SECTION 8

TRANSDUCERS AND SENSORS

Measurements by direct comparison with a reference standard having the same characteristics as those of the quantity measured are called *direct measurements*, but most measurements yield results in a more indirect way. They are based on knowledge of the relationship between the quantity to be measured and the response of the measuring instrument or system influenced by it. Moving-coil meters are an example: under the influence of the applied voltage or current (or both) a mechanical torque is generated. The pointer attached to the moving coil acquires its final position indicative of the electrical quantity measured, the mechanical torque being balanced by a spring. Thus an electrical quantity is first translated into a torque, which in turn is translated into a position on a scale calibrated in units of the quantity measured.

In this example, the electrical quantities are translated into mechanical ones. In contrast, *transducers* translate primarily nonelectrical quantities into electric signals.

The term transducer has been applied to a variety of devices, including measuring instruments, acoustic-energy transmitters, signal converters, and phonograph cartidges. With the vast increase in the development and use of electronic measuring systems, however, instrumentation engineers found it necessary to devise a more limited definition of transducer as a device used for measurement purposes.

Transducers covered in the first four chapters of this section include those for mechanical, thermal, acoustic, optical, and electrical quantities.

A chapter on microsensors and microactuators based on microfabrication techniques emphasizes physical, chemical, and biomedical sensors. A microelectromechanical (MEMS) instrumentation system can be considered to consist of an input sensor, an output actuator, and a signal processing element. H.N., D.C.

In This Section:

On the CD-ROM:

Norton, H. N., "Transducers for Nuclear Radiation," reproduced from the 4th edition of this handbook.

CHAPTER 8.1

TRANSDUCER CHARACTERISTICS AND SYSTEMS

Harry N. Norton

INTRODUCTION

American National Standard, ANSI MC6.1, Electrical Transducer Nomenclature and Terminology (see Ref. 1), defines a *transducer* as "a device which provides a usable output in response to a specified measurand." The *measurand* is "a physical quantity, property or condition which is measured." The *output* is "the electrical quantity, produced by a transducer, which is a function of the applied measurand." Only the last of these three definitions applies specifically to electrical transducers. It could apply equally well to transducers with pneumatic output if the word "electrical" in the definition were omitted. Only electrical transducers are covered in this handbook.

ANSI MC6.1 also applies to the construction of transducer nomenclature (see Table 8.1.1). When used in titles or for indexes, the sequence shown in the table should be used, e.g., "transducer, acceleration, potentiometric, ±5*g*." When the nomenclature is used in the text, the opposite of the sequence shown in the table should be used, e.g., "A 0- to 8-cm dc output reluctive displacement transducer was installed on the actuator."

Transducer Classes and Elements

Thermocouples are representatives of a transducer class in which transduction takes place in a single component. An electric signal is generated between the terminals of the two dissimilar wires forming the thermocouple when they are exposed to a temperature difference. This is the simplest class of transducer. It is also *self-generating,* the output signal being produced without an additional power source. Piezoelectric transducers are also of the self-generating type, electric charge or potential being generated when the crystal is exposed to stress.

The thermocouple (or *thermoelectric temperature transducer*) is one of the few transducer types in which the *sensing element* (the element on which the measurand acts directly) also acts as the *transduction element* (the element in which the output of a transducer originates). Most transducer types have separate sensing and transduction elements. For example, in a piezoelectric pressure transducer the pressure acts on a diaphragm (sensing element) which deflects with applied pressure and then stresses the piezoelectric crystal (transduction element) in which the output originates.

The self-generating piezoelectric transducer is an example of a transducer whose transduction element is "active." In the majority of transducer types the transduction element is "passive," i.e., it requires the application of *excitation* power from an external source. Some "passive" transduction elements can accept either ac or dc excitation (e.g., strain-gage bridges, potentiometric elements), whereas others can accept only ac excitation (e.g., reluctive, inductive, capacitive elements).

