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Instrumentation System Fundamentals

1.1 INTRODUCTION

Transducers are used as *sensing devices* in measurement systems as well as control systems. *Measurement systems* are used to obtain *information*: one or more quantities are sensed and the measured values are displayed. How the displayed information is used is basically up to a human observer. *Control systems* are used to keep a quantity at a desired value. A human operator adjusts settings on electronic equipment, the sensing device feeds information to this equipment, and the equipment then sends a signal to a control device that adjusts the quantity.

1.2 MEASUREMENT SYSTEMS

The simplest measuring "system" would be a sensing device that also displays the measured value, such as a mercury-in-glass thermometer or a pressure gage. If the measured value needs to be recorded at certain times, a human observer with a clipboard, pencil, and wristwatch can be employed for this purpose. A more advanced method utilizes an automatic camera that takes pictures of the gage or thermometer, together with a clock, at regular intervals. In these examples, the operator, clipboard, pencil, and wristwatch, or the camera and clock, become a part of the system.

When a measured value is to be displayed some distance away from the point of measurement, a link between the two points becomes necessary.

This link can be mechanical (e.g., an automobile speedometer cable), pneumatic (a pipe filled with air whose pressure is varied by the sensing device, with a pressure indicator used for display), or electrical (an electrical cable). Electrical wiring is used in *electronic measuring systems,* in which the sensing device (transducer) has an *electrical* output and the display device accepts an *electrical* signal. Only transducers with electrical output are covered in this book, since almost all modern instrumentation systems are electronic.

1.2.1 Measurand

The term *measurand* is used throughout the book and needs to be clearly understood. The measurand is the quantity, property, or condition that is measured (then sensed and converted into a usable electrical output) by a transducer. Thus, if the measurand is temperature, it is measured by a temperature transducer; if it is pressure, it is measured by a pressure transducer. The chapters of this book subsequent to the introductory chapters are organized by measurand.

1.2.2 Basic Electronic Measuring System

A basic electronic measurement system is shown in Figure 1–1. It consists of:

1. The *transducer*, which converts the measurand into a usable electrical output.
2. The *signal conditioner*, which converts the transducer output into the type of electrical signal that the display device will accept.
3. The *display device* (or readout device), which displays the required information about the measurand.
4. The *power supply*, which feeds the required voltages to the signal conditioner, to all except "self-generating" (see Chapter 2) types of transducers, and, at times, to certain kinds of display devices.

Because of their immense variety, transducers constitute the key portion of each of the measuring systems in which they are used. Signal con-

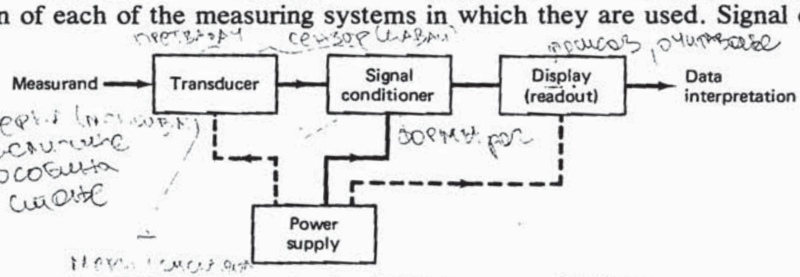

FIGURE 1–1. Basic electronic measuring system.

ditioners may vary in complexity from a simple resistance network or impedance-matching device to multistage amplifiers with or without demodulators analog-to-digital converters, and other elaborate circuitry. Among commonly used display (readout) devices are circular-chart and strip-chart recorders, analog or digital meters, character printers, oscilloscopes (which may be equipped with a camera so that permanent records can be obtained) and discrete-level indicator lights.

A few types of measuring systems (e.g., synchro systems) operate without any signal conditioning. Most systems, however, employ signal conditioning either packaged as a separate unit, or included in the transducer or the readout equipment. Similarly, the power supply function may be included in the readout equipment or provided as a separate unit.

1.2.3 Multiple-Data Measuring Systems

Most measurement systems are designed to handle and display the output of two or more transducers. The transducers feeding into such a multiple data measuring system can be of the same type (e.g., several thermocouples or of different types (e.g., temperature, pressure, and vibration transducers) Signal conditioning in the system can be minimized by "standardizing" the transducer output, that is, having each transducer provide the same full scale output to the system, regardless of type or measuring range.

Typical multiple-data measuring systems are illustrated in Figure 1–2 Each system provides for at least some amount of signal conditioning i addition to whatever conditioning is incorporated within the transducer Transducer excitation power, if any, is either connected to all transducers simultaneously or switched to each transducer (in selectable systems) as is being read out, usually by a second set of contacts in the stepper or selector switch. The latter method reduces transducer power consumption substantially.

The simplest system, shown in Figure 1–2(a), is one in which the transducer to be read is selected manually, such as by means of a rotary select switch. When a number of different measurements must be monitored repeatedly at relatively short intervals, a system such as the one shown Figure 1–2(b) can be used, wherein an automatically operating stepper sequencer scans the transducer outputs and the readout device also displa an identifying number for the measurement being displayed. The tempor ("volatile") display on a digital meter can be augmented or replaced b permanent record, such as one obtainable from a printer. A simultane display of several measurements on a multichannel strip-chart recorder in Figure 1–2(c), is most frequently used when several related measureme are expected to fluctuate rapidly. Numerous variations of the system lustrated exist, including those in which the transducer outputs, toge with a timing signal (*clock*) and a means of identifying each measurem

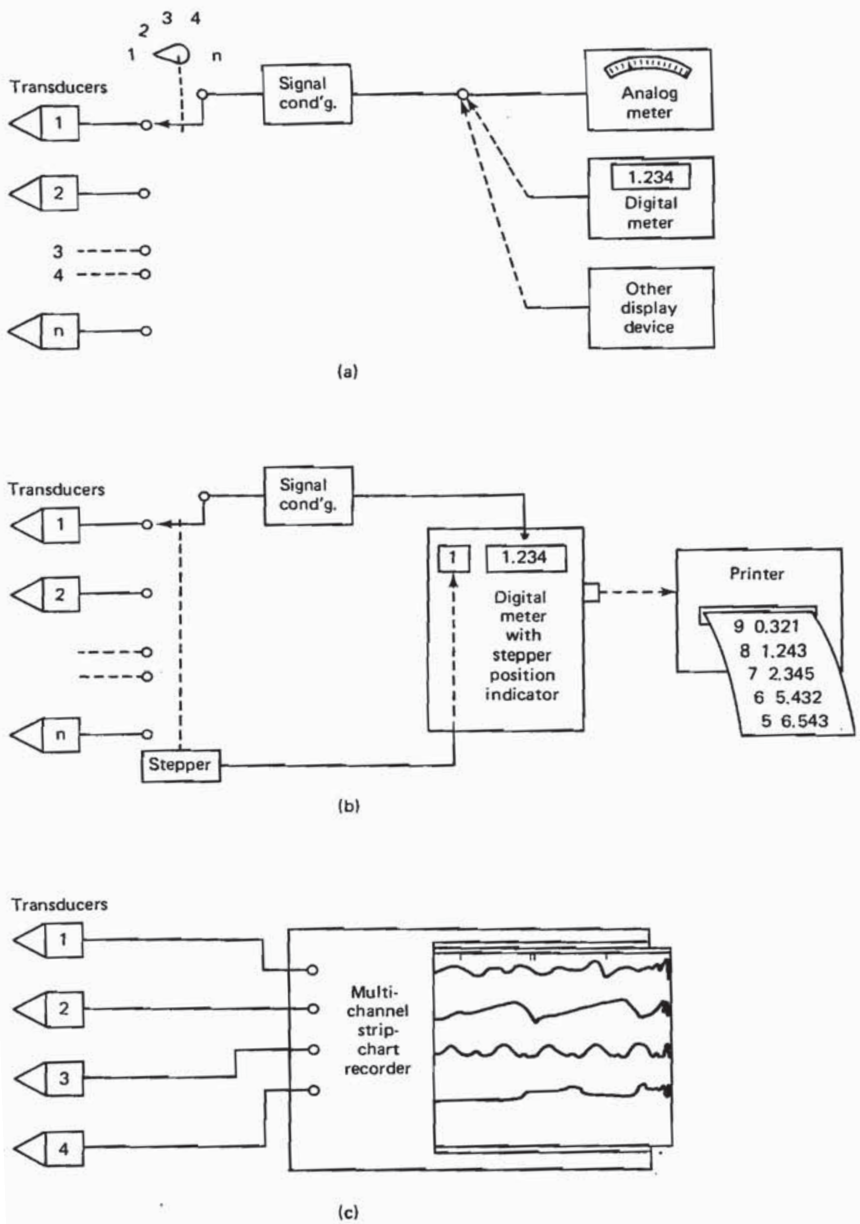

FIGURE 1–2. Typical multiple-data measuring systems: (a) manually selected measurements; (b) automatically selected measurements; (c) simultaneously displayed measurements.

are stored on magnetic tape which can be played back later into one or more display devices.

1.3 TELEMETRY SYSTEMS

Although all remote-display electronic measuring systems could be termed *telemetry* systems, this term is usually reserved for multiple-data systems using a modulated high-frequency carrier to transmit the information about the measurements from one point to another.

A generalized basic telemetry system is illustrated in Figure 1–3. The outputs from the transducers or other sensing devices, which may or may not require signal conditioning, are fed to a commutator (*multiplexer*), which combines them into a single *composite* signal. This signal is applied to the high-frequency transmitter, where it modulates the output of an oscillator. The modulated *carrier* is amplified and then fed to an antenna. The transmitting antenna, which can be highly directional, radiates the modulated carrier toward a receiving antenna. The received signal is amplified and applied to a *demodulator*, which separates the modulating information from the high-frequency carrier. This process reconstitutes the composite signal at the receiving end of the system. A *decommutator* is then employed to extract signals corresponding to the respective sensing-device outputs, so that each measurement can be displayed and evaluated individually. A *data processor* may or may not be required for the desired form of display.

In some types of telemetry systems the radio link is replaced by a conducting link. An example of this is the *carrier-current system* used by utility companies, in which the modulated carrier is coupled directly on a power transmission line and then decoupled from this line at the receiving end. Another example is *landline* (or "hardline") telemetry, where either a modulated high-frequency carrier is transmitted to a remote receiving station through a coaxial cable, or multiconductor shielded cables are used to feed a number of individual transducer outputs to a remote display center.

1.3.1 Carrier Modulation

The manner in which the transmitter's carrier signal is modulated—the type of *modulation*—deserves a more detailed description since it normally determines the nomenclature of the telemetry system (see Figure 1–4). The frequency of an *amplitude-modulated* (AM) carrier remains constant while its amplitude changes with the modulating signal. The frequency and amplitude of a *phase-modulated* (PM) carrier remain constant while its phase changes with the modulating signal. The amplitude of a *frequency-modulated* (FM) carrier remains constant while its frequency changes with the modulating signal.

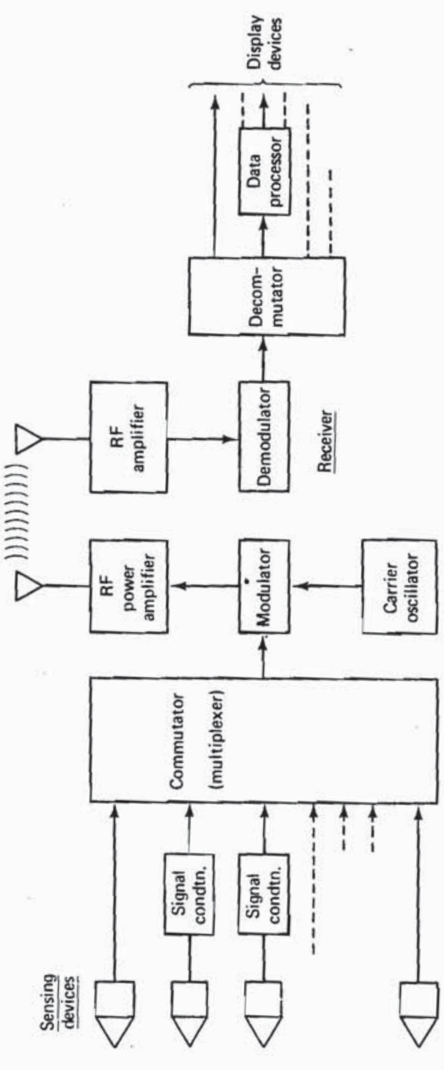

FIGURE 1–3. Basic radio telemetry system.

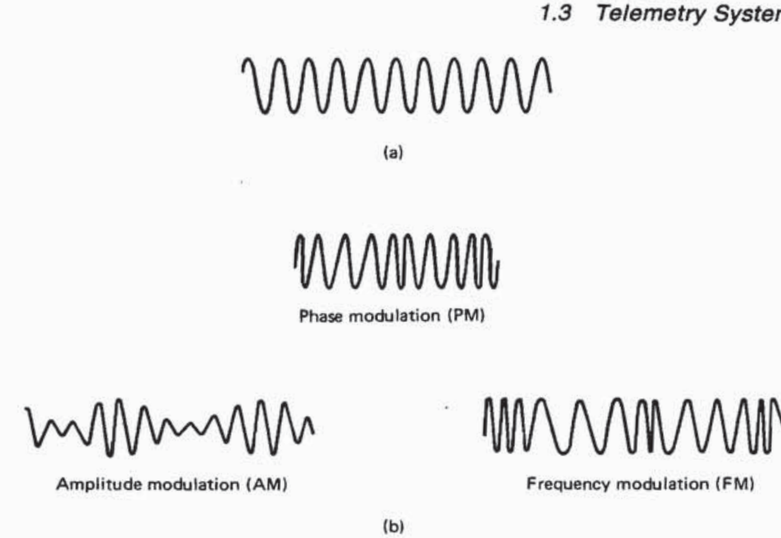

FIGURE 1–4. Principal types of carrier modulation: (a) unmodulated carrier; (b) modulated carrier.

1.3.2 Multiplexing

Two different methods are used to combine individual measurements into a composite signal for transmission over a single data link.

Frequency-division multiplexing (see Figure 1–5) allows the continuous display of several measurements. Each sensing-device output is fed to a different *subcarrier oscillator* (SCO). Each SCO is tuned to a different frequency in the general range 0.4 to 70 kHz. The SCO outputs are then linearly summed to form the composite signal. At the receiving station the composite signal is fed through band-pass filters, one filter for each SCO used in the transmitter, and tuned to the respective SCO frequency. The demodulated output of each band-pass filter then represents the corresponding measurement.

Time-division multiplexing (TDM) involves the time sharing of a number of individual measurements. This method does not permit a continuous display of each measurement. However, the measurement can be reconstituted from samples of the sensing-device output if the sampling occurs frequently enough. The sampling rate for any given measurement depends on its expected rate of fluctuation with time. The measurements are sampled by *commutating* them, that is, by switching them sequentially into a common output circuit.

Figure 1–6 shows a simple commutation scheme as well as a method for *subcommutation* which permits a number of relatively slowly varying *measurement* signals to be switched sequentially into one segment of a commutator to whose other segments the relatively rapidly varying measureme

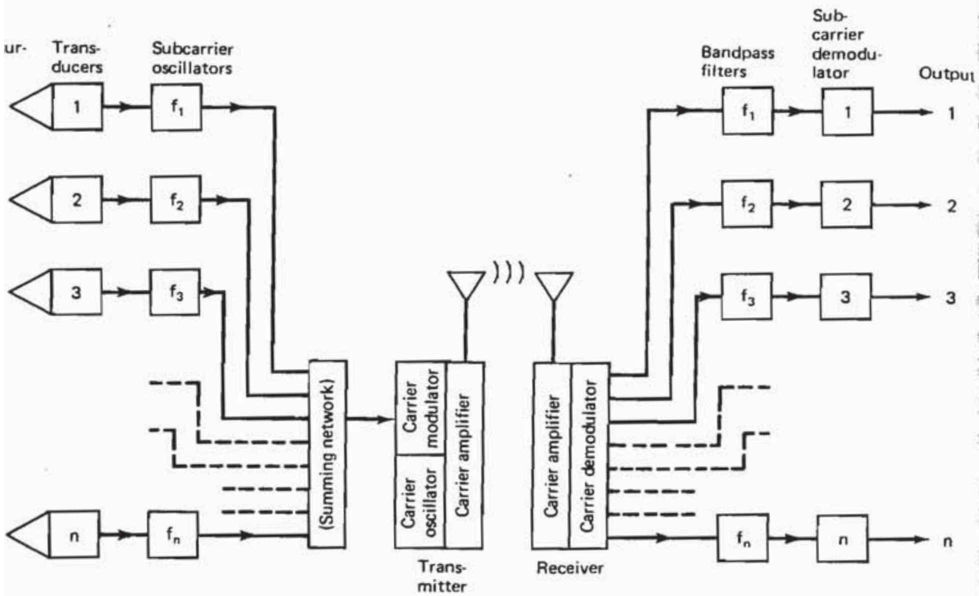

FIGURE 1–5. Frequency-division multiplex telemetry system.

