SENSORS AND TRANSDUCERS

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Summary

Our capacity to interact with the environment depends largely on the knowledge we have of the processes—either human induced or natural—that occur in the real world. Though our physical senses help us to understand and comprehend much of the world around us, there are situations that are better described by using synthetic sensors and

devices. Industrial-plant variables, ocean streams, and electric and magnetic fields are examples of quantities it is more convenient to detect and measure by sensors.

There are many reasons why we need to have numerical information about the quantities that characterize processes. Sustainable development is one of the major ones. For example, monitoring environmental parameters helps us to understand if human activities are changing the equilibrium of the earth, and, hence, inform us about the need to change our behavior. Also, the availability of information about the state of any process due to human activity plays a fundamental role in establishing control policies.

Sensors and transducers are devices that accept an input variable and produce a corresponding output that can be further manipulated. In this context they are devices that make up for our deficiencies of sense, and can be used to extract numerical information about the real world. In recent years, the use of sensors has undergone an explosive growth due in part to the availability of processing devices to manipulate their output signals, but also to the ease of electric-signal transmission. A further contributing factor to the progress in sensors and transducers has been the rapid growth and expansion of digital-computing devices. Digital environments are used for the processing and transmission of signals after their conversion from analog forms to digital equivalents.

1. Introduction

A transducer can be defined as a device that transforms an input signal into a corresponding output signal that is more suitable for further manipulation. For example, a thermocouple generates an output signal that depends on the temperature of the body under investigation. In the field of measurement systems, the objective of the signal manipulation is for the extraction of information on the state of the observed system. Hence, measuring devices are designed in such a way that they make the interaction between the measured system and the measuring device as viable as possible with minimum undesired effects.

Sensors are quite different from transducers because they are not required to convert the input signals to different forms, but are expected to indicate the state of the physical variable. Sensors can be thought of as extensions of our sensing capabilities. Sensors usually generate electrical signals that can easily be processed and transmitted by synthetic devices or systems of devices.

Of course, devices that produce nonelectric output signals also exist, and can be the only solution in some applications. For example, pneumatic sensing/transmitting systems are used in industrial plants—such as those with explosive environments—where electrical signals are unsafe. This article, however, concentrates on sensors and/or transducers that operate on electrical signals.

Even with this restriction in mind, the number of available sensing techniques and variety of sensors is enormous. A comprehensive discussion on all types of sensors and transducers in a limited space like this is impossible. Also, there are a number of methods of approaching the presentation of sensors and transducers. One approach refers to the nature of the sensed parameter—temperature, pressure, and so on. This approach is useful for those who want to observe particular parameters of physical variables and select suitable devices for monitoring them. Another approach is the classification of sensors and transducers by reference to the nature of their output signals—resistive, voltage-generating sensors, and so on. This approach is useful for those who want to design a measuring system and process the outputs of the sensors by using appropriate hardware and software.

Whatever the approach may be, it has been found useful to generalize the description of sensors and transducers as much as possible in order to give a reasonable enough insight into the topic—one that addresses the needs of a wide range of readers. Therefore, in this article, the generalization approach has been adopted.

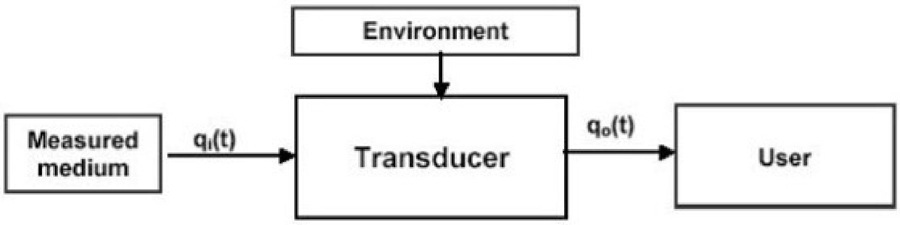

Figure1. A schematic representation of a transducer

A schematic representation of a transducer is illustrated in Figure 1.

Sensors and transducers produce output signals, $q_o(t)$, in response to input signals, $q_i(t)$, that characterize the state of the measured system (the measurand). An ideal sensor should not respond to any parameters other than the parameter it is intended for. Unfortunately, this is a simplified assumption and many sensors and transducers are also unintentionally sensitive to a number of other parameters. This is the reason why an interaction between the environment and the measuring system is indicated in Figure 1.
For an ideal transducer, the relation between the system input and output can be expressed by:

$$q_o(t) = f(q_i(t)). \tag{1}$$

This equation shows an ideal case. In practice, the output depends on a number of different parameters affecting the system and the corresponding equations are much more complex.