TABLE 8.1.1 Construction of Typical Transducer Nomenclature and Examples of Modifiers

Main noun	First modifier, measurand, examples	Second modifier, restricts measurand, examples	Third modifier, electrical transduction principle, examples	Fourth modifier[a] sensing element, special features or provisions, examples	Range, examples	Unit, examples
Transducer	Acceleration	Absolute	Capacitive	AC output	0 to 1000	A
	Air speed	Angular	Electromagnetic	Amplifying	±5	°C
	Attitude	Biaxial	Inductive	Bellows	−100 to + 500	cm
	Attitude rate	Differential	Ionizing	Bondable	−430 to −415	cm/s
	Current	Gage	Photoconductive	Bonded		deg
	Displacement	Infrared	Photovoltaic	Bourdon tube		°F
	Flow rate	Intensity	Piezoelectric	Capsule[b]		ft/s
	Force	Linear	Potentiometric	DC output		g
	Heat flux	Mass	Reluctive	Diaphragm		Hz
	Humidity	Radiant	Resistive	Digital output		in./s
	Light	Relative	Strain gage	Discrete-increment		in.
	Liquid level	Surface	Thermoelectric	Dual-output		K
	Mach number	Total	Vibrating-element	Exposed-element		kg
	Nuclear radiation	Triaxial		Frequency output		lb/min
	Pressure	Volumetric		Gyro		m
	Speed[c]			Integrating		mmHg
	Sound pressure			Self-generating		N
	Strain			Semiconductor		% RH
	Temperature			Servo[d,e]		lb/in.^{2}
	Torque			Switch		kPa
	Velocity			Toothed-rotor		mbar
				Turbine		rad/s
				Ultrasonic		
				Unbonded		
				Weldable		

[a] Nomenclature may include two of these terms.
[b] Preferred to “aneroid.”
[c] Scalar quantity.
[d] Preferred to “force balance” or “null balance.”
[e] When this modifier is used, the third modifier (“transduction principle”) may be omitted.
[f] Vector quantity.

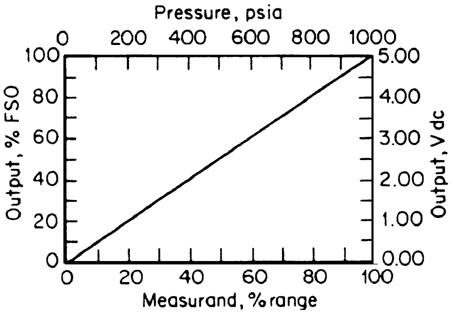

FIGURE 8.1.1 Output-measurand relationship of ideal linear-output transducer as exemplified for a dc-output transducer. (*From Ref. 2 by permission*)

Signal Conditioning

The widespread acceptance of industrial standards specific to a particular industry or application demands that the transducer output be in a specific form and within a specific range. Process industry standards, for instance, typically demand a transducer output signal either in the form of a direct current in the range from 4 to 20 mA or a dc voltage between 0 and 5 V. Transducers delivering control signals to microprocessors often require a digital output; this also applies to transducers used in digital data acquisition systems.

The process and the steps involved to provide an output signal in whatever specific form required are referred to as *signal conditioning*. The equipment may include ac or dc amplifiers, rectifiers, demodulators, circuits for square-root extraction, logarithmic amplifiers, and so forth, depending on the laws governing the relationship between the measurand and the desired output signal. For example, the radiation emanating from the surface of a body is an exponential function of its temperature. Thus to obtain a linear temperature scale at the output, logarithmic amplifiers are typically involved in the signal-conditioning process. In addition, excitation voltage or current regulation circuits are used in many instances to ensure accuracy and repeatability.

When a transducer system includes all the above-mentioned elements and circuits and is packaged in a single-housing, it is referred to as an *integrally conditioned transducer.* Recent examples include integrated-circuit semiconductor transducers for temperature-compensated pressure measurements contained in a single miniature housing.

Transfer Function

Every transducer design can be characterized by an ideal or theoretical output-measurand relationship (*transfer function*). This relationship is capable of being described exactly by a prescribed or known *theoretical curve* (see Fig. 8.1.1), stated in terms of an equation, a table of values, or a graphical representation. This applies primarily to the *static characteristics* of a transducer, i.e., the output-measurand relationship for a steady-state or very slowly varying measurand. It can also apply to the transducer's *dynamic characteristics,* i.e., the output-measurand characteristics for a relatively rapidly fluctuating measurand. However, this dynamic behavior is described by relationships other than the transducer's theoretical curve.

