters constant.

Other operating environmental effects on the behavior of a sensor during its normal operation which should be known and included in specifications include humidity or immersion in liquid; corrosive effects of high salt concentration in the ambient atmosphere; various effects of measured fluids on the sensing elements; the influence of ambient electromagnetic fields on sensor elements and integral circuitry; and the effects of radiation on various internal sensor elements.

Besides operating environmental conditions, there are other conditions to which a transducer may be exposed, but the sensor is not expected to operate within specified tolerances while exposed to them. However, the sensor is expected to perform within specified tolerances after exposure to such environmental conditions, called nonoperating environmental conditions (11).

In the following, the most common environmental effects are presented together with the parameter usually used to express them.

Temperature Effects. The operating range is the range of ambient temperatures, given by their lower and upper extremes within which the sensor is intended to operate and within which all specifications related to temperature effects apply. The maximum temperature is the highest (or lowest) temperature to which a sensor can be exposed without being damaged or subsequently showing performance degradation beyond specified tolerances. A more general and inclusive way of specifying thermal effects on performance characteristics is given by the temperature error, which is the maximum change in output when the temperature is changed from room temperature to specified temperature extremes. Analogously, a temperature error band is defined as the error band applicable over the operating temperature range. For some sensors, temperature effects are stated only in terms of thermal zero shift and thermal sensitivity shift, which cause a parallel displacement and a slope change, respectively, of the calibration curve. Knowledge of these individual errors is useful when the prevailing temperature during a measurement procedure is known and appropriate corrections to final data are to be made (11).

It is necessary to emphasize that temperature also affects dynamic characteristics. Consequently, the specifications should include corresponding thermal effects.

Pressure Effects. In some sensors calibrated at room barometric pressure and used where the ambient pressure is very low (e.g., at high altitude on aircraft) or where the pressure is very high (far underground or deeply submerged underwater), significant variation of performance may arise. Ambient-pressure error is the maximum change in output at any measurand value within the sensor's range, when the ambient pressure is changed between specified values, usually between room pressure and a lower or higher ambient pressure. The pressure error can be stated in terms of an ambient-pressure error band. Sometimes the pressure error is referred to as altitude error, and ranges of pressures are stated in terms of altitude above sea level (11).

Acceleration Effects. Quasi-steady-state acceleration of internal elements of a sensor may act directly on a mechanical sensing element or its linkage and cause errors in its output. When a sensor is to be used in an application where it experiences acceleration, the possibility of acceleration errors must be considered and tolerances must be established for such error. The acceleration error is defined as the maximum difference between output readings taken without and with the application of specified constant acceleration along specified axes. The acceleration effects, in fact, are typically more evident when the acceleration is applied along one axis of the sensor than when it is applied along other axes. This error can also be reported in terms of acceleration error band (11).

Vibration Effects. Vibration acceleration affects a sensor in the same manner as steady-state acceleration. Stronger effects, however, are connected with the frequencies of vibration. Amplified vibration (resonances) of internal elements can occur at one or more frequencies, and different resonances may be observed for different measurand values, particularly when the sensor incorporates a mechanical sensing element. Vibration error is defined, then, as the maximum change in output when a vibration level of specified amplitudes and ranges of frequency is applied to the sensor. Consequently, it may be necessary to predict the measurand value most likely to be observed by the sensor while it is exposed to the most severe vibration environment, and then to specify and verify vibration errors at that value (11).

Mounting Effects. A sensor's performance may be changed during its installation, for example, when the mounting surface of the sensor is not evenly machined so that the case becomes deformed when all the mounting hardware is tightened or when the torque applied to the coupling nut on a pressure fitting causes sensing element deformations. Mounting error is the error resulting from mechanical deformation of the sensor caused by mounting the sensor and making all electrical and measurand connections. Mounting error, obviously, is not included in specifications. However, it may be necessary to verify its absence (11).

Environmental Effects Reduction Technique. The most obvious method of reducing the effects of environmental parameters is that of isolation, which allows reducing undesirable electric, magnetic, electromagnetic, and mechanical coupling among various parts of the system and between the system and the outside (4).

The most successful techniques are the opposition method and the differential approach. The first is based on opposing environmental inputs. Suppose that an element is affected by an environmental parameter. Then a second element, subject to the same environmental input [see Fig. 9(a)], is introduced into the system so that the two effects cancel each other. An example of a differential system is shown in Fig. 9(b). As can be seen, two identical sensors are placed to sense the measurand and its opposite. Because both are affected by external quantities which are presented to both with the same sign, by calculating the difference between the two outputs, such effects can be eliminated. Naturally, environmental effects may be also compensated for by using the previously presented high-gain negative feedback and using a feedback system which is unsusceptible to environmental input (13).

Now the technique of computer estimation of measured value can also be used. A good model of the element in the system is required for this method. In fact, knowing the relationship between the sensor output, the environmental parameters, and the values of these parameters, the environmental effects can be numerically eliminated by the sensor output value.

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ELECTRIC SHOCK. See SAFETY SYSTEMS.