A number of different approaches are used to describe the sensors and transducers, and comprehensive descriptions can be found in the literature listed in the bibliography. Some of these approaches consider the static and dynamic characteristics of sensors and transducers. More information can be found on the characteristics sensors and transducers in the *Instruments and Measurements* section of this encyclopedia. Manufacturers usually supply information primarily on the static characteristic of their devices, since dynamic characteristics may be application-specific on the user end.

Owing to the availability of space and in order to avoid repetition, examples of only a limited number of sensors and transducers will be given in this article. Interested readers can refer to the bibliography for further information. Also, there are comprehensive descriptions of sensors and transducers in specific articles in this encyclopedia (see *Measurements and Instrumentation*, *Ammeters and Voltmeters*, *High-Voltage Measurements*, *Magnetic Measurements*, *Telemetry*, and *Instrumentation Systems*).

2. Motion Sensors

Motion sensors are one of the most important classes of sensors, since they are used for measuring the distance between points in space and for estimating other quantities (for example, temperature and pressure). There are many different types of motion sensors, ranging from simple resistive potentiometers to highly sophisticated optical and laser devices.

2.1. Resistive Potentiometers

Resistive potentiometers are basically resistance elements that have a movable arm that transform mechanical displacements into voltage forms. A simple potentiometric sensor is illustrated in Figure 2.

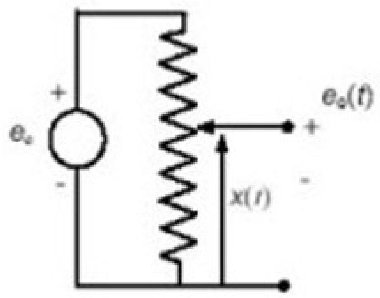

Figure 2. Schematic representation of a potentiometer

In Figure 2, e_e is the excitation voltage and $e_o(t)$ is the output voltage. The input signal is proportional to the displacement $x(t)$ of the wiper. Under no-load conditions the output voltage is a linear function of the displacement. However, when a user device is connected to the output $e_o(t)$ a loading effect occurs that can make the device nonlinear. There are a number of techniques available to minimize loading effects.

The basic transducer structure shown in Figure 2 can be realized physically in different forms for sensing linear or rotational motions. Moreover, different techniques are used for the construction of the resistance element. The wirewound and nonwirewound potentiometers are by far the most common ones on the market. The nonwirewound devices tend to have longer life spans compared to wirewound potentiometers.

Potentiometers with wide input spans are commercially available. The span of short-stroke potentiometers is about 10 mm, while the long strokes can be as large as 3 m (see the Novotechnick US Corporation catalog). The typical accuracy of these devices is 0.1% of the full scale (FS). Rotary devices are also available in a variety of ranges, spanning from 10° of rotation to as much as 60 turns. Generally, accuracy is better for large, multiturn devices.

2.2. Linear Variable Differential Transformers (LVDT)

Linear variable differential transformers (LVDTs) are distance-sensing devices that are classed as the variable-reactance devices in motion measurements. Although they are more complex in their construction, excitation, and output-signal detection compared to potentiometers, they have many advantages. They offer smaller mechanical loads and have much longer lives. They are known as “frictionless motion detectors.” These advantages make LVDTs a better choice in a number of sensitive applications.

A LVDT is a voltage transformer with a primary coil and two secondary coils, as shown in Figure 3. The two secondary coils are generally connected in series opposition. A core moves inside the coil in response to an external displacement $x(t)$. Usually, the excitation voltage e_e is a sinusoidal voltage with frequencies up to 30 kHz. The sensor output is the voltage $e_o(t)$ and has the form of an amplitude-modulated signal, the carrier being the excitation voltage and the modulating signal being proportional to the displacement $x(t)$ of the moving core. The amplitude of the modulated signal is a linear function of the core position.

A demodulating system is required in order to obtain a voltage-output signal that represents the core displacement. Such signal demodulation can easily be performed when the maximum input signal frequency is much smaller than the carrier frequency. This consideration establishes an upper limit to the frequency spectrum of the input signals.