Transducer Errors

Because of a variety of factors, the behavior of a real transducer is nonideal. These factors include production variations, as well as the use of nonideal materials, production methods, ambient conditions during manufacture, and testing methods. It must also be recognized that many trade-offs enter into the design of a marketable transducer and that our knowledge (the *state of the art*) is limited with regard to producing an ideal transducer design and then compensating it perfectly for aging effects and a variety of environmental conditions the transducer may be subjected to during its operation.

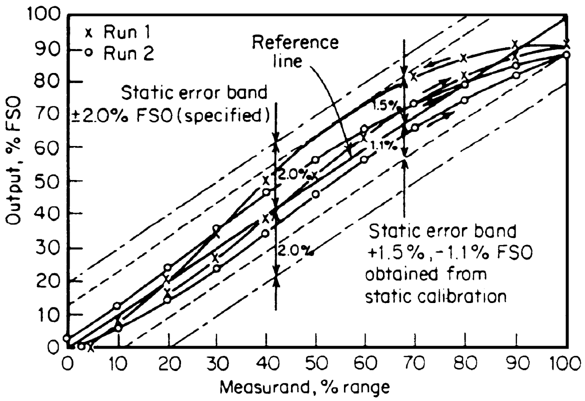

FIGURE 8.1.2 Static error band referred to terminal line (error scale 10:1). (*From Ref. 2 by permission*)

Hence the measurand value indicated by the transducer may often differ from the true measurand value or the specified theoretical value. The algebraic difference between the indicated and the true value is the *error.*

Error Band

A convenient manner of determining or specifying transducer errors is to state them in terms of the band of maximum (or maximum allowable, for a specification) deviations from a specified reference line or curve. This band is defined as the *error band.* The *static error band* (see Fig. 8.1.2) is that error band obtained (or obtainable) by means of a *static calibration,* which is performed under "room conditions" (controlled room temperature, humidity, and atmospheric pressure) and in the absence of any vibration, shock, or acceleration (unless one of these is the measurand) by applying known values of measurand to the transducer and recording corresponding output readings. Other types of error band are applicable under somewhat different (and rigorously specified) conditions. Reference lines for error bands are not limited to the terminal line.

Dynamic Characteristics

When a step change in a measurand is applied to a transducer, the transducer output does not instantaneously indicate the new measurand level. Examples of such step changes are mechanical shock, a sudden pressure rise when a solenoid valve opens, or a temperature transducer is rapidly immersed in a very cold liquid. The lag between the time the measurand reaches its new level and the corresponding steady (final) transducer output reading is defined in various ways. The time required for the output change to reach 63 percent of its final value is the *time constant* of the transducer. The time required to reach a different specified percentage of this final value (say 90 or 98 percent) is the *response time.* The time in which the output changes from a small to a large specified percentage of the final value (usually from 10 to 90 percent) is the *rise time.* The output may rise beyond the final value before it stabilizes at that value. This *overshoot* depends on the *damping* characteristics of the transducer.

When the measurand fluctuates (sinusoidally) over a stated frequency range, the transducer output may not be able to indicate the correct amplitude of the measurand over these excursions. An example is the mechanical vibration (vibratory acceleration) of an engine housing. The output may be somewhat higher at certain measurand frequencies but usually drops off as the frequency increases until the output is essentially zero. The change with measurand frequency of the output-measurand amplitude ratio is the *frequency response* of the transducer, always stated for a specified frequency range. The above characteristics, as well as other transducer dynamic characteristics, are defined in the terminology section of ANSI Standard MC6.1-1975.

Environmental Characteristics

In most applications transducers are used only under the controlled room conditions of the facility where they are calibrated and where various static performance characteristics are determined. The external conditions to which a transducer is exposed not only while operating but also during shipping, storage, and handling can contribute additional errors, such as temperature error, acceleration error, or attitude error. Such environmental conditions (which can also include corrosive atmosphere, salt-water immersion, or nuclear radiation) may even cause a permanent deterioration or malfunction in the transducer.