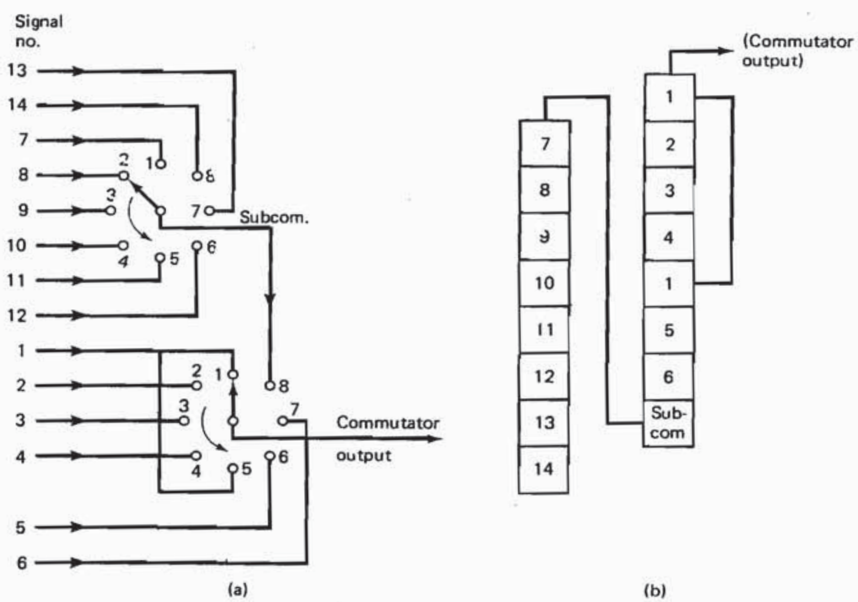

FIGURE 1–6. Commutation (multiplexing) and subcommutation (submultiplexing): (a) electromechanical representation; (b) solid-state representation.

signals are connected. In the example illustrated, the commutator output contains signal 1 sixteen times as often as signals 8 through 15, and it contains signals 2, 3, 4, 5, and 6 eight times as often as signals 7 through 14. This is because the subcommutator advances by only one segment for each full rotation of the commutator, and because signal 1 is *cross-strapped* from commutator segment 1 to segment 5. The example shows a representation typical for electromechanical commutators as well as an equivalent layout for a solid-state commutator that uses solid-state switching logic instead of a motor-driven rotary switch. Virtually all modern multiplexers are solid state.

The reverse process, *decommutation*, is used at the receiving end of the data transmission system to separate the time-sharing measurement signals from the commutated composite data stream. To synchronize the decommutator with the commutator, the transmitted data contain appropriate synchronization signals. They can also contain calibration reference signals, such as the zero- and full-scale levels of a measurement-circuit reference voltage, useful in evaluating the received data accurately.

1.3.3 Modulation Methods for TDM Data

One of the following four basic methods (see Figure 1–7) is generally used to modulate the telemetry subcarrier or carrier with time-division-multiplexed composite signals. In each method the sequential sampling of measurement signals results in a series of pulses (*pulse train*). The simplest of these methods is *pulse-amplitude modulation* (PAM), in which the amplitude (height) of each pulse is an analog of the measurement-signal value at the time it is being sampled by the commutator. The other three methods require a converter to modify the analog measurement signals into the appropriate pulse-type signals.

In *pulse-duration modulation* (PDM) the duration of each pulse (*pulse width*) represents the value of the measurement-signal sample. In *pulse-position modulation* (PPM) this value is represented by the position, in time, of a pulse. A reference pulse train can be transmitted together with the signal pulse train to serve as a repetitive time reference for the positions of the signal pulse. Both PDM and PPM are forms of *pulse-time modulation*.

Pulse-code modulation (PCM) is the most efficient of the four modulation methods because the transmitter power needed to send a given amount of information is less than for the other three methods. The analog signals are converted into a pulse code, usually a series of binary digits, by an analog-to-digital converter (ADC). The value of the sampled measurement signal is thus represented as a discrete amplitude increment, by a digital word. The number of bits used to form each word dictates the resolution obtainable for the data; for example, 127 discrete increments are available when seven-bit words are used ($2^7 - 1$), whereas 511 discrete increments are available when nine-bit words are used in a PCM system (see Table 1–1).

Table 1–1. RESOLUTION OF DIGITIZED ANALOG MEASUREMENT AS FUNCTION OF LENGTH OF DIGITAL WORD

Number of Discrete Increments	*Word Length (bits)*
1	1
3	2
7	3
15	4
31	5
63	6
127	7
255	8
511	9
1023	10
2047	11
4095	12
8191	13
16 383	14
32 767	15
65 535	16
131 071	17
263 143	18
524 287	19
1 048 575	20
2 097 151	21
4 194 303	22
8 388 607	23
16 777 215	24
33 554 431	25

Alternative methods of digital encoding are *frequency-shift keying* (FSK), used in PCM/FM systems, and *phase-shift keying* (PSK), where the transducer output is converted into fixed-step changes of the phase of the modulating signal.

In some time-division multiplex systems a "zero" reference pulse, of the same type as the signal pulse but of a fixed low level, is inserted between consecutive signal pulses. The resulting *return-to-zero* (RZ) waveform affords only a 50% duty cycle but facilitates signal separation after decommutation. The PAM illustration (Figure 1–7(a)) shows such a waveform. When no such signal separation is required, the 100% duty cycle *non-return-to-zero* (NRZ) waveform is used.

Combined multiplexing (time division as well as frequency division) is often used in FM systems in which groups of measurements are commutated into subcarrier oscillators.

The nomenclature of a telemetry system is given by the type of modulation used; for example, in a PAM/FM system a PAM pulse train frequency-modulates the radio-frequency (RF) carrier.

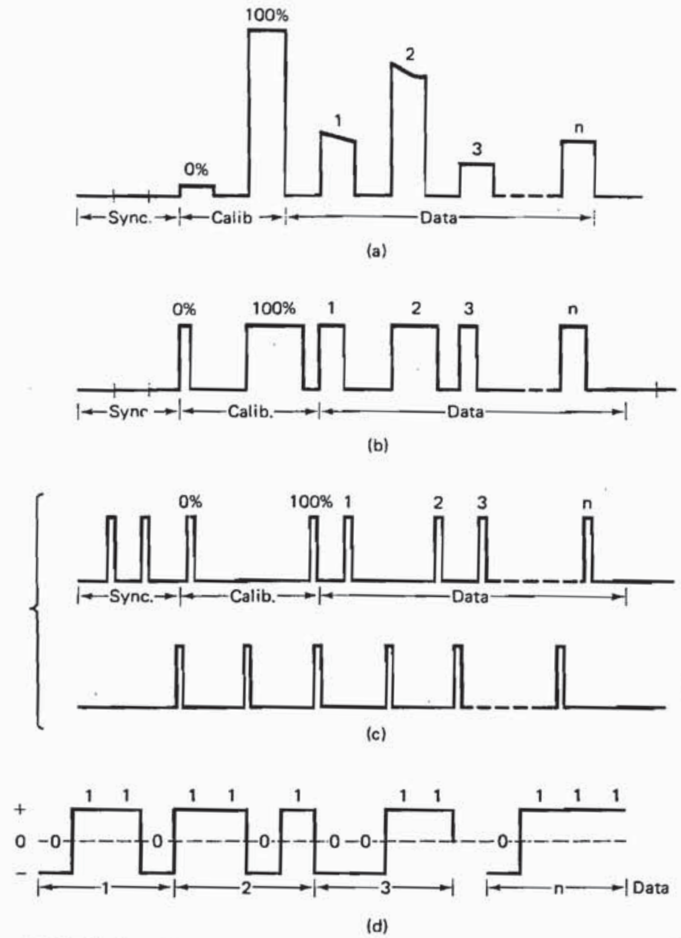

FIGURE 1–7. Time-division multiplexing (TDM) methods: (a) pulse-amplitude modulation (PAM); (b) pulse-duration modulation (PDM); (c) pulse-position modulation (PPM); (d) pulse-code modulation (PCM) (NRZ waveform, four-bit binary encoding).

1.4 DATA CONDITIONING, PROCESSING, AND DISPLAY

1.4.1 Analog Data

The "raw" data provided by a measuring or analyzing system often require a number of different operations to be performed on them to facilitate the determination of the required information (the *data reduction*).

Amplifiers can be used to make the full-scale amplitude of the system output data compatible with the capabilities of a given display unit. Filters can be used to remove noise from data signals or to eliminate high-frequency components (*low-pass filter*), low-frequency components (*high-pass filter*), or frequency components above and below a given frequency band (*band-pass filter*). *Amplitude discriminators* can be employed to create an "on-off" signal as a function of the difference in amplitude between the data signal and a reference signal. *Frequency discriminators* (frequency-to-dc converters) convert frequency variations into amplitude variations. *Rectifiers* convert ac amplitude variations into dc amplitude variations. Bias networks can be used to display only that portion of a data signal that is above or below a preset level. A composite system containing such devices is shown in Figure 1–8.

Data can be recorded on magnetic tape or stored in a computer memory for later playback or readout (*data storage*). Analog data can be digitized (*analog-to-digital converter*), and digital data can be converted into analog form (*digital-to-analog converter*).

1.4.2 Digital Data

The processing of digital data, such as PCM telemetry data or digitized analog data, is usually handled by computer systems. The availability of digital computer systems, varying widely in cost, capability, and complexity, has facilitated data reduction to such an extent that such systems have become attractive to designers and users of even relatively small measuring or analysis systems.

A typical system for digital data processing and display is illustrated

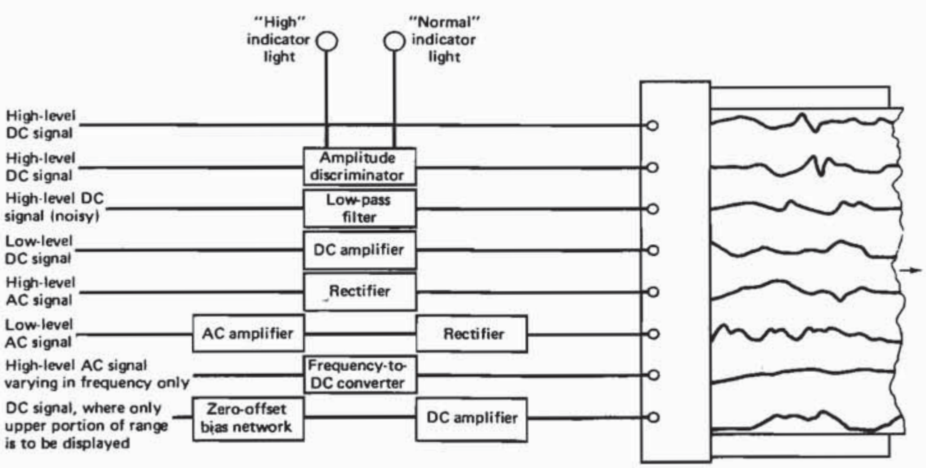

FIGURE 1–8. Analog data conditioning (with displays on multichannel oscillograph).

in Figure 1–9. The incoming composite data stream (from which any RF carrier has been removed) usually consists of a number of sequential data frames. Each data frame starts with a frame synchronization word (typically between 7 and 31 bits in length) and one or more additional identifier words (often including a word indicating at what time the data were acquired); these are followed by the data words. Each word is a group of bits representing either one digitized analog measurement, one event count, or one group of state or mode indications. It is desirable to keep the length of all data words (the number of bits in each word) the same.

The data stream is usually stored on magnetic tape. In some systems it is necessary to delay any further processing at that time, such as when the computer is at a different location or when the computer is not available to the user at the time data are being received. The tape is then played back through the computer at a later time (*recorded data processing*). In the system illustrated, the data stream is simultaneously fed directly to the computer (*real-time data processing*). If any errors occur during processing, or if the data must be processed again for other reasons, the recorded data are then still available on a reel of magnetic tape.

The data are interfaced to the computer. The essential portions of the

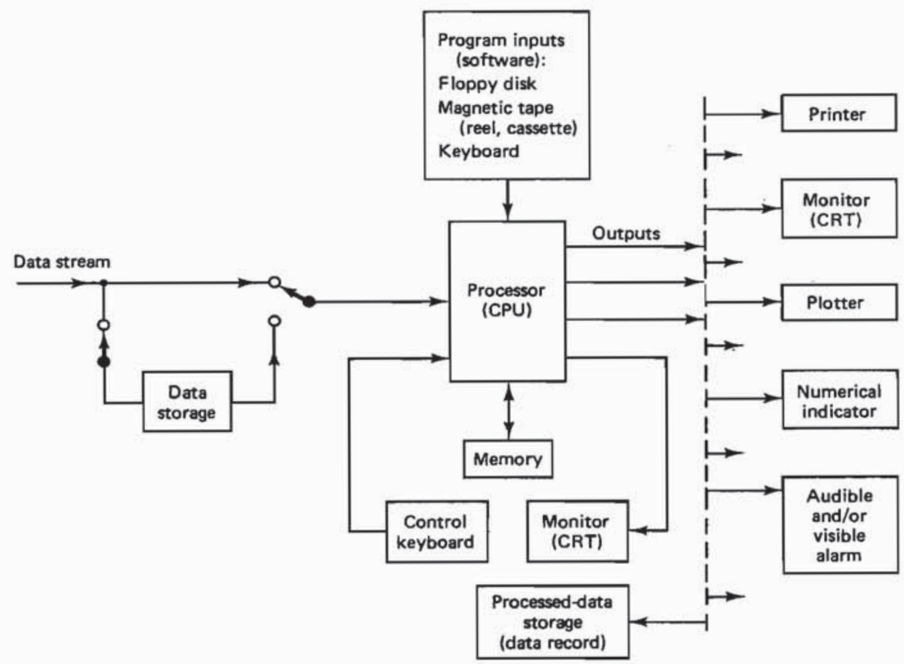

FIGURE 1–9. Digital data processing and display system, block diagram.

data computer are the *processor* (central processing unit or CPU) and the *memory* (typically a magnetic core). Programs required to process the data and to display them in the desired form on various display devices are stored on magnetic tape or disks, or generated from a keyboard. Reader units then feed the appropriate programs to the CPU and its memory. At least one operator's console is a part of the computer system. A keyboard control unit allows the operator to modify or override stored data-processing programs, to alter data display, and to perform diagnostic operations when computer functions are improper.

Among the variety of display units available for computer systems, the most popular are printers and cathode-ray-tube (CRT) monitors, both of which can display data in alphanumeric form (numbers and characters of the alphabet). Printers provide a permanent record of data on paper strips or sheets. Strip printers print one or two relatively short groups of characters per line of an approximately two-inch-wide paper tape (similar to cash-register receipt strips). Line printers (page printers) print a relatively large number of characters on one line of a wide prefolded paper sheet, and then reset to the next line so that sequential pages of data printouts can be obtained. CRT units can similarly show page-type displays of data in alphanumeric form, but do not provide a permanent record. They can also be programmed for display in graphical form. When permanent data records are required in graphical form, X-Y plotters are employed to provide plots of the variation of a given measurand with time or another reference or measurand.

1.4.3 Data Processing

Computer systems allow many different types of special data processing in addition to a sequential display of decommutated data. A few examples are:

1. Converting the decimal equivalent of a digital data word into a decimal number representative of the measured value, expressed in engineering units on the basis of a calibration record (*engineering-unit conversion*).
2. Limiting the display of each measurement to those times when the change of the measured value, compared to its previous value, is significant (i.e., exceeds a specified tolerance). Such *data suppression* facilitates the evaluation of data from a multimeasurement system by a single observer and results in shorter data records.
3. Comparing each data value to predetermined upper and/or lower limits and providing an alarm when the limit is exceeded (*alarm limit test*). The alarm can be in the form of a special character (e.g., an asterisk) next to the display of the data word. It can also be in the form of a warning light or audible tone.
4. Accumulating successive values of the same measurement over a specified period of time, averaging those values, and then displaying the average value (*data averaging*).
5. Accumulating successive values of the same measurement over a specified period of time (or a specified number of data words), determining the largest of these values, and displaying the largest value (*peak search*).
6. Performing mathematical operations on data for one or more measurements and displaying the results (*computer-derived data*), such as multiplying a current measurement by a voltage measurement to display electrical power.
7. Comparing variations of a measurement, over a specified interval, with computer-stored data representative of a "model" of such variations, and displaying data resulting from such a comparison.

1.5 CONTROL SYSTEMS

The purpose of measuring systems is to provide the user with information (data). In control systems employing a human operator as part of the control loop, this information can then be used by the operator to effect a control function manually (e.g., increase a temperature, reduce a pressure, stop a flow, fill a tank, or change a speed). In automatic control systems the output of the sensing or analyzing device is used to effect a control function without the use of a human operator. The former are known as *open-loop* control systems, the latter as *closed-loop* control systems.

The most commonly used automatic control systems are closed-loop systems employing feedback. A feedback loop includes a forward signal path, a feedback signal path, and a signal summing point, which together form a closed circuit. A typical basic closed-loop control system is illustrated in Figure 1–10. It operates in the following manner (equivalent terms commonly used in process control are shown in brackets):

A specific quantity within a *controlled system* [*process*] is to be maintained at a specified magnitude. This *controlled quantity* [*controlled variable*] is measured by a sensing device, usually a transducer [*transmitter*]. The output of the sensing device, which may or may not have to be conditioned in some manner, is fed to a *comparing element*, or *summing point* [*set point*], in a *regulating device* [*controller*]. At this point, the signal fed back from the *sensing device* [*feedback signal*] is compared with a *reference signal* [*set-point signal*]. If the two signals are of the same magnitude, or within a relatively narrow tolerance from each other [*dead band*], no further action occurs. If the two signals differ from each other by an amount larger than that tolerance, a regulating signal is sent to a *control device* [*final controlling element*]. This signal causes the control device to change a quantity or condition (*manipulated quantity*) [*manipulated variable*] in the controlled

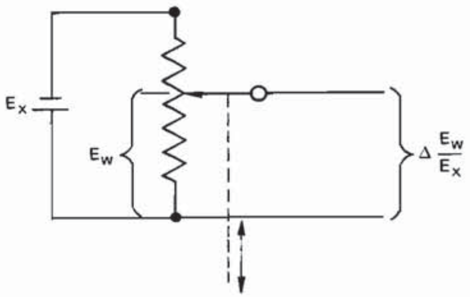

FIGURE 2–7. Potentiometric transduction.

stone bridge. This transduction principle is a special version of resistive transduction; however, it involves either two or four resistive strain transducers (*strain gages*) connected into a Wheatstone-bridge circuit across which excitation is applied, so that the output is a voltage change (Figure 2–8). Upward arrows in the illustration indicate increasing resistances, and downward arrows indicate decreasing resistances, in the arms of the bridge, that are simultaneously effected (in a *four-active-element bridge*) by a change in measurand due to the placement and connection of the individual resistive elements; in the example illustrated (an unbonded-strain-gage element) the indicated directions of the resistance changes would occur as the sensing link moves toward the left.