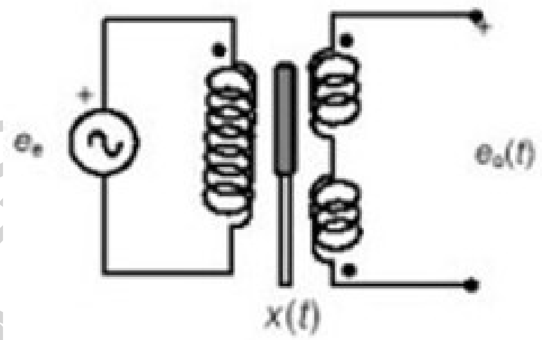

Figure 3. Schematic representation of a LVDT with secondary coils connected in series opposition

Both linear motion and rotational motion LVDTs are commercially available. In the first case, the span ranges from about 0.13 mm to 760 mm (see the Trans-Tek Inc., USA, catalog). In the second case, they can sense rotations up to 360°. Accuracy can be down to 0.1% of FS.

Some LVTDs are classified as DC/DC LVDTs. They operate on an external DC supply and generate DC output signals. This is achieved by converting the DC signals to the AC in the input stages and converting the AC output back to the DC.

2.3. Capacitive Sensors

Like the LVDTs, the capacitive sensors are variable-reactance devices. They transform the input motion into the corresponding reactance by the changes in the capacitance values.

Considering a parallel-plate capacitor, the capacitance can be expressed as:

$$C = \varepsilon_o \ \varepsilon_r \ \frac{A}{d}, \qquad (2)$$

where ε_o is the dielectric constant for vacuum (8.85 pF/m), ε_r is the relative dielectric constant, A is the plate area (m^2), and d is the distance (m) between plates.

In capacitive-displacement sensors, there are three different ways of producing changes in the capacitance values, as illustrated in Figure 4.

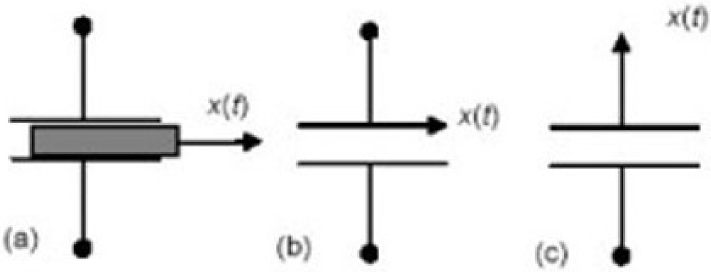

Figure 4. Capacitive sensors for displacement transduction

In Figure 4a, the motion $x(t)$ changes the value of the dielectric properties of the capacitor. As can be seen in equation 2, a linear relationship between the motion and the corresponding capacitance value can be obtained as the dielectric properties change. In Figure 4b, the motion $x(t)$ is used to change in the area of the plate. Equation 2 indicates that the dependence of the capacitance value on the change in area is linear. In Figure 4c, the motion $x(t)$ causes a change in separation d of the plates, giving a hyperbolic changes on the capacitance values.

The first method is seldom used since the dielectric substance attached to the system in motion or shaft can produce a large mechanical load on the system. The method shown in Figure 4c is the most commonly used configuration. It is generally preferred because of its simplicity and for its good sensitivity to small displacements.

Unfortunately, the inherent nonlinearity moving-plate configuration can cause some problems; hence, many different methods have been developed for the linearization of the signals because of variations in plate distances. While a number of hardware solutions have been proposed, digital- and hybrid-sensing devices also allow for a software solution. In this case, either an explicit linearization of the input–output characteristic of the system is performed or lookup tables are used.

Capacitive sensors are preferred in many application because of their mechanical simplicity, small mechanical-loading effects, and their high sensitivity. Unfortunately, this class of sensor is characterized by very large impedance values that can cause electrical-loading problems, unless for signal conditioning, high-input impedance devices are used (for example, charge amplifiers).

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Biographical Sketch

Salvatore Graziani received a degree in Electronic Engineering from the Università di Catania, Italy, in 1990, and a PhD degree in Ingegneria Elettrotecnica in 1994. Since 1992 he has been working as an Assistant Professor in Misure Elettriche ed Elettroniche, Dipartimento Elettrico, Elettronico e Sistemistico, Università delgi Studi, Catania. He has undertaken collaborative research activities with the Instituto Internazionale di Vulcanologia (CNR), Catania; Laboratorio di Ricerca CoRiMMe (ST-Microelectronics), Cantania; Dipartimento di Chimica. Università degli Sutidi, Catania; and the Space and Naval Warfare Systems Center, San Diego, USA. His research areas are innovative techniques for signal manipulation, elaboration of data on pollution, smart sensors for industrial application, and noise-added systems. He is a coauthor of over 100 technical publications.