Transduction Principles

The most essential determinant of any one transducer type is its transduction principle. How the electrical output is originated affects most other characteristics of the transducer. The most frequently used transduction principles are described below and illustrated in Fig. 8.1.3. It should be noted that photovoltaic, piezoelectric,

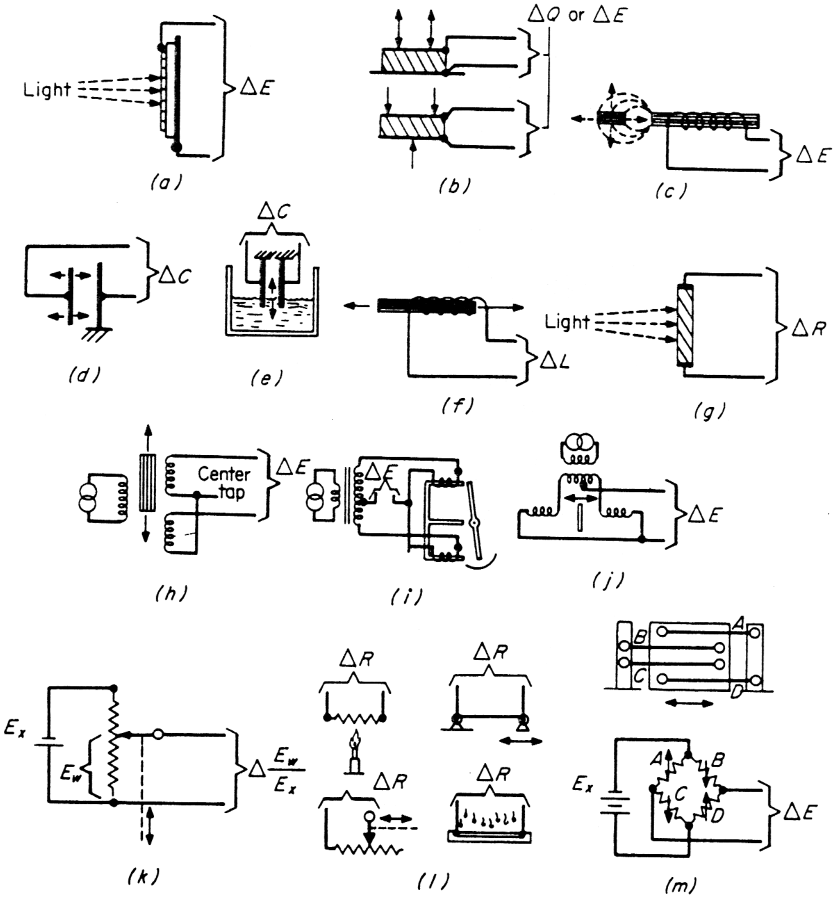

FIGURE 8.1.3 Transduction principles: (*a*) photovoltaic; (*b*) piezoelectric; (*c*) electromagnetic; (*d*), (*e*) capacitive; (*f*) inductive; (*g*) photoconductive; (*h*), (*i*), (*j*) reductive; (*k*) potentiometric; (*l*) resistive; (*m*) strain page. (*From Ref. 2 by permission*)

and electromagnetic transduction are used in *self-generating* transducers, whereas all other transduction methods illustrated require some sort of external excitation power.

Photovoltaic Transduction. The measurand is converted into a change in the voltage generated when a junction between certain dissimilar materials is illuminated. Used primarily in optical sensors, this principle has also been employed in transducers incorporating mechanical-displacement shutters to vary the intensity of a light beam between a built-in light source and the transduction element.

Piezoelectric Transduction. The measurand is converted into a change in the voltage E or electrostatic charge Q generated by certain crystals when mechanically stressed by compression or tension forces or by bending forces. Either natural or synthetic crystals (usually ceramic mixtures) are used in such transduction elements.

Electromagnetic Transduction. The measurand is converted into a voltage (electromotive force) induced in a conductor by a change in magnetic flux, usually because of a relative motion between a magnetic material and a coil having a ferrous core (electromagnet).