Photoconductive transduction elements convert a change in measurand into a change in the resistance (or conductance) of a semiconductor material due to a change in the amount of illumination incident upon the material (Figure 2–9).

Photovoltaic transduction elements convert a change in measurand into a change in the voltage generated when the illumination incident upon a junction between certain dissimilar materials changes (Figure 2–10).

Thermoelectric transduction elements convert a change in measurand into a change in the electromotive force (emf) generated by a temperature difference between the junctions of two selected dissimilar materials (due

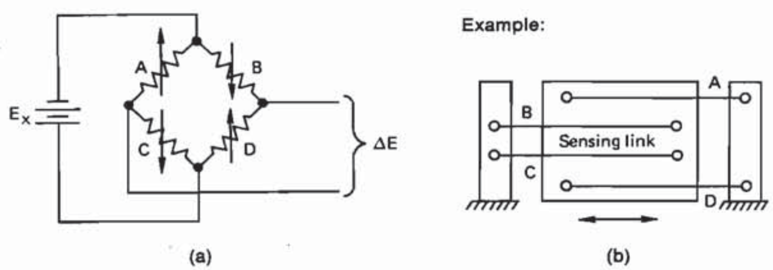

FIGURE 2–8. Strain-gage transduction: (a) basic circuit; (b) example.

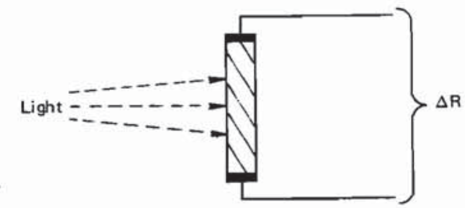

FIGURE 2–9. Photoconductive transduction.

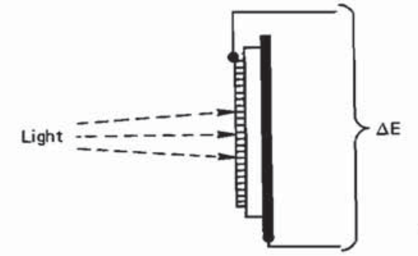

FIGURE 2–10. Photovoltaic transduction.

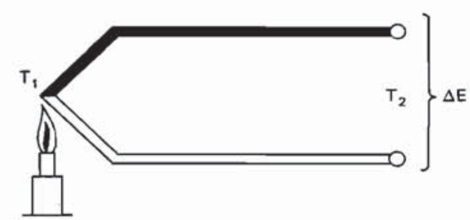

FIGURE 2–11. Thermoelectric transduction.

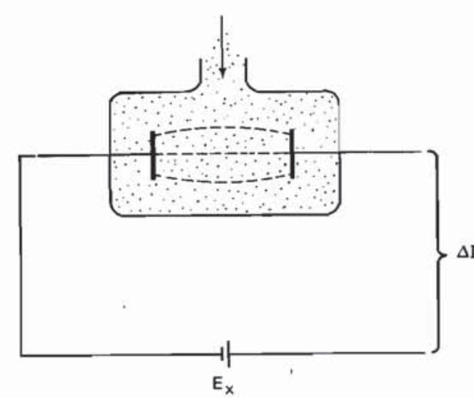

FIGURE 2–12. Ionizing transduction.

to the *Seebeck effect*). In the basic thermoelectric element shown in Figure 2–11, a junction between the output terminals (at which temperature T_2 prevails) would be formed, for example, by a voltmeter connected across the terminals.

Ionizing transduction elements convert a change in measurand into a change in ionization current, such as through a gas between two electrodes (Figure 2–12).

2.3 GENERAL TRANSDUCER CHARACTERISTICS

In general, transducer characteristics can be categorized into design, performance, and reliability characteristics. Sections 2.4, 2.5, and 2.6 define and explain a fairly complete set of these characteristics. All of these should be considered when specifying a transducer or selecting one from manufacturers' catalogs and bulletins; however, not all of them may be important or applicable to a given type of transducer. On the other hand, a few specialized characteristics are only important to one category of transducers; these are not included here, but are explained in the chapter dealing with this category.

Throughout this book, when two or more terms are shown for some of the transducer characteristics, as well as for some other expressions, the preferred term (which is usually a term defined in ANSI Standard MC6.1, "Electrical Transducer Nomenclature and Terminology") is printed in italics. Alternative terms whose usage is generally acceptable in a proper context are shown in parentheses. Terms whose usage is not recommended are shown in quotation marks.

2.4 DESIGN CHARACTERISTICS

The design characteristics of a transducer describe or specify how the transducer is (or should be, in a user-written specification) designed and constructed and what its "rating" is in terms of measuring range. As shown in Table 2–2, they pertain to the range, the electrical design, and the mechanical design of a transducer.

2.4.1 Measurand Characteristics

A transducer is normally designed to sense a specific measurand and to respond only to this measurand. For example, pressure transducers provide an output indicative of pressure, and acceleration transducers (accelerometers) provide an output representative of acceleration. Other measurands can often be calculated by their known relationship to the measurand sensed by the transducer. Thus, velocity can be calculated from measurements of displacement and time, and altitude (above sea level) as well as water depth

Table 2–2. TRANSDUCER DESIGN CHARACTERISTICS

Measurand	*Electrical*	*Mechanical*
Range	Excitation	Configuration
Overrange	Isolation	Dimensions
Recovery time	Grounding	Mountings
	Source impedance	Connections
	Load impedance	Case material
	Input impedance	Materials in contact with measured fluids
	Output impedance	Case sealing
	Insulation resistance	Identification
	Breakdown voltage rating	
	Gain instability	
	Output	
	End points	
	Ripple	
	Harmonic content	
	Noise	
	Loading error	

(below sea level) can be derived from pressure measurements. Various de terminations can be inferred from one or more transducer output signals For example, bearing wear can be inferred from accelerometer outputs, an electrical power can be calculated from the outputs of a current transduce and a voltage transducer. Each transducer, however, is specified by its basi measurand and its measuring range.

The *range* of a transducer is given by the upper and lower limits c measurand values it is intended to respond to within specified performanc tolerances. A range can be *unidirectional* (e.g., "0 to 5 cm"), or *bidirection* (either symmetrically, e.g., "±20 N", or asymmetrically, e.g., "−10 t +30 N"), or *expanded* (*zero-suppressed*) (e.g., "90 to 120 L/s"). The a gebraic difference between the two range limits is the *span* of the transduce The span of a 90-to-120 L/s flowmeter is 30 L/s; the span of a −10-to-+3 N force transducer is 40 N.

The *overrange* (overload, maximum measurand; *proof pressure* for pressure transducer) is the maximum magnitude of measurand that can b applied to a transducer without causing a change in performance beyor specified tolerances. The *recovery time* is the amount of time allowed t elapse after removal of an overrange condition before the transducer aga performs within the specified tolerances.

2.4.2 Electrical Design Characteristics

The basic electrical design characteristics of a transducer are illustrated Figure 2–13, in which a transducer is viewed as a "black box," that i without regard to its internal workings and primarily as a device with whic other electrical or electronic equipment must interface electrically.

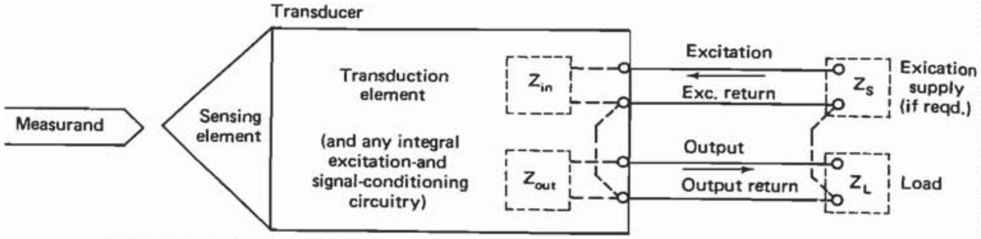

FIGURE 2–13. Basic "black-box" electrical characteristics of a transducer.

With the exception of the self-generating types (unless they include integrally packaged conditioning circuitry), transducers require *excitation,* i.e., externally supplied electrical power (expressed in terms of voltage or current, or both) applied to them for their proper operation. The impedance of the excitation supply presented to the transducer is the *source impedance* (Z_s), of which the impedance of the excitation cabling is considered a part. In the opposite direction, the impedance of the transducer presented to the excitation supply is the *input impedance* (Z_{in}). The impedance measured across the output terminals of the transducer is the *output impedance* (Z_{out}). In the opposite direction, the impedance presented to these output terminals by the external circuitry they connect into is the *load impedance* (Z_L). The impedance of the cabling between the transducer and the external circuitry (the *load*) is included in Z_L.

The diagram in Figure 2–13 is intended to be general. The excitation return and output return are separate for many types of transducers, such as the strain-gage types (see Figure 2–8), as well as for the many designs incorporating excitation conditioning or signal conditioning (or both) inside the transducer housing. Some types of transducers (e.g., the potentiometric versions; see Figure 2–7) use only one return, and this is indicated by the dashed jumpers at both ends of the return lines. Other types, e.g, resistive transducers (see Figure 2–6), may be simple two-terminal devices in which the passive transduction element is essentially connected between "excitation" and "excitation return."

Shielding and grounding considerations are very important in instrumentation systems, in which signal levels are typically quite low and can be affected by noise pickup, ground loops, and common-mode voltages. When a transducer is enclosed in a housing (case) the return lines (and internal grounds) are usually not electrically connected to the case; instead, a single-point ground is established at the excitation supply or at the load. The excitation and output lines may stay entirely disconnected from an external ground (earth ground), and only the shielding of the wires is eventually connected to such a ground. At the transducer end, the shield around the wires is kept unconnected, unless it is connected to a terminal leading to an

internal shield (*a guard*) which itself is not connected to the case or any internal grounds (*floating grounds*). In some transducers, special provisions, such as transformer coupling, are included to isolate the excitation side completely from the output side.

When two or more portions of a transducer are electrically insulated from each other, the resistance between them, as measured while a specified dc voltage is applied, is the *insulation resistance*. The degree of insulation can also be expressed in terms of the *breakdown voltage rating,* the magnitude of ac or dc voltage that can be applied across specified insulated portions without causing arcing and without causing conduction between the portions, above a specified value of current. The *breakdown voltage,* which is established by a test generally considered destructive, is the magnitude of voltage at which arcing or excessive conduction occurs.

Output is the electrical quantity produced by a transducer and is a function of the applied measurand. The output is usually a continuous function of the measurand (*analog output*) in the form of voltage amplitude, voltage ratio, or current, or sometimes just as changes in capacitance, inductance, and so on. *Frequency output,* where the number of cycles or pulses per second are a function of the measurand, and *frequency-modulated output*, i.e., frequency deviations from a "center" frequency (e.g., "3000 ± 200 Hz"), are also forms of analog output. *Digital output* represents the measurand in the form of discrete quantities coded in some system of notation (e.g., binary code). Output that represents the measurand in the form of discrete or quantized values not coded in any system of notation is sometimes referred to as *discrete-increment output*; such an output is exemplified by that of a switch-type transducer.

End points are the output values at the lower and upper limits of the range of a transducer. They can be the mean of end-point readings determined over two or more consecutive calibration cycles. When end points are specified, a tolerance is usually applied to them (e.g., "0.00 ± 0.02 and 10.00 ± 0.01 V dc"). No such tolerances are allowed for *theoretical end points*, the points between which the theoretical curve is established (see Section 2.5.1). Theoretical end points are not necessarily established at 0% measurand, 0% output (lower end point) and 100% measurand, or 100% output (upper end point); however, when they are set at these values, they are referred to as *terminal end points*.

As for any other electronic device, it is important for transducers to be appropriately matched to, and interfaced with, the associated measurement system. One of the areas that tends to be overlooked is matching output impedance to load impedance. A mismatch in these impedances can cause *loading error,* which increases with the ratio of output impedance to load impedance. Careful attention must also be paid to manufacturer-recommended excitation supply characteristics.

Certain electrical characteristics need to be watched (and probably need tolerances assigned to them in a transducer specification) when excitation-conditioning or output-conditioning circuitry is incorporated within a transducer. The output of an ac-to-dc converter (demodulator) in a transducer, for example, may contain a measurable ac component (*ripple*). Similarly, the output from an integrally packaged amplifier may contain random disturbances (*noise*) and may be subject to changes in the characteristics of amplifier components that result in *gain instability*. When the output of a transducer is sinusoidal ac, it may contain distortions due to the presence of harmonics (frequencies other than the fundamental frequency); this *harmonic content* is usually expressed as a percentage of the rms output of the transducer.

2.4.3 Mechanical Design Characteristics

Mechanical design characteristics complement the electrical design characteristics in that they define primarily the *physical* interfaces of the transducer.

The mass ("weight") typically starts the list of these characteristics. Next is the configuration (best shown in the form of a drawing), which shows all pertinent dimensions and the location and orientation of all external mechanical, electrical, and fluid connections, including any mounting holes. The locations of any special provisions, such as those used for zero and gain adjustment, are included on the drawing. All external connections should be identified by type and (unless they are defined by an industrial or government standard) by their dimensions and materials. Case (housing) materials (and finish) and the type of case sealing should be specified. The materials that can come in contact with a measured fluid should also be stated; alternatively, the categories of measured fluids that may come in contact with those portions of a transducer that can be exposed to them can be specified (e.g., "noncorrosive liquids and gases" or "nonconductive fluids").

Some applications require that certain industrial or governmental standards or codes be adhered to by the transducer. This is often the case when, for example, a transducer must operate as part of a sealed system, must be explosion proof, must be waterproof, or must operate in a hazardous environment such as might contain nuclear radiation. The codes or standards that the transducer can meet are then stated.

Identification (nameplate information) is another important mechanical characteristic. Such information either is shown on a separate nameplate attached to the transducer case, or is directly etched or engraved on the case. Except for those rare instances when such information is limited by a very small transducer size, it is possible to include fairly complete information. It should really be possible for a user to install and connect a transducer without looking up drawings and specifications. Thus, the nameplate

information should include proper nomenclature and the most pertinent characteristics, such as range, excitation, output, identification of electrical connections, and, of course, the name and location of the manufacturer and the part number and serial number of the transducer. Additional information may be required by applicable standards or codes and (when user specified) by special needs of the user.

2.5 PERFORMANCE CHARACTERISTICS

Transducer performance characteristics, summarized in Table 2–3, are generally categorized as follows:

Table 2–3. TRANSDUCER PERFORMANCE CHARACTERISTICS

Static	*Dynamic*	*Environmental*
Resolution	Frequency response	Operating environmental effects
Threshold	Transient response:	Operating temperature range
Creep	Response time	Thermal zero shift
Hysteresis	Rise time	Thermal sensitivity shift
Friction error	Time constant	or
Repeatability	Natural frequency	Temperature error
Linearity (+ reference line)	Damping	or
Sensitivity	Damping ratio	Temperature error band
Zero-measured output	Overshoot	Temperature gradient error
Sensitivity shift	Ringing frequency	Acceleration error
Zero shift		or
Conformance (+ reference curve)		Acceleration error band
or		Attitude error
Static error band (+ reference line or curve)		Vibration error
Reference lines:		or
Theoretical slope		Vibration error band
Terminal line		Ambient-pressure error
End-point line		or
Best straight line		Ambient-pressure error band
Least-squares line		Mounting error
Reference curves:		Nonoperating environmental effects
Theoretical curve		Type-limited environmental effects
Mean-output curve		Conduction error
		Strain error
		Transverse sensitivity
		Reference-pressure error

1. *Static characteristics,* which describe performance at room conditions, with very slow changes in the measurand, and in the absence of any shock, vibration, or acceleration (unless one of these is the measurand); although there is some disagreement as to what conditions constitute *room conditions,* they have generally been established as the following (unless specifically stated otherwise): a temperature of 25 ± 10°C, a relative humidity of 90% or less, and a barometric pressure of 880 to 1080 mbar (88 to 108 kPa).
2. *Dynamic characteristics,* which relate to the response of a transducer to variations of the measurand with time.
3. *Environmental characteristics,* which relate to the performance of a transducer after exposure (*nonoperating* environmental characteristics) or during exposure (*operating* environmental characteristics) to specified external conditions (such as temperatures, shock, or vibration).

2.5.1 Static Characteristics

An ideal or theoretical output-measurand relationship exists for every transducer. If the transducer were ideally designed by ideal designers, and if it were made from ideal materials by using ideal methods and workmanship, the output of this ideal transducer would always indicate the true value of the measurand. The output would follow exactly the prescribed or known *theoretical curve* which specifies the relationship of the output to the applied measurand over the transducer's range. Such a relationship can be stated in the form of a table of values, a graph, or a mathematical equation. Figure 2–14 illustrates a theoretical curve both in general terms (percent of full-scale output, or *% FSO,* vs. measurand expressed in percent of range) and for the example of a pressure transducer whose range is 0 to 1000 psia (0 to 6895 kPa) and whose output is 0 to 5 V dc, for the case of a *linear* output–measurand relationship, which causes the curve to be a straight line.

The output of an actual transducer, however, is affected by the nonideal behavior of the transducer, which causes the indicated measurand value to deviate from the true value. The algebraic difference between the indicated value and the true (or theoretical) value of the measurand is the transducer's *error.* Error is usually expressed in % FSO, sometimes in percent of the output reading of the transducer ("% of reading"), or in terms of units of the measurand. *Accuracy* is defined as the ratio of error to full-scale output, usually expressed in the form "within ± ____% FSO," sometimes in terms of units of measurand or in percent of the error/output ratio.

Although the simplest way to consider transducer errors is in terms of maximum deviations from a specified reference line or curve which defines the output-measurand relationship over the transducer's range (*error band*),

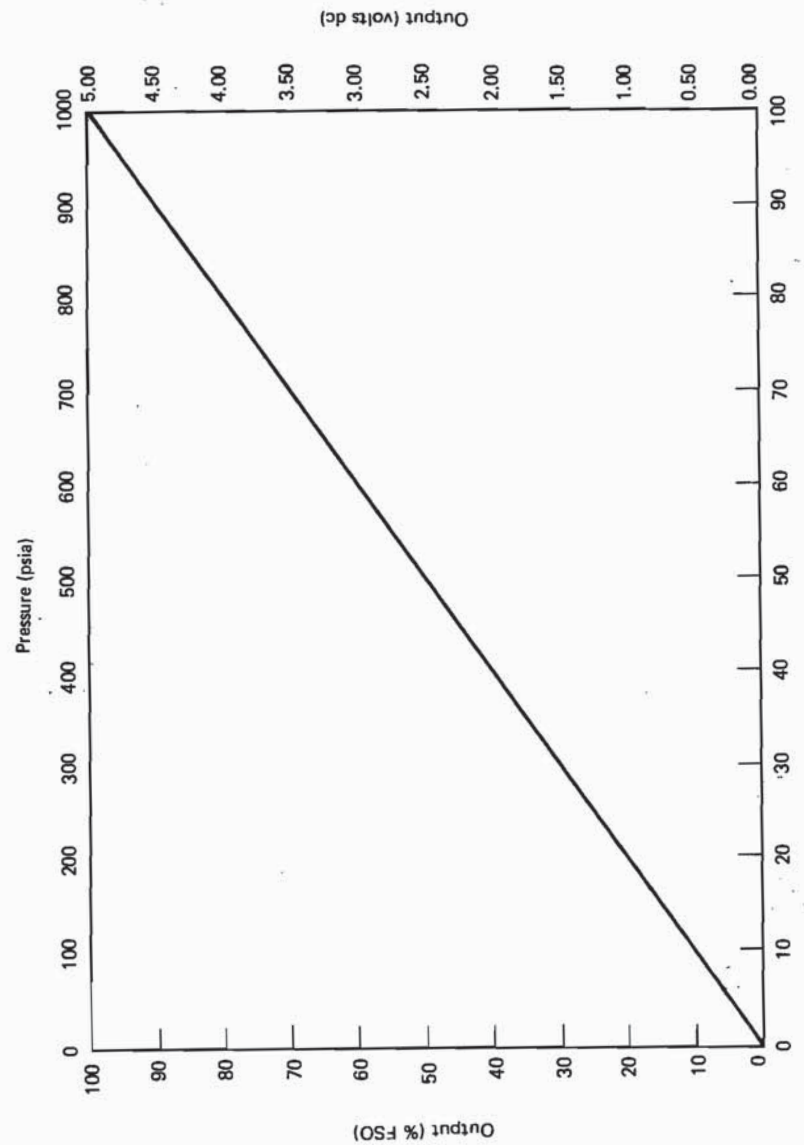

FIGURE 2–14. Output-measurand relationship of ideal linear-output transducer (including application of general example to a typical dc output pressure transducer).

the existence of individual errors such as nonlinearity, nonrepeatability, hysteresis, zero shift, and sensitivity shift must be recognized, and the nature of these errors must be understood. The effects of these errors on transducer behavior and data obtained should be known; such knowledge can often be used to correct final data and increase data accuracy.

Error characteristics are determined by *calibration*. This term usually implies a *static calibration*, performed for the purpose of determining static characteristics, unless the term *dynamic calibration* (see Section 2.5.2) is specifically used. A (static) calibration is a test during which known values of measurand are applied to a transducer and corresponding output readings are recorded. The resulting test record, when in the customary tabular form, is the *calibration record*. When it is in graphical form, it is referred to as *calibration curve*. Note that a calibration curve can also be plotted on the basis of a calibration record, manually or by the use of a computer. A single performance of this test over the entire range of the transducer (unless a *partial-range calibration* is specified), once with increasing and once with decreasing measurand, is called a *calibration cycle*. A complete calibration usually comprises two or more calibration cycles, which are commonly referred to as "Run 1," "Run 2," and so on.[1] Individual errors, as determined by calibration, are explained subsequently.

Hysteresis (see Figure 2–15) is the maximum difference in output, at any measurand value within the (specified) range, when the value is approached first with increasing and then with decreasing measurand. Many types of transducers exhibit hysteresis, which is typically caused by a lag in the action of the sensing element. Hysteresis is expressed in % FSO. The hysteresis seen when only a portion of the range is traversed (e.g., 0 to 30%, as shown in the illustration) is always less than the total hysteresis. Some type of transducers, notably potentiometric transducers, exhibit an error that looks like hysteresis but should not be confused with it. This error is typically caused by sliding friction between the wiper arm and the potentiometric element and is called *friction error*. Such friction effects can be minimized by *dithering* the transducer, i.e., applying intermittent or oscillatory acceleration forces to it (sometimes called "tapping"). When such a transducer is dithered during a calibration, its true hysteresis can be established. However, unless dithering is specified, friction error is included with hysteresis. *Friction error* is often determined as the maximum change in output at any measurand value within the range before and after minimizing friction within the transducer. A calibration during which dithering is employed (e.g., by mounting a small buzzer against the transducer) is called a *friction-free calibration*. Such a calibration should be used only when the intended application of the transducer can reasonably be expected to minimize friction error equally.

[1] Calibrations of certain categories of transducers, e.g., temperature transducers, are performed quite differently (see the subsequent chapters dealing with these categories).

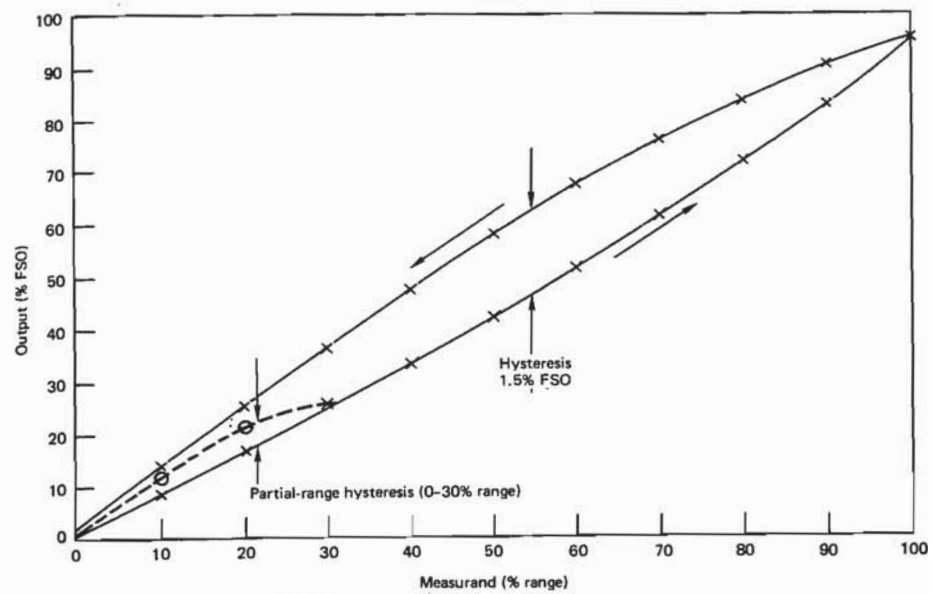

FIGURE 2–15. Hysteresis (scale of errors 10:1).

Repeatability (sometimes called "reproducibility") is the ability of a transducer to reproduce output readings when the same measurand value is applied to it consecutively under the same conditions and in the same direction. It is expressed as the maximum difference between output readings as determined by two calibration cycles (see Figure 2–16), unless otherwise specified, and is usually stated as "within ____% FSO." If the sampling is increased by increasing the number of calibration cycles, a better statistical measure of repeatability can be obtained.

Linearity is the closeness of a transducer's calibration curve to a specified straight line. It is expressed as "within ±____% FSO" (in a specification) or as "within +____, −____% FSO" (as a result of a calibration)—in effect, the maximum deviation of any calibration point from the corresponding point on the specified straight line during any one calibration cycle. When more than one calibration run is made, the worst linearity seen during any one calibration cycle is stated. "Linearity," when not accompanied by a statement explaining what sort of straight line it is referring to, is meaningless. A transducer may have an independent linearity within ±0.5% FSO while its terminal linearity is within ± 3.5% FSO. The specific type of reference line is stated either by adding a modifier to the word "linearity" (e.g., "terminal linearity") or by adding a statement such as "referred to the best straight line." The various types of linearity are as follows.

Theoretical-slope linearity is referenced to the *theoretical slope*, the

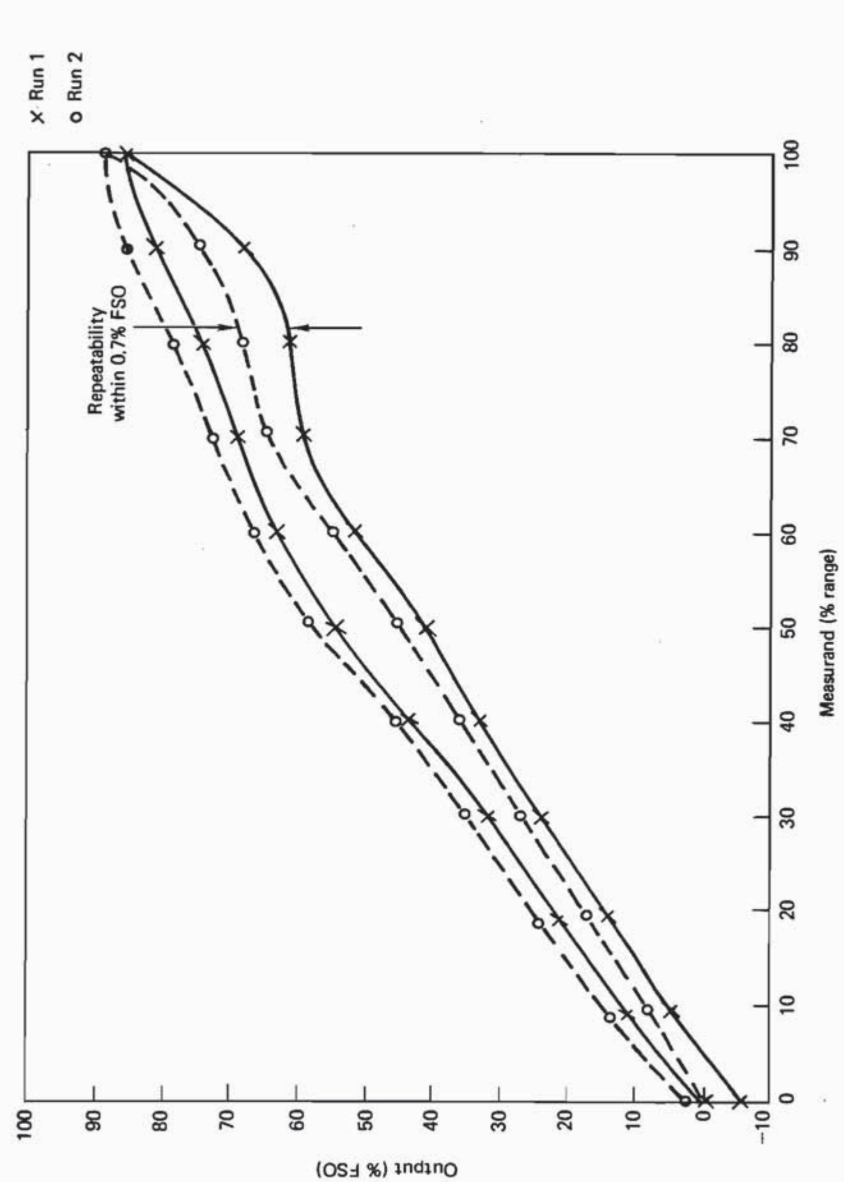

FIGURE 2–16. Repeatability (scale of errors 10:1).

straight line between the *theoretical end points*. These are usually close to 0% FSO (for 0% range) and close to 100% FSO (for 100% range), but can be purposely offset (e.g., 5% FSO at 0% range and 95% at 100% range). Since no tolerances apply to theoretical end points, the theoretical slope can always be drawn without referring to any measured values.

Terminal linearity is referenced to the *terminal line* (see Figure 2–17), a special form of theoretical slope for which the theoretical end points are exactly 0% and 100% of both the range and the full-scale output.

End-point linearity is referenced to the *end-point line,* the straight line between the *end points*, i.e., the outputs at the upper and lower range limits obtained and averaged (unless otherwise specified) during any one calibration. End-point tolerances should be specified.

Independent linearity is referenced to the "*best straight line*" (see Figure 2–18), a line midway between the two parallel straight lines closest together and enveloping all output values on a calibration curve. The best straight line can be drawn only after a calibration has been completed.

Least-squares linearity is referenced to the *least-squares line,* that straight line for which the sum of the squares of the residuals is minimized. The term "residual" refers to the deviations of output readings from their corresponding values on the straight line calculated. The calculation is usually performed with the aid of a computer.

Some additional types of linearity have been used at times, such as

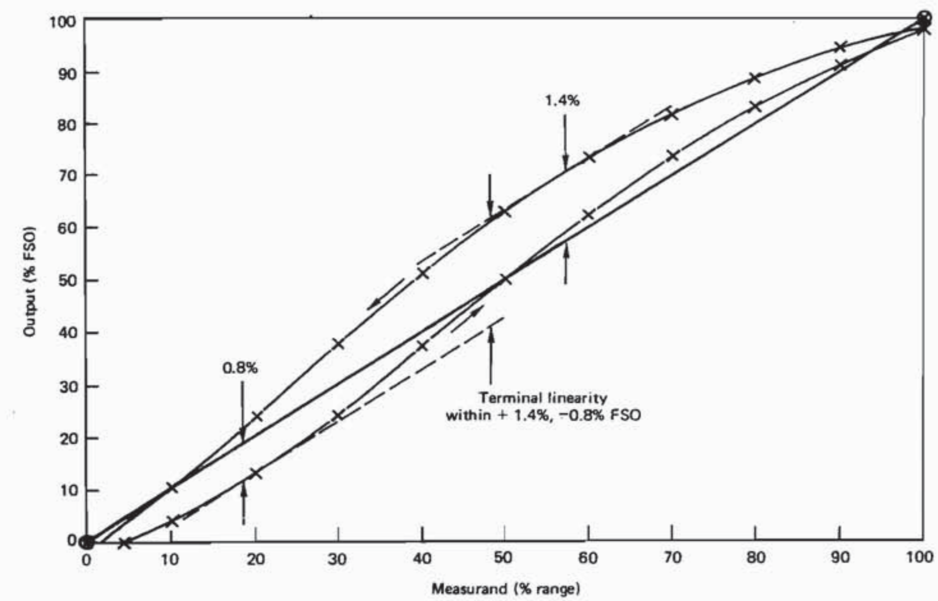

FIGURE 2–17. Terminal linearity (scale of errors 10:1).

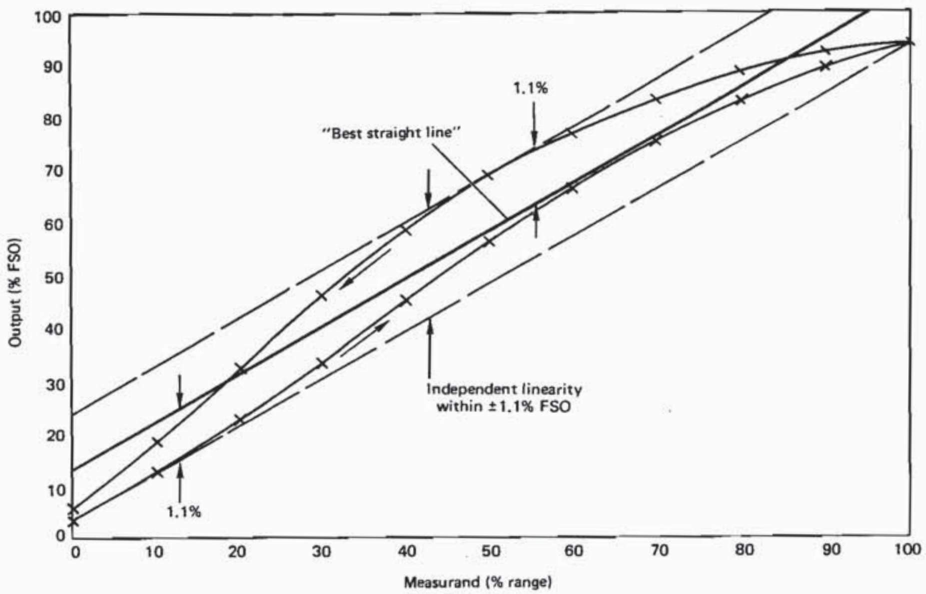

FIGURE 2–18. Independent linearity (scale of errors 10:1).