Capacitive Transduction. The measurand is converted into a change of capacitance. This change occurs typically either by having a moving electrode move to or from a stationary electrode or by a change in the dielectric between two fixed electrodes.

Inductive Transduction. The measurand is converted into a change of the self-inductance of a single coil.

Photoconductive Transduction. The measurand is converted into a change in conductance (resistance change) of a semiconductive material because of a change in the illumination incident on the material. This transduction is implemented in a manner similar to that explained for the case of photovoltaic transduction, above.

Reluctive Transduction. The measurand is converted into an ac voltage change by a change in the reluctance path between two or more coils while ac excitation is applied to the coil system. This transduction principle applies to a variety of circuits, including the differential transformer and the inductance bridge.

Potentiometric Transduction. The measurand is converted into a change in the position of a movable contact on a resistance element. The displacement of the contact (wiper arm) causes a change in the ratio between the resistance from one end of the element to the wiper arm and the end-to-end resistance of the element. In its most common applications the resistance ratio is used in the form of a voltage ratio when excitation is applied across the resistance element.

Resistive Transduction. The measurand is converted into a change of resistance. This change is typically effected in a conductor or semiconductor by heating or cooling, by the application of mechanical stresses, by sliding a wiper arm across a rheostat-connected resistive element, or by drying or wetting electrolytic salts.

Strain-Gage Transduction. The measurand is converted into a resistance change, due to strain, usually in two or four arms of a Wheatstone bridge. This principle is a special version of resistive transduction. However, the output is always given by the bridge-output voltage change. In the typical configuration illustrated in Fig. 8.1.3 the upward arrows indicate increasing resistance, and the downward arrows decreasing resistance, in the respective bridge arms for sensing link motion toward the left.

Transducers in Process Control

The availability of an output signal responding to a measurand makes transducers key elements in the many areas of industrial process control. It permits direct comparison of a transducer output with an adjustable electric reference signal, calibrated in units of the measurand. Both the transducer output and the adjustable reference signal are fed into the input terminals of a differential amplifier. When any deviation of the transducer output from the adjustable reference signal (*set point*) occurs, an error signal is supplied to the controller, which in turn causes the control element to acquire such a position that the measurand again causes the transducer to deliver an output equal to the adjustable reference signal. This control process can be carried out in several alternative modes, e.g., on-off or proportional.

REFERENCES

1. "Electrical Transducer Nomenclature and Terminology," *ANSI MC 6.1/ISA-S37.1,* Instrument Society of America, 1982.
2. Norton, H. N., "Handbook of Transducers," Prentice Hall, Englewood Cliffs, 1989.

BIBLIOGRAPHY

Chesmond, C. J., "Control System Technology," Instrument Society of America, 1984.

"Dynamic Response Testing of Process Control Instrumentation." *ANSI MC 4.1/ISA-S26.* Instrument Society of America, 1975.

Engstrom, R. W., "Photomultiplier Handbook," Burle Industries, 1980.

Jones, B. E., "Instrumentation, Measurement and Feedback," McGraw-Hill (UK), 1977.

Kuo, B. C., "Automatic Control Systems." 3rd ed. Prentice Hall, 1975.

McCaw, L., "Industrial Measurements—A Laboratory Manual," Instrument Society of America, 1987.

Morrison, R., "Grounding and Shielding Techniques in Instrumentation," 2nd ed., Wiley, 1977.

Morrison, R., "Instrumentation Fundamentals and Applications," Instrument Society of America, 1984.

Murrill, P. W. "Fundamentals of Process Control Theory," Instrument Society of America, 1981.

Norton, H. N. (ed.), "Sensor and Transducer Selection Guide," Elsevier Science, 1990.

Norton, H. N., "Electronic Analysis Instruments," Prentice Hall, 1992.

"Process Instrumentation Terminology." *ANSI/ISA S51.1*, Instrument Society of America, 1979.

Strock, O. J., "Introduction to Telemetry," Instrument Society of America, 1986.

Sydenham, P. H., "Basic Electronics for Instrumentation," Instrument Society of America, 1982.

Travers, D., "Precision Signal Handling and Converter-Microprocessor Interface Techniques," Instrument Society of America, 1984.