"independent linearity with forced zero" or "with fixed *Y*-intercept," which require that the best straight line also pass through a specified point (*point-based linearity*). It has been argued that specifications (and calibration results) for linearity actually include hysteresis, since linearity is determined by means of a bidirectional calibration cycle; some commercial literature, therefore, refers to "combined linearity and hysteresis," referred to a specific straight line, typically the "best straight line."

Conformance (or "conformity") is a term that has sometimes been applied to the closeness of a calibration curve to a specified curve for an inherently nonlinear transducer. It is typically referred to a theoretical curve, although least-squares and other fits have also been used.

Resolution and *threshold* are both descriptive of "smallest increment," but are quite different characteristics. When the measurand is continuously varied over the range, the output of certain transducers will not be perfectly smooth, but instead will change in small (but measurable) steps. This is typical for potentiometric transducers with wire-wound elements: small step changes in the output occur as a result of the wiper sliding from wire turn to wire turn. The magnitude of the output step changes as the measurand is continuously varied over the range is the *resolution* of the transducer. It is expressed in % FSO and is not equal for potentiometric transducers with wire-wound elements. Some steps will be larger and some smaller, varying with minute variations in turn spacing and wire thickness. The term *average*

resolution, then, is applied to the reciprocal of the total number of output steps over the range, multiplied by 100 and expressed in % FSO (or percent of voltage ratio, i.e., % *VR*). The magnitude of the largest of all observed output steps, also expressed in % FSO or % VR, is the *maximum resolution*. The resolution of digital-output transducers (for which step changes are inherent and equal) is given by the number of bits in the data words or, in the case of incremental digital-output transducers, by the number of "on" indications obtained per unit length or angle or revolution. When there are no measurable step changes in the output of a transducer, it is said to have *continuous resolution* (sometimes erroneously referred to as "infinite resolution," since "infinitesimal" would be more appropriate).

A change in measurand of finite magnitude is required to cause a change in the output of any transducer. In some types of transducers, those minimal measurand changes are not measurable. In others they may be measurable but are negligible for a given application, or they may be significant only at the lower limit of the range. The smallest change in measurand that will result in a measurable change in output is the *threshold* of the transducer. It is usually stated in terms of measurand and may have different values in different portions of the range.

Sensitivity (which has at times been confused with threshold) is simply the ratio of the change in output to the change in the value of the measurand. It establishes the slope of the calibration curve.

There are three characteristics which are time dependent: creep, zero shift, and sensitivity shift. *Creep* is a change in output occurring over a specific time period during which the measurand is held constant (at a value other than zero) and while all other conditions that may influence the reading (e.g., environmental conditions) are held constant. The determination of creep cannot be done by means of a static calibration; it requires a separate test. *Zero shift* is a change in the zero-measurand output over a specific period of time at room conditions (in a specification it is the maximum allowable change). The *zero-measurand output* (the "zero") is the output of the transducer under room conditions with nominal excitation and zero measurand applied. Zero shift is characterized by a parallel displacement of the entire calibration curve. *Sensitivity shift* is a change in the slope of the calibration curve due to a change in sensitivity over a specific period of time at room conditions (in a specification it is the maximum allowable change). Zero shift can be determined by a simple test, equivalent to the beginning of a calibration cycle. Sensitivity shift can be determined by performing one calibration cycle (or more than one if a statistical refinement of the result is needed) at the end of the specified time period. There is a difference between *short-term* and *long-term* zero and sensitivity shifts: the former tend to be specified in terms of hours, the latter (which could be considered reliability characteristics) in terms of months or years.

The concept of *error band* was originally developed by the author, assisted and inspired by his colleagues at a large aerospace facility, to simplify the specification and determination of transducer errors. An *error band* is the band of maximum deviations of output values from a specified reference line or curve due to causes attributable to the transducer. Since such deviations may be due to nonlinearity, nonrepeatability, hysteresis, zero shift, sensitivity shift, and so on, it can be seen that transducer characteristics are easier to specify and determine when individual characteristics need no longer be specified and determined. An error band is specified in terms of "± ____% FSO," and is determined on the basis of maximum deviations observed over at least two consecutive calibration cycles (so as to include repeatability) and then expressed as "+____%, −____% FSO." A specific reference line or curve must be stated for an error band, and the term "error band" is modified by a term denoting applicable environmental conditions and, when required, other special conditions. The types of straight lines an error band can be referred to are the same as those used for linearity.

The *static error band* is the error band applicable at room conditions and in the absence of any shock, vibration, or acceleration (unless one of these is the measurand). Figure 2–19 illustrates a static error band referred to the terminal line, as it may have been specified (as "±2.0% FSO") and as it may have been determined over two consecutive calibration cycles. It can be seen that the actual error band, "+1.5%, −1.1% FSO," indicates that the transducer is well within specifications. Further scrutiny of the calibration curves (which, however, is not needed for making an accept/reject decision) shows enough information for determination of individual characteristics when such knowledge is required.

When a number of transducers of the same design, range, and output ("of the same part number and dash number") are used in a given measurement system, and when errors within the error band specified for this transducer are acceptable to the system, the calibrations for each of these transducers (as long as each unit was accepted) can be considered *interchangeable* (within the error-band tolerances). This means that it would not be necessary to use individual calibration records for data reduction; the individual calibrations then serve merely as "acceptance records."

Static error bands can be referred to any of the lines explained for *linearity*. They can also be referred to any curve that can be specified by means of a graph, a table of values, or a mathematical equation. Figure 2–20 shows a static error band referred to a theoretical curve (i.e., one that can be drawn before any measured values are obtained); the shape of the curve was selected arbitrarily for the purpose of illustration. Narrower static error bands can be obtained when linearity, or conformance to a prescribed curve, is not required. Such requirements can be waived when final data are to be reduced on the basis of a complex curve that represents the actual transfer function of the transducer over its measuring range. The curve is

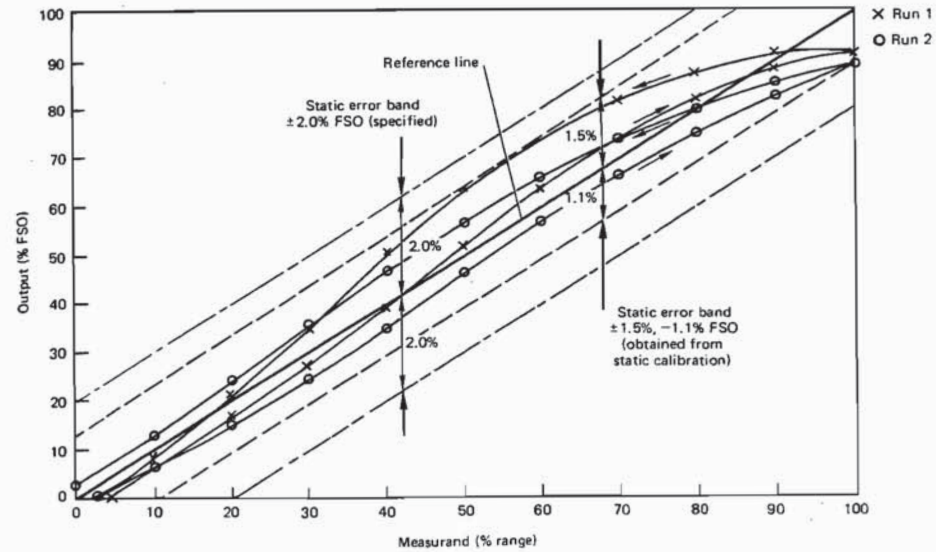

FIGURE 2–19. Static error band referred to the terminal line (error scale 10:1).

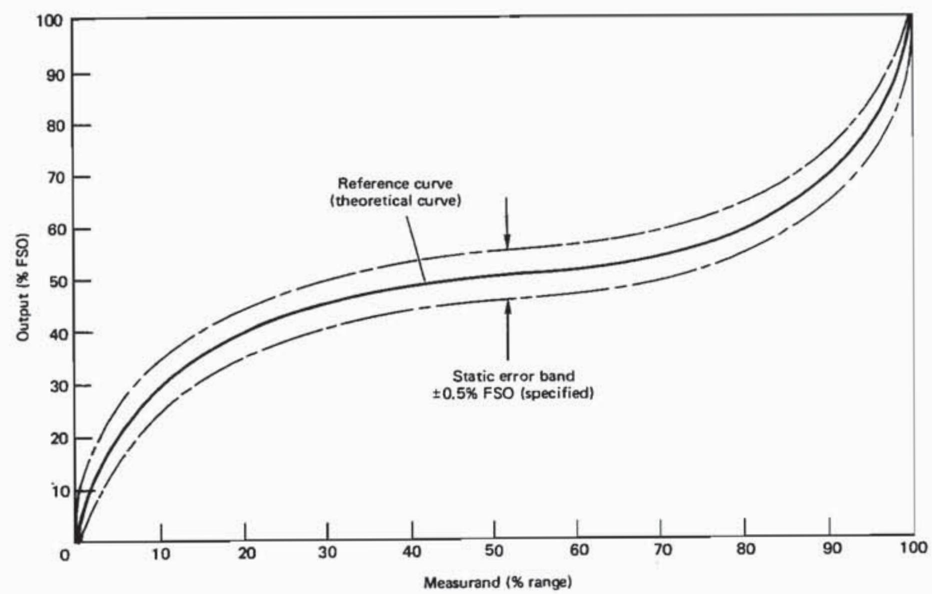

FIGURE 2–20. Static error band referred to a theoretical curve (error scale 10:1).

usually different for every transducer of the same part number. Data reduction then requires that a calibration record be generated for each transducer on the basis of multiorder polynomials. (This may sound difficult, but it is really quite a simple programming task.) A hard copy can then be obtained for each calibration record by using a plotter. More importantly, the conversion file is stored in the computer that is used for data reduction, so that incoming data are automatically reduced on the basis of the respective calibration records. An example of such an error band is shown in Figure 2–21. This static error band is referred to the *mean-output curve*, the curve plotted through the mean of output readings obtained during a specified number (three in the example shown) of consecutive calibration cycles. It can be seen that the deviations of output readings are due to nonrepeatability and hysteresis only.

In some applications transducer accuracy is of prime importance in only a limited portion of the range; accuracy in the other portions can be sacrificed. For such cases a *stepped static error band* can be used (see Figure 2–22 for an example; the theoretical end points were arbitrarily offset). Specifying this type of error band relieves the transducer manufacturer from providing very low error over the entire range of the transducer, while offering the user very good accuracy in the portion of the range of primary interest.

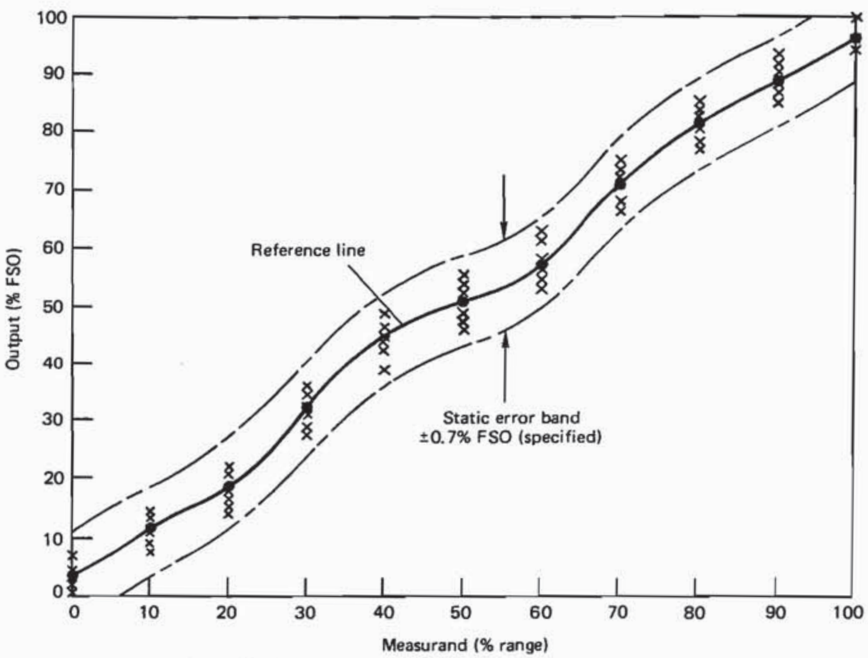

FIGURE 2–21. Static error band referred to a mean-output curve (error scale 10:1).

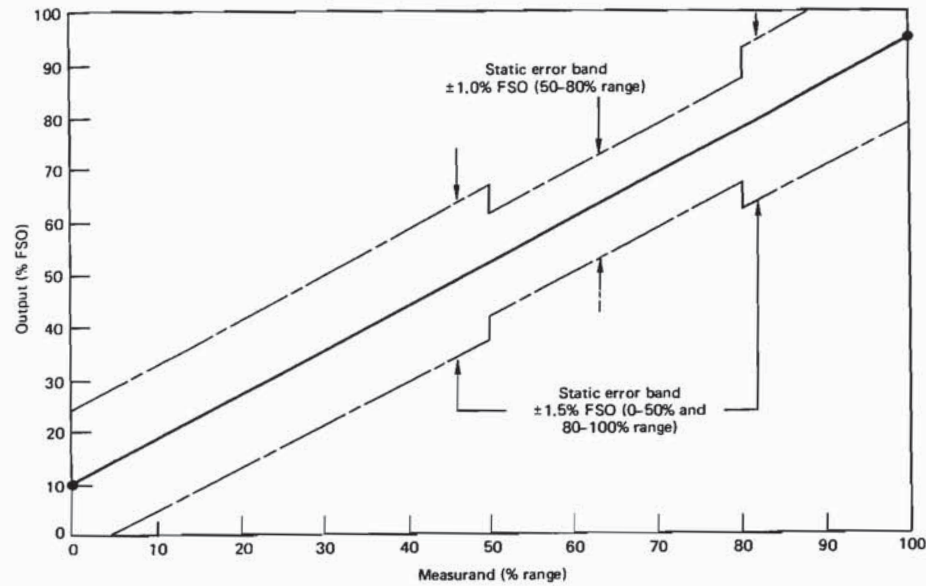

FIGURE 2–22. "Stepped" static error band referred to the straight line between theoretical end points 10% FSO at 0% range, 95% FSO at 100% range (error scale 10:1).

The selection of a reference line for a static error band of a bidirectional-range transducer involves the consideration of the intercept of the line with the zero-measurand output. When a theoretical slope or a terminal line is used, such a consideration is usually not necessary. However, when an end-point line is used and end-point tolerances are established, additional tolerances may have to be applied to the zero-measurand output. A stepped static error band can be useful in such cases. The band can be narrower near the zero measurand, near the end points, or in portions of the range along each direction, depending on the user's requirements.

2.5.2 Dynamic Characteristics

When a transducer is used for a measurement where rapid measurand variations occur, or where step changes in measurand have to be monitored with good fidelity, the transducer's dynamic characteristics must be established. These can be stated and determined in terms of frequency response, response time, or damping and natural frequency, depending on the type of transducer involved and its application. Note that some of the determinations require test methods and equipment of fairly high complexity as well as considerable expertise in test personnel. Tests have been standardized for many types of transducers by professional societies and by government laboratories such as, in the United States, the National Bureau of Standards. Unless otherwise stated in a specification, specified dynamic characteristics are applicable at room conditions.

Frequency response is the change with frequency of the output-measurand amplitude ratio within a stated range of frequencies of a sinusoidally varying measurand applied to a transducer. It is also the change with frequency of the phase difference between this measurand and the output. Frequency response is usually specified as "within ±___% (or ±___ dB) from ___to ___Hz" and should be referred to a frequency within the specified frequency range and to a specific measurand value. Figure 2–23 shows two typical response curves considering only amplitude ratio, not phase difference (the output will lag behind the measurand). Curve A shows the response of a transducer that can be used for static as well as dynamic measurements; in this example the frequency response is within ±5% from 0 to 300 Hz, referred to 10 Hz. Curve B shows the response of a transducer usable only for dynamic measurements; the response is within ±5% from 10 to 3500 Hz, referred to 100 Hz. A reference amplitude was not stated for these generalized examples. A commonly found colloquial expression for the response of curve A is that the response is "from *dc* to

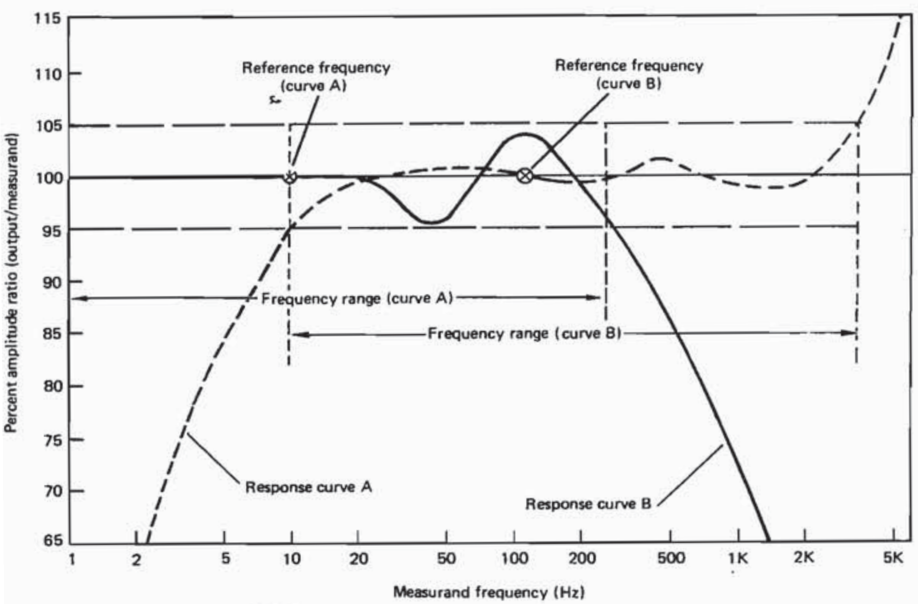

FIGURE 2–23. Frequency response.

300 Hz (within ±5%)." Similarly, the response of curve B could be called "*flat* (within ±5%) between 10 and 3500 Hz."

Response time, rise time, and time constant characterize the response of a transducer (that is not underdamped) to a step change in measurand (see Figure 2–24). When such a step change is applied, the output will change nonlinearly toward the final value (100% output change) over a period of time. The length of time required for the output to rise to a specified percentage of its final value (as a result of a step change in measurand) is the *response time*. The percentage is typically stated in the form of a modifier of "response time," e.g., "95% response time" or "98% response time." A special term and symbol have been assigned to 63% (actually 63.2%) response time: the *time constant* τ. Another term, *rise time*, is used to state the length of time for the output to rise from a small specified percentage to a large specified percentage of its final value. Unless otherwise specified (e.g., "5 to 90% rise time" in Figure 2–24), the percentages should be assumed to be 10% and 90% of the final value. The general term for a transducer's response to a step change in measurand is *transient response*. In some cases it is possible to calculate frequency response from a transducer's transient response, its mechanical properties, or its geometry; if so, it should be referred to as *calculated frequency response* and the basis for calculation should be identified.

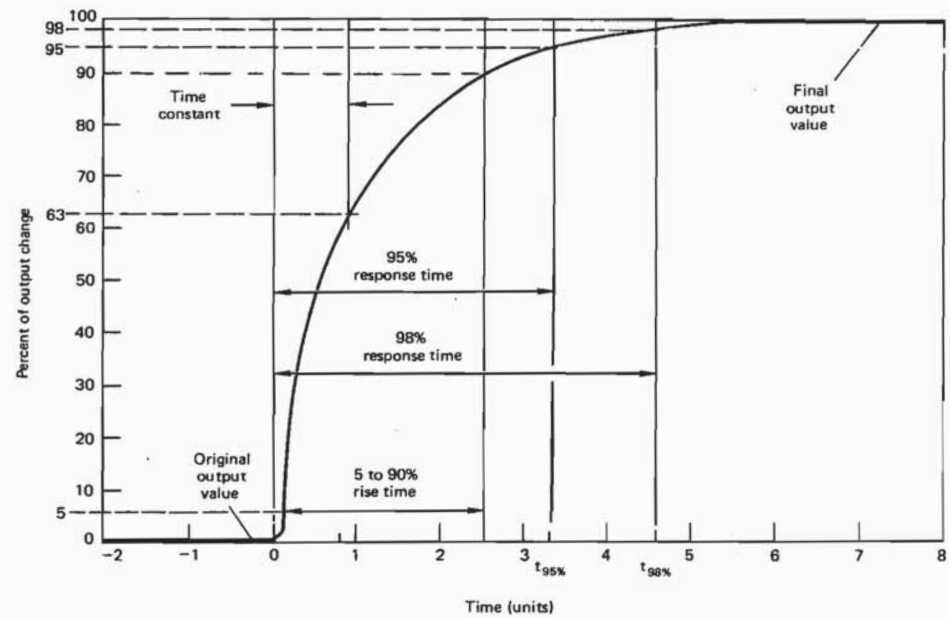

FIGURE 2–24. Response time, rise time, and time constant.

Damping is the energy-dissipating characteristic which, together with natural frequency (see shortly), determines the upper limit of frequency response as well as the transient-response characteristics of a transducer. In response to a step change in measurand, an *underdamped* system oscillates about its final steady value before coming to rest at that value (see Figure 2–25), an *overdamped* system comes to rest without overshoot, and a *critically damped* system is at the point of change between the underdamped and overdamped conditions. When a transducer's sensing element is set into free oscillation, the frequency of this oscillation is the *natural frequency*. It is important that this oscillation is free, not forced. Natural frequency has also been defined as that frequency of a sinusoidally applied measurand at which the output lags the measurand by 90°. Figure 2–25 shows that time constant is still a valid characteristic of an underdamped transducer, but that such characteristics as 95% response time could not be stated due to the *overshoot* and oscillations about the final value; the frequency of this oscillatory transient is the *ringing frequency* of the transducer.

The ratio of the actual damping to the degree of damping required for critical damping is the *damping ratio* (damping factor). A damping ratio of 1.0 indicates critical damping, damping ratios larger than 1.0 signify overdamping, and damping ratios less than 1.0 represent underdamping. Figure 2–26 shows responses of a typical mechanical sensing element (spring-mass

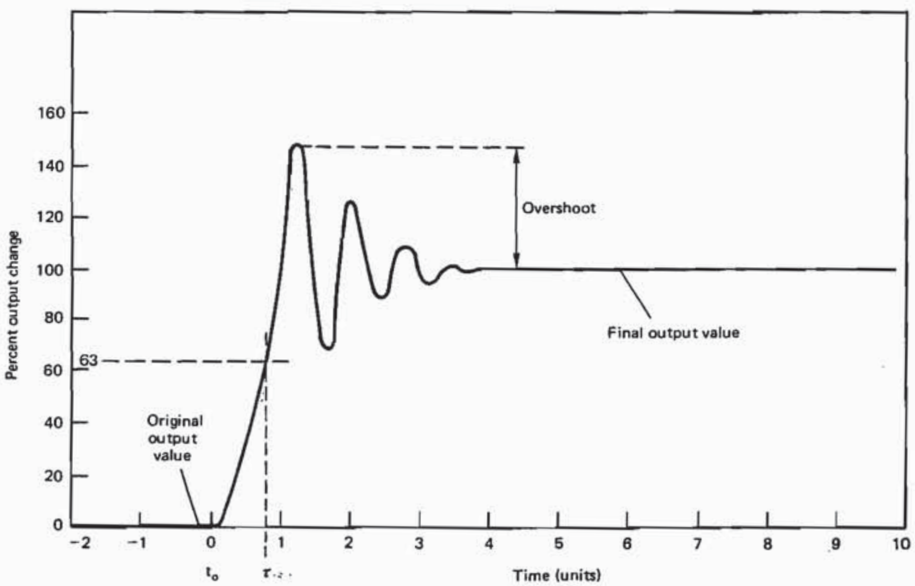

FIGURE 2–25. Response of underdamped transducer to step change in measurand.

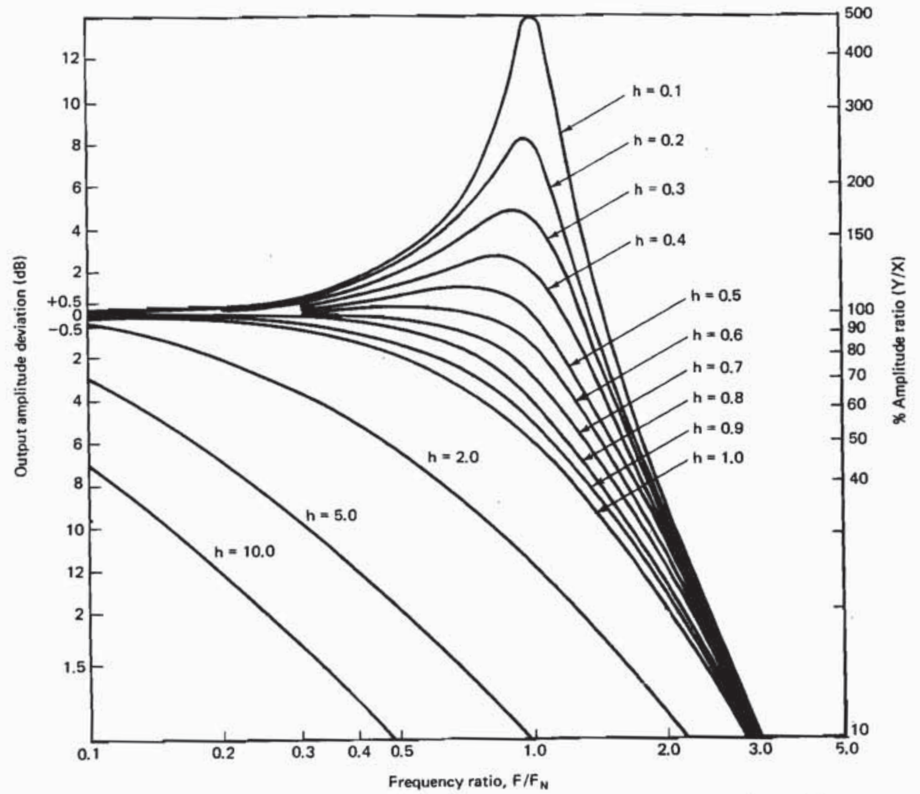

FIGURE 2–26. Relative response curves for various damping ratios h as a function of the ratio of frequency F to natural frequency F_N.

system) to a sinusoidally varying measurand for various damping ratios. Some types of transducers are inherently overdamped, others achieve some degree of damping by incorporating a fluid (*viscous damping*) or electromagnetic action (*magnetic damping*), and still other types are purposely left underdamped.

2.5.3 Environmental Characteristics

The static performance characteristics as well as the dynamic performance characteristics of transducers are specified, and verified, as those which the transducer exhibits at room conditions and in the absence of any external conditions (*environmental conditions*) that may affect the transducer's performance. When a transducer can reasonably be expected to operate under conditions (*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 limited by tolerances (in a specification) and determined by tests. Such additional environmental tests (temperature tests, vibration tests, ambient-pressure tests, etc.) may have to be performed on each transducer used; more commonly they are performed on a *sampling* basis (test one of every *n* transducers of each model and range), but sometimes only on a *qualification* basis (test one representative transducer). Environmental testing of transducers requires considerable skill and expertise from test personnel as well as appropriate test equipment and test setups whose behavior in the course of a test is well understood.

Besides operating environmental conditions, there are other environmental conditions to which a transducer may be exposed, but the transducer is not expected to operate within specified tolerances (or operate at all) while exposed to them. However, the transducer is expected to perform within specified tolerances *after exposure* to such *nonoperating environmental conditions*. When nonoperating environmental conditions, including those encountered during storage (e.g., while the device is in a warehouse or is installed in its application awaiting activation of the system in which it is to operate), shipping, and handling, are known or suspected to alter the behavior of a transducer, they should be included in a specification and the absence of out-of-tolerance nonoperating environmental effects should be verified by testing.

Temperature effects must be known and accounted for, for essentially all types of transducers. The *operating temperature range* is the range of ambient temperatures, given by their lower and upper extremes (e.g., "−50 to +250 °C") within which the transducer is intended to operate and within which all specifications related to temperature effects apply (unless they specifically relate to nonoperating temperatures). Some manufacturers of transducers incorporating elements intended to compensate for temperature effects call this the "compensated temperature range." When the temperature of a *measured fluid* can cause significant temperature effects in the transducer, the *fluid temperature range* is specified, sometimes instead of the operating temperature range, and then governs temperature-related specifications.

For some transducers, temperature effects (thermal effects) are stated only in terms of the zero shift (*thermal zero shift*) and sensitivity shift (*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 temperature prevailing while a measurement is made is known and appropriate corrections to final data are to be made. However, thermal effects on hysteresis and repeatability are not included in such specifications.

A more general and inclusive way of specifying thermal effects on performance characteristics is given by the term *temperature error*, the maximum change in output (at any measurand value within the transducer's range) when the (operating or fluid, as applicable) temperature is changed from room temperature to specified temperature extremes. The simplest way of specifying tolerances on thermal effects is provided by the error-band concept, whose use also facilitates verification. The *temperature error band* is simply the error band (see Section 2.5.1) that is applicable over the operating (or fluid) temperature range. This form of specification is particularly useful when the error band is referenced to a theoretical slope, such as the terminal line (see Figure 2–27).

It is also important to specify the *maximum* (*ambient* or *fluid*) *temperature*, the highest (or lowest) temperature that a transducer can be exposed to without being damaged or subsequently showing a performance degradation beyond specified tolerances.

When a transducer is exposed to a step change in (ambient or fluid) temperature, a transient output deviation (*temperature gradient error*) can appear in its output (see Figure 2–28). Tolerances on this error should be specified for a stated rate of change of temperature, for the two temperatures between which the step change occurs, and for a specific measurand value.

Temperatures will also affect dynamic characteristics, particularly when they employ viscous damping. Specifications should then cover thermal effects appropriately (e.g., "Damping ratio: 0.7 ± 0.2, between 0 and

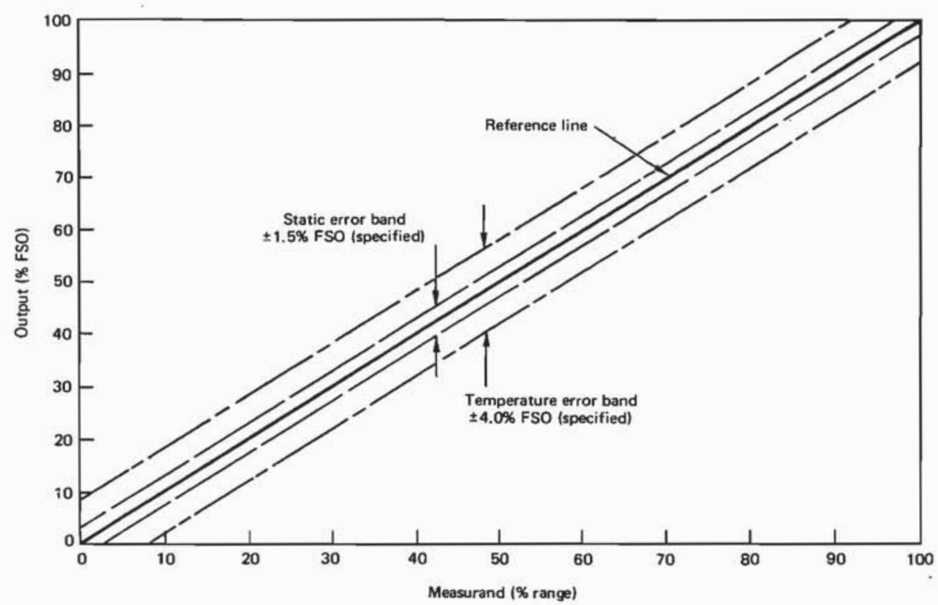

FIGURE 2–27. Temperature error band referred to terminal line (error scale 2:1).

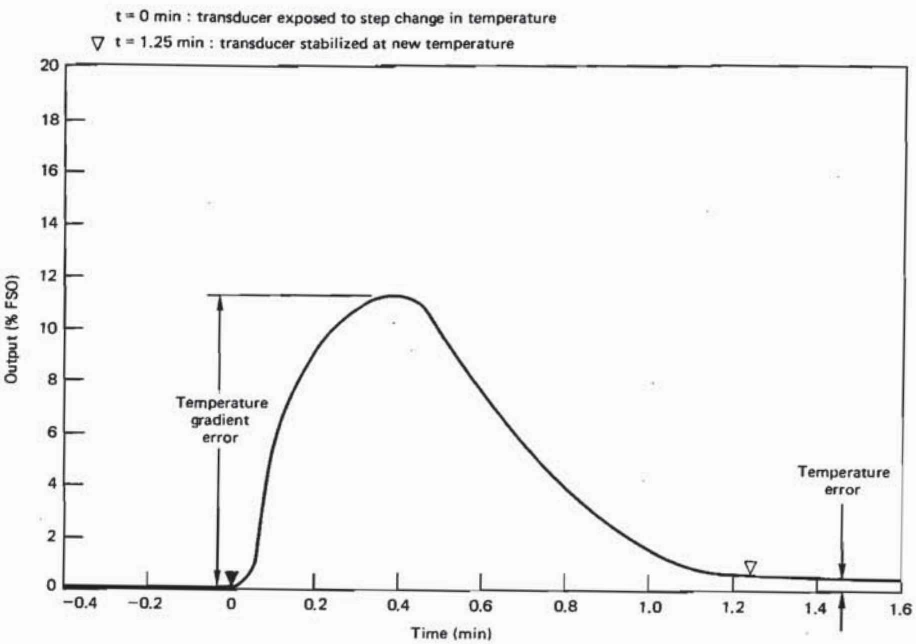

FIGURE 2–28. Temperature gradient error (typical example shown for output at zero measurand).

100°C," and "Frequency response: within ±5% from 30 to 5000 Hz, referred to 100 Hz, between −20 and +120°C").

Acceleration effects are the effects of quasi-steady-state accelerations on internal elements of a transducer, causing errors in its output. The acceleration error is typically more severe when acceleration is applied along one axis of a transducer than when it is applied along other axes. Error-causing acceleration may act directly on a mechanical sensing element or its linkage and cause spurious deflections; upon structural supports, causing distortion which may even result in failure; upon bearing-supported rotating members, causing eccentric loading and increased friction; and in a number of other ways, causing mass shifts, deformations, and distortions.

When a transducer is to be used in an application where it will experience acceleration (e.g., on moving vehicles, or on moving mechanical members), the possibility of acceleration errors must be considered and tolerances must be established for such errors. In order to reach an understanding about these with the transducer's manufacturer, one begins by agreeing on a labeling of the axes of the transducer (see Figure 2–29). The manufacturer can then inform the user that this particular transducer design is more sensitive to accelerations along, say, the *X*-axis than along the

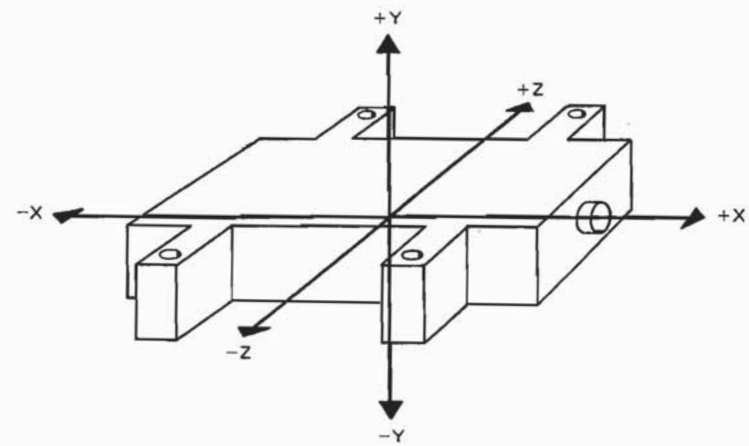

FIGURE 2–29. Typical labelling of acceleration axes for a transducer.

Y- or *Z*-axes. With this information in hand, the user can assure that the transducer gets installed in such an orientation that acceleration along its *X*-axis is minimized.

Acceleration error is the maximum difference (at any measurand value within the transducer's range) between output readings taken without and with the application of specified constant acceleration along specified axes. In a specification the maximum expected acceleration in each axis and, if necessary, in each of the two directions, is specified in conjunction with the maximum allowable acceleration error [e.g., "Acceleration error: ±2.5% FSO for: $10g(+X)$, $2g(-X)$, $5g(\pm Y)$, $3g(\pm Z)$." This error can also be specified or determined in terms of *acceleration sensitivity* within a stated range of acceleration values acting along specified axes (e.g., "0.2%/g, over 0 to 10g, *X*-axis, and 0.15%/g, over 0 to 10g, *Y*- and *Z*-axes"). For acceleration transducers, sensitivity to acceleration acting along other than the measured axis is known as *transverse sensitivity*.

When the error-band concept is used, the *acceleration error band* will include acceleration errors as well as static errors; the latter may actually be reduced by accelerations in some designs.

Some types of transducers are so sensitive to acceleration forces that even the acceleration due to the earth's gravity can cause undesirable effects. The error due to the orientation of a transducer relative to the direction in which gravity acts upon it is called *attitude error*. When this error in the different transducer axes is known, it is often possible to install the transducer in such a position that attitude errors are minimized.

Vibration effects, the effects of vibratory acceleration, can affect transducers in the same manner as steady-state acceleration. More severe effects, however, are connected with the frequencies of vibration. As the vibration frequency is varied over a stated range and along a specific axis, amplified vibrations (*resonances*) of internal elements can occur at one or more frequencies. Figure 2–30 illustrates typical vibration effects; a potentiometric transducer was chosen for this example, which includes evidence of a reduction in friction error due to vibration; it also shows vibration error at several resonances as well as the equivalent *vibration error band,* at the largest resonance, identified as one-half the vibration error band since error bands always have bipolar tolerances.

Vibration error is the maximum change in output (at any measurand value within the transducer's range) when vibration levels of specified amplitudes and ranges of frequency are applied to the transducer along specified axes (at room conditions). Note that different resonances and, hence, different vibration errors may be observed for different measurand values, particularly when the transducer incorporates a mechanical sensing element. It may be necessary, therefore, to predict the measurand value most likely seen by the transducer while it is exposed to the most severe vibration environment and then to specify and verify vibration errors at that value.

Ambient-pressure effects can be observed in some transducer designs when the transducers are calibrated at room barometric pressure and then

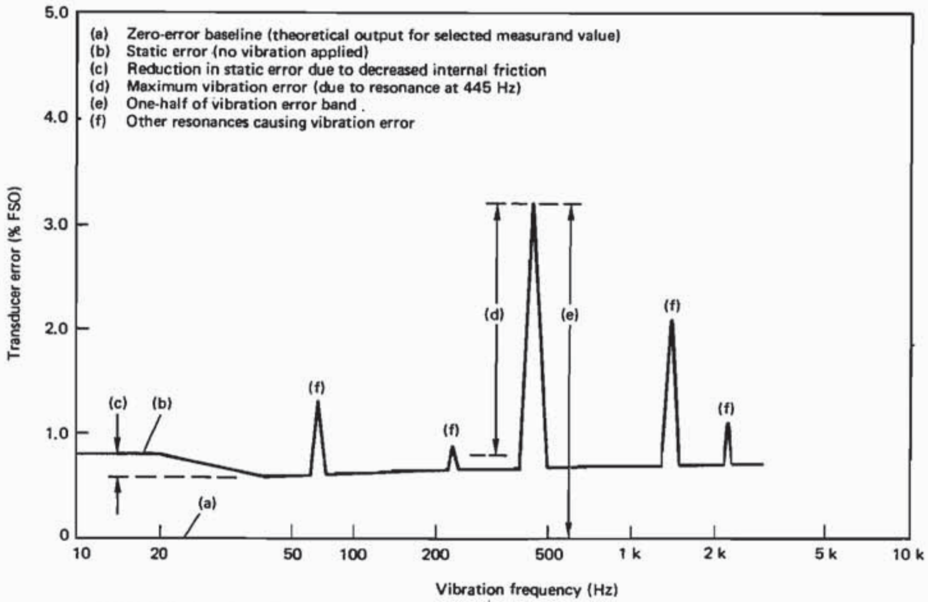

FIGURE 2–30. Typical results of vibration test on potentiometric transducer at a given program of vibration amplitudes, from 10 to 3000 Hz, at one measurand value, along one transducer axis.

used either at very high altitudes or on aircraft or spacecraft, where ambient pressures approach a vacuum, or when they are used far underground (e.g., in deep mines or wells) or at deep submersion underwater, where pressures are very high. Transducer performance can be affected by resulting case deformations and changes to the internal geometry of a transducer. It can also be degraded to the point of failure when a poorly sealed transducer is exposed to a vacuum environment and internal materials outgas, wires self-heat in the absence of air as a heat-transfer medium, internal sealed cavities start to bulge or leak, or corona-arcing occurs across high-voltage terminals.

Ambient-pressure error is the maximum change in output (at any measurand value within the transducer's range) when the ambient pressure is changed between specified values, usually between room pressure and a lower or higher ambient pressure. Such errors can also be stated in terms of an *ambient-pressure error band*. Ambient-pressure error has at times been referred to as "altitude error," with ranges of (low) pressures stated in terms of altitude above sea level.

Mounting effects can occur during the installation of a transducer and may result in subsequent performance changes when, for example, the mounting surface of the transducer is not evenly machined so that the case gets deformed when all 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 transducer caused by mounting the transducer and making all electrical and measurand connections. Mounting error is not commonly included in specifications; however, it may be necessary to verify its absence (e.g., by performing an in-situ calibration check).

Other operating environmental effects on the behavior of a transducer during its normal operation which should be known and included in specifications include humidity or immersion in liquid (affects poorly sealed transducers, starting with a reduction of insulation resistance); corrosive (and insulation-reducing) effects of high salt concentrations (or concentrations of other corrosive substances) in the ambient atmosphere; various effects of measured fluids on the sensing elements of transducers; the influence of ambient electromagnetic fields on transduction elements and integral circuitry; and the effects of radiation (nuclear, ionizing) on various internal transducer elements.

Nonoperating environmental effects on the performance of a transducer subsequent to its exposure to such environmental conditions should be understood and, if necessary, limited by inclusion in a specification. These environmental conditions do not only include temperatures, vibration, shock, moisture, etc., encountered during storage, shipping, and handling; they may also include environmental conditions in excess of limits of operating conditions specified for a transducer that can be encountered while the transducer is installed in its intended application. All overrange, or overload, characteristics can be classified as nonoperating conditions. Some examples of nonoperating environmental conditions that tend to be overlooked are room temperature, for a light sensor or radiation sensor which normally operates while cooled to low temperatures; any significant vibration, for any transducer used on a satellite, where it need not operate until after separation of the satellite from its booster stages; and low temperature, together with a liquid state, of a fluid that is intended to be measured only when the fluid is gaseous and at a significantly higher temperature.

Type-limited environmental effects are significant to certain types of transducers, or to transducers for certain measurands, in addition to the generally applicable (to varying degrees) environmental effects previously described. These effects include:

1. *Conduction error,* the error in a temperature transducer due to heat conduction between the sensing element and the mounting of the transducer.
2. *Strain error,* the error resulting from a strain imposed on a surface to which a transducer is mounted; this error is significant primarily for surface-temperature transducers and is not intended to relate to strain gages.
3. *Reference-pressure error,* the error resulting from changes of the reference pressure, the pressure relative to which a *differential-pressure transducer* measures pressure, within a specified reference-pressure range.
4. *Transverse sensitivity,* the response of acceleration transducers to acceleration forces in axes transverse to the sensing axis.

2.6 RELIABILITY CHARACTERISTICS

Although some operating and most nonoperating environmental characteristics relate to a transducer's reliability, the characteristics considered here are only those relating to the useful life of a transducer as well as to any characteristics that may have adverse effects on the system in which the transducer is installed when the transducer fails in a particular mode.

The useful life of a transducer can be expressed in one of two ways: *operating life* is the (specified) minimum length of time over which the transducer will operate, either continuously or over a number of on-off cycles whose duration is specified, without changing its performance characteristics beyond specified tolerances; *cycling life* is the (specified) minimum number of full-range excursions (or specified partial-range excursions) over which a transducer will operate (as specified) without changing its performance beyond specified tolerances.

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

Reliability characteristics relating to adverse effects on the system in which a transducer is installed are generally application dependent. They include any characteristics controlled by applicable health and safety codes. They further include any characteristics deemed important after a determination of the effects of failure modes has been made. An example is the results of internal short-circuiting (protection may be included in the associated electrical system or may have to be included within the transducer). Another example is the *burst-pressure rating* of a transducer, i.e., the pressure that may be applied to the sensing element or the case, as specified, of a transducer without rupture of sensing element or case, respectively. When a sensing element ruptures, the measured fluid may come in contact with materials it is not compatible with and the results may range from measured-fluid contamination to an explosion. When a case ruptures, portions of it may hit surrounding personnel or equipment and cause damage.

Because of this hazard, rare as its occurence may be, it has been necessary to specify a separate *case-burst pressure rating* for transducers used in certain critical installations. The test to verify this is necessarily destructive: a hole is drilled into the sensing element so that the pressurized fluid can enter the case. The pressure is then raised to the specified pressure rating, and any significant case deformation, cracking, or actual rupture is observed. The pressure is then bled off. This test must be performed within an enclosure that offers protection from any resulting explosion to the operator.

Some potential failures and their effects simply cannot be provided for by writing a specification. An example is an in-line flowmeter in a pipeline, such as a turbine flowmeter, whose turbine blades may separate, move downstream, and then cause a pump to fail. It is, therefore, important to assess the impact of any possible failure on the system in which a transducer is installed and then take steps to build appropriate protection into the system.

3

Criteria for Transducer Selection

The selection of a particular transducer design is based primarily on a measurement requirement. This requirement is sometimes established by the person responsible for the selection; much more frequently, however, it is established by someone else, typically a project engineer or the cognizant engineer of a subsystem. Typically, too, the data system (including power supplies) with which the transducer must interface and operate either already exists or has already been designed. There can also be other constraints on transducer selection: there may be a project policy to use only parts (including transducers or electronic parts within a transducer) that are on an "approved list" or that have previously passed a qualification test for specific applications; or the purchasing department may have a list of "approved vendors," based on prior procurement and quality control experiences; or regulations may prohibit buying transducers from another country unless it can be proven that a manufacturer there is the only possible source. There are almost always sound reasons for such policies. It should be evident, then, that transducer selection is often an iterative process, and that there can be times when measurement requirements have to be negotiated with the originator.

The following listing of guidelines is meant to be fairly complete. For some applications a number of these considerations can be omitted. For others, additional factors may have to be considered. Some of the entries tend to imply possible incompatibilities. For example, if the measurement requirement calls for a frequency response that is flat up to 3000 Hz, and the data system can only handle up to 500 Hz, the measurement requirement

will most likely have to be negotiated downward. Cost and availability can affect measurement requirements similarly.

3.1 MEASUREMENT CONSIDERATIONS

1. What is the real purpose of the measurement?
2. What is the measurand?
3. What range of measurand values will be displayed in final data?
4. Will the measurand only increase, or only decrease, or both?
5. What overrange conditions may occur before or during the time data are required?
6. With what accuracy must the measurement be presented in the final data?
7. What are the dynamic characteristics (e.g., fluctuation frequency range, step changes) of the measurand?
8. What frequency response or transient response must be visible in the final data?
9. If a fluid is being measured, what are its physical and chemical characteristics?
10. Where and how will the transducer be installed?
11. In what manner, and to what extent, is it permissible for the transducer to modify the measurand while it is being measured?
12. What ambient environmental conditions will the transducer be exposed to?

3.2 DATA SYSTEM CONSIDERATIONS

1. What is the general nature of the data system (e.g., radio telemetry, hard-wired telemetry, individual direct display)?
2. Is the data system inherently analog or digital?
3. What is the nature of the major elements in the data system:
   a. Signal conditioning, multiplexing, analog-to-digital conversion, pretransmission buffering?
   b. Data transmission link?
   c. Data processing, data storage?
   d. Data display?
4. What are the accuracy and frequency response characteristics of the end-to-end data system, exclusive of those of the transducer?

5. What form of transducer output will the data system accept with minimum additional signal conditioning?
6. What load impedance will be seen by the transducer?
7. Is frequency filtering or amplitude limiting of transducer output required, and can the data system handle this?
8. What transducer excitation voltage is most readily available?
9. How much current may the transducer draw from the excitation supply?
10. Are special transducer-related checking functions (e.g., "ready" check, electrical calibration check) required by the data system, and does the data system provide circuitry for these?

3.3 TRANSDUCER DESIGN CRITERIA

In the step-by-step design process presented in this chapter, criteria for transducer design and, hence, selection are based primarily on the preceding lists of considerations. However, as mentioned earlier, cost and availability factors, as well as policies governing procurement, may influence design decisions and can translate into measurement requirement changes.

1. What constraints are imposed on transducer mass, configuration, excitation, and power consumption?
2. What are the transducer output requirements?
3. Which transduction principle is most suitable?
4. What accuracy and other performance characteristics must the transducer provide: static? dynamic? environmental (operating)? environmental (nonoperating)?
5. What operating or cycling life is required?
6. If a fluid is to be measured, what will be the effects of the measured fluid on the transducer?
7. Will the transducer affect the measurand to the extent that erroneous data will be obtained?
8. What constraints are imposed on the transducer by any applicable governmental standards or industrial codes?
9. What are the failure modes of the transducer? What hazards would a failure present to the system in which it is installed? to adjacent components or systems? to the data system, especially the power supply provided by it? to the area in which the transducer operates? to personnel working in that area?

10. What is the lowest level of technical competence to be possessed by any and all personnel expected to handle, install, and use the transducer? What human-engineering requirements should be incorporated in the transducer design?
11. What testing methods (including calibration) will be used to verify performance? What tests will be performed by the manufacturer, and what tests will be run by the user? Are those tests adequate? Are the test methods correct? Is the test equipment appropriate? Are the test methods simple and well established?

3.4 AVAILABILITY FACTORS

1. Is a transducer that fulfills all the requirements available "off the shelf"?
2. If the answer to the preceding question is "no," the following should be considered:
   a. Will minor redesign of an existing transducer be sufficient, or will a major development effort be required?
   b. How many transducers of identical design will be procured at this time and in the future?
   c. What manufacturer has demonstrated the ability to produce a transducer similar to the required item?
   d. What has past experience been like in dealing with a proposed manufacturer?
   e. Can the transducer(s) be delivered in time to meet installation schedules?

3.5 COST FACTORS

1. Is the quoted cost of the transducer compatible with the measurement function it will provide?
2. What additional costs will be incurred by required transducer testing, periodic recalibration, handling, and installation?
3. Which requirement imposed on the transducer is the major cost driver?
4. What relatively minor compromises in requirements could lead to substantial savings?
5. What modifications to the data system (including power supplies) could lead toward reduced costs of a number of different transducers used in that system, and what cost trade-offs would be involved?

3.6 LOCATION OF PROCESSOR ("SMART SENSORS")

An additional consideration in selecting a transducer is the location of the processor that performs at least some of the data processing as well as some transducer control functions. The continuing development of microprocessors has made it possible to package such a processor integrally with the transducer, i.e., contained within the transducer housing. The capabilities of such built-in processors vary over a wide range. Some fairly simple transducers are available with a built-in processor that performs such operations as analog-to-digital conversion, storage of the calibration curve and conversion factors, and output of data in engineering units (in digital form). Additional capabilities can be internal buffering (storage) of data to provide a "data dump" when "polled" by the data system; decoding of command sequences and their conversion into transducer operating-mode changes; responding to a transducer's own observation and changing an operating mode (e.g., amplifier gain) and sampling rate; and combining data words with time tags obtained from a clock signal, with error correction codes, with data about internal operational states, and with headers that the data system accepts as the beginning of a data sequence ("frame, packet").

Transducers that incorporate such microprocessors are often called "smart" or "intelligent" sensors (or transducers). Making a choice between a "smart" and a "normal" transducer involves primarily trade-offs of cost vs. data system capability vs. convenience. For example, multiplexing standardized transducer outputs into a single analog-to-digital converter (ADC) is probably cheaper than paying for an ADC for each transducer. On the other hand, multiplexing (formatting) digital data may facilitate programmability. Or, if the existing data system already provides for programmable decalibration and engineering-unit conversion, there is really no need to have these functions also residing in a microprocessor in the transducer. On the other hand, if the data system is new and was specifically designed for having these functions performed by each transducer, the overall cost may be the same, and the cost of expanding the data system (for additional transducers) may even be less.

4

Transducer Performance Tests

Transducer specifications, selection criteria, and tests for performance determination are strongly interrelated. Every specified characteristic, and their tolerances when also specified, should be able to be verified by a test. Some of these tests are relatively simple, and test equipment is readily available; such tests can be performed quickly and at no significant additional cost. Other tests require elaborate setups, equipment that is expensive and not readily available, and highly skilled test engineers and technicians; these tests are expensive and time consuming. Yet, for certain critical applications, a complex, lengthy, and costly test program is not only justifiable but necessary. An example of such an application is an instrumentation system that operates unattended for extended periods of time and under a variety of harsh environmental conditions, especially when an instrumentation failure can cause a system failure that carries a high penalty in terms of replacement cost, loss of revenue, critical time, or endangering human life. Such combinations of conditions can be found in some industrial installations, but are more typical for nuclear power stations, military vehicles and systems, aircraft, and space vehicles.

Because of the wide range of test complexity, it is important for the transducer user to have some knowledge of the tests needed to determine or verify transducer characteristics. The user will then be in a better position to judge what specifications to impose or not to impose, and be better equipped to understand a test report and its implications.

It is poor practice to specify anything that has never been or is never intended to be verified by a test, or to specify something that can only be verified by a test whose costs cannot be justified by the application. It is meaningless to specify error tolerances that are tighter than those offered by the best available test setup. On the other hand, it is quite acceptable for a user to ask a manufacturer for a copy of a test report that substantiates a specification in his or her catalog or bulletin. It is also acceptable for a manufacturer's sales or marketing engineer to ask a potential user what the real application is, and whether he or she really needs to specify certain characteristics or certain tolerances on them.

This chapter describes generally applicable transducer tests and typical equipment and setups used for these tests. Some considerations applicable to calibration and test methods are described under "Transducer Characteristics" in subsequent chapters.

The general categories that call for one or more of the individual performance tests described subsequently to be performed are stated in various ways. The nomenclature that is typically used for such test categories assumes that a quantity of transducers bearing the same part number (the same design, with the same optional features) are being purchased. These tests are all in the overall category of *performance verification tests*, meaning that the objective of the test is to determine whether or not the actual performance complies with applicable specifications. The results show primarily a "pass" or "fail" status, although other information about the behavior of the transducer can usually be extracted from the test records. By contrast, a *performance determination test* is performed primarily to characterize the behavior of the transducer; sometimes specifications and tolerances are established on the basis of such a test.

The performance verification test that each transducer of a lot is subjected to is the *acceptance test*, which always includes a calibration and often includes additional tests. A *qualification test* ("type test") is usually performed on only one transducer that is then considered representative of the entire lot purchased. This type of test consists of a comprehensive series of subtests, including environmental tests performed at the extremes of specified environmental levels. Some users will accept the results of a qualification test performed for another user in lieu of having such a test performed for themselves (and paying for it). In some cases, for example, when a transducer of the same model number as those being purchased but varying from it in some relatively minor way such as range has passed a qualification test (complete enough to satisfy the user's needs), the units being purchased can be declared as "qualified by similarity" to the unit that passed the qualification test.

Some applications (or procurement policies) call for a test that is intermediate between the relatively simple acceptance test and the usually quite complex qualification test; viz., a *sampling test*, which is performed on one out of a specified number of transducers (of the same part number). A sampling test includes electrical tests additional to those performed during

the acceptance test, as well as some dynamic and environmental tests, often at environmental levels less than the maximum levels specified. Sampling tests are normally *nondestructive*, which means that the transducer is fully usable after the test. A qualification test, however, is usually *destructive*. Even if the transducer is still functional after completion of all tests, it should not be used, if only because the qualification test includes a life test, in which all the useful life has been "tested out" of the transducer.

4.1 ELECTRICAL TESTS

Different types of electrical tests are routinely performed on transducers. The most important group of electrical tests comprises output tests, i.e., measurements of the transducer's output (especially during a calibration) in whatever form it may be. Most frequently, the output is in the form of a dc or (less often) ac voltage. Sometimes, notably in potentiometric transducers, it is a voltage ratio. It can also be an ac output varying in frequency, or pulses whose repetition rate (pulses per second) varies (a pulse count). Some types of transducers have an inherently digital output (e.g., angular and linear encoders), or provide a digital output by virtue of a built-in analog-to-digital encoder. Other categories of transducers don't provide an output signal of any of the foregoing types; instead, their output is in terms of change in resistance, capacitance, or inductance. (These changes in a passive element are subsequently signal-conditioned into an active signal.)

Other electrical tests, usually performed apart from acceptance tests, are used to measure output impedance, noise (of built-in conversion electronics), loading error, threshold, and resolution; to characterize excitation parameters; and to check the degree of insulation of active circuitry from an external ground such as the transducer case (housing).

It is very important that the test equipment be properly calibrated and that the calibration be traceable to a standard maintained by the government agency responsible for providing and maintaining very accurate standards. (In the U.S.A. the responsible agency is the National Bureau of Standards (*NBS*).) Some of the equipment mentioned in what follows is of the type used as secondary or transfer standards. It is good practice for any company or facility to have their transfer standards certified periodically by an agency such as NBS. (The certification will show by how much a secondary standard deviates from a primary one, or a tertiary standard deviates from a secondary one.) Such a local standard then becomes a *transfer standard*. It is equally good practice to establish periodic recalibration intervals for all measurement equiment used for production inspection and testing. (These recalibrations are usually performed by the company or facility's own standards laboratory.)

4.1.1 Voltage Measurement

Electronic voltmeters with a high input impedance and now mostly with a digital display are generally used for dc transducer output voltage measurements, from millivolts to volts; electronic voltmeters of special design can be used to obtain readings in the microvolt range. Such voltmeters provide adequate accuracy as long as they are periodically recalibrated against a transfer standard such as a *voltage potentiometer*. This instrument measures dc voltages from microvolts to about 1.5 V by balancing the voltages against a known voltage. The known voltage is obtained between the wiper arm and one end of a very precisely wound potentiometer across which a battery is connected (see Figure 4–1). The wiper is moved across the potentiometer element, usually by turning a knob, until a null balance is observed on the null indicator. The wiper is mechanically linked to a calibrated dial on which the voltage necessary to balance the unknown voltage can be read.

Voltage potentiometers are calibrated by connecting a known voltage across the measurement terminals. An accurate voltage source used for this purpose is the *standard cell*, which produces slightly over one volt. Many voltage potentiometers have a built-in standard cell as well as other useful features, such as range-multiplier resistors, optical aids to facilitate the null reading, and devices that minimize thermoelectric potentials generated by frictional heating at the contacting point of the wiper arm. A voltage potentiometer always reads the open-circuit output voltage of a transducer because the potentiometer presents a theoretically infinite impedance to the transducer at the precise point of null balance.

For voltages over 1.5 V the choice of readout equipment is practically

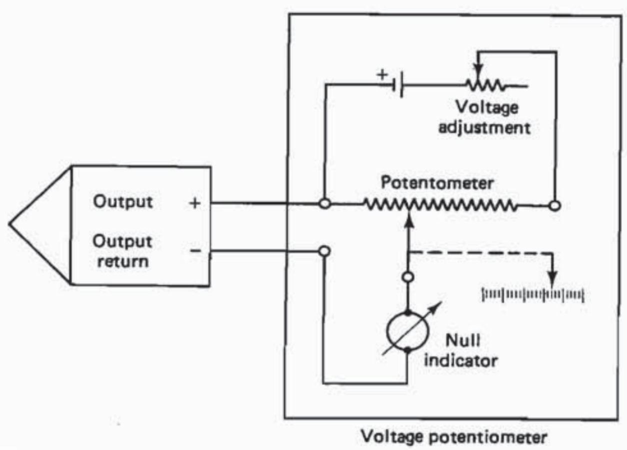

FIGURE 4–1. DC output voltage measurement by a voltage potentiometer.

limited to the digital electronic voltmeter, which also operates on the voltage-balance principle. Instead of using a continuously variable resistance (a potentiometer), this device employs precision resistors that divide the voltage into discrete increments. The unknown voltage is balanced in the voltmeter in decade steps, using transistor switching circuits to select the internal balancing voltage by successive approximation so that an increasingly finer null is obtained. The state of each decade switching network (equivalent to the position of a selector switch) is displayed by a numeral on the display. For example, on a five-digit voltmeter, a voltage of 21.453 V would be successively approximated to, first, 20 V on the "tens switch," then 1 V on the "units switch," 0.4 V on the "tenths switch," 0.05 V on the "hundredths switch," and, finally, 0.003 V on the "thousandths switch." Most digital voltmeters now provide for automatic range switching and polarity indication.

Ac voltages can also be measured by a digital voltmeter if it is equipped with an ac-to-dc converter that responds either to the average, peak, or rms value of the ac voltage. On some meters the type of value is selectable. Very accurate measurements can be obtained by using a ratio transformer in conjunction with a transfer-standard ac voltmeter or voltammeter.

4.1.2 Current Measurement

Precision electronic multimeters are normally used for production-type measurements. For current calibrations of such instruments, as well as for more accurate current measurements, a transfer-standard ac voltammeter is used for ac currents; dc currents are passed through a *shunt*, in this case a stable precision resistor of accurately known value (standard resistor), and the resulting voltage drop across the shunt is read on a voltage potentiometer or digital voltmeter.

4.1.3 Frequency and Pulse-Count Measurement

A considerable number of different types of transducers have frequency or pulse-count outputs. Such outputs are usually measured by means of an electronic counter or an events-per-unit-time (*EPUT*) meter. These indicators display the periodic or aperiodic transducer output in digital form, using special logic circuitry to count the "events" (cycles or pulses) repetitively over a preselected time interval (e.g., 0.1 s, 1 s, 10 s, etc.). Since time is used as reference, and since it is possible to determine time with close accuracy, electronic counters and EPUT meters have inherently very small errors.

Where poorer accuracy is permissible, two other types of indicators can be used. The "integrating" frequency or pulse-count meters display a voltage representing the number of "events" as integrated by suitable electronic circuitry over a fixed time interval. Somewhat better accuracy is obtained with the discriminator type of frequency meter, which converts the deviation from a given center frequency into a dc voltage over a limited range of frequencies. Discriminators are useful in measuring any rapidly fluctuating frequency-modulated transducer outputs, such as those encountered during dynamic tests of FM output transducers.

4.1.4 Digital Output Measurement

Digital output is displayed by an indicator containing a converter that changes the digitally coded number into a decimal number and then displays this number. Some indicators are designed to convert the output of an angular encoder directly into radians, or into degrees, minutes, and seconds.

4.1.5 Voltage Ratio Measurement

The output of potentiometric transducers is a voltage ratio—the ratio of the voltage between the wiper and the signal-return side of the potentiometer (resistance) element to the excitation voltage applied across the entire potentiometer element. This makes it possible to measure this form of output as a ratio, independently of excitation-supply variations.

The two types of indicators used most commonly for voltage ratio measurements are the digital electronic voltmeter with ratio-measurement provisions and the manually balanced or servo-balanced resistance-bridge ratiometer. The former is a digital voltmeter modified to measure and display the ratio between two voltages, one of which can be the excitation voltage and the other the output of the transducer. The latter (see Figure 4–2) is essentially a precision potentiometer of either the continuous or the decade type or a combination of these two, with digital indicator dials connected mechanically to the potentiometer shaft or (concentric) shafts so as to indicate the relative position of the potentiometer's wiper arm. A null indicator

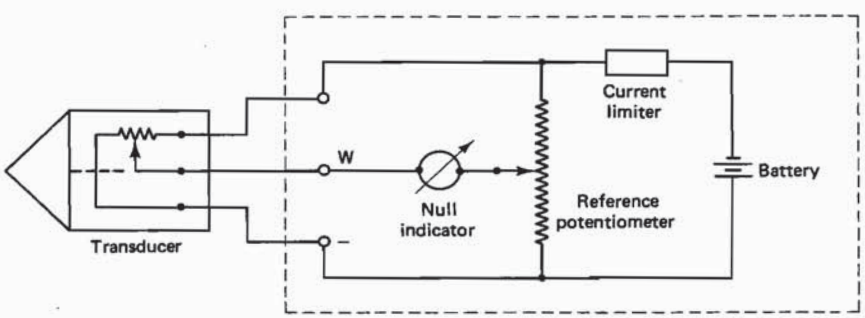

FIGURE 4–2. Basic measuring circuit of a resistance-bridge ratiometer.

(or null-indicating galvanometer) is connected between the wiper and the external wiper terminal, while a battery is connected across the potentiometer as well as across the external (transducer) excitation terminals. The transducer output is read as "percent of voltage ratio (%VR)" directly off the mechanical indicating dials after a fine null reading has been obtained on the null indicator.

A current-limiting device, which can be a simple resistor, should always be connected in series with the battery in order to avoid burning out the transducer whenever it is incorrectly connected so as to apply the excitation between its wiper and "ground" terminal.

4.1.6 Resistance Measurement

The resistance-change output of resistive transducers is almost invariably measured by means of a resistance bridge. Various commercial resistance bridges are available, all modifications of the basic bridge circuit first used by Wheatstone in 1843 and, hence, known as the *Wheatstone bridge* [see Figure 4–3(a)]. The bridge is balanced when the current through the galvanometer (null indicator) is zero. This occurs when the ratio between resistors A and B equals the ratio between the unknown resistor X and the "standard" (reference) resistor S, or

$$\frac{R_A}{R_B} = \frac{R_X}{R_S}$$

The unknown resistance is then obtained by multiplying the value of the known resistor S by the ratio of resistances A to B, or

$$R_X = R_S \frac{R_A}{R_B}$$

Interchanging the galvanometer and the battery in their circuit position does not affect bridge-balancing conditions.

The basic bridge circuit is made usable for resistance measurement by connecting a rheostat into the circuit as resistance S and connecting the unknown resistance across terminals X_1 and X_2. The electrical position of the wiper of the rheostat, which can be continuously variable or vary in predetermined discrete intervals (by decade switches), is mechanically indicated by a numerical display dial, or by a number of dials indicating decade switch positions. The basic measuring circuit is illustrated in Figure 4–3(b). One important refinement of this circuit is the replacement of fixed resistor A or B, or both, by adjustable resistors connected to a selector switch so as to allow ratios of R_A/R_B other than unity, e.g., 10:1, 100:1, etc., and 1:10, 1:100, etc. Further refinements and modifications are included in such commercially available resistance bridges as the "guarded Wheatstone

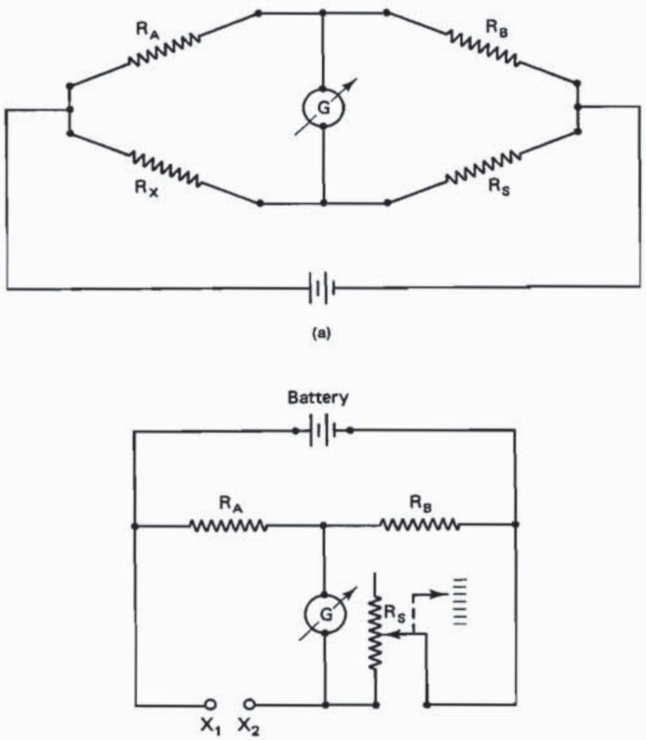

FIGURE 4–3. Wheatstone bridge: (a) basic bridge circuit; (b) basic resistance bridge for resistance determination.

bridge'' and the Mueller bridge, which is used exclusively for the accurate determination of the resistance of platinum-wire resistive temperature transducers.

4.1.7 Capacitance and Inductance Measurement

Although the output of a capacitive or inductive transducer is rarely in the form of a capacitance or inductance change, it is sometimes necessary to measure such outputs.

AC-excited reactance bridges (*impedance bridges*) of various types are most commonly used for measuring inductance as well as capacitance. These are similar in basic design to the Wheatstone bridge, except that no more than two legs of the bridge can be purely resistive. The ''standard'' or ''reference'' leg is reactive and is frequently a series or parallel combination of an adjustable resistor and an adjustable capacitor. The reactance (capacitive or inductive) across the transducer output terminals is then balanced against

the ''standard'' leg of the bridge. The bridge dials are so arranged and labeled as to permit a direct reading of capacitance or inductance.

4.1.8 Output Impedance Tests

The output impedance of capacitive, inductive, resistive, reluctive, and strain-gage transducers whose output is not modified by active circuitry within the transducer is simply measured with an impedance or resistance bridge.

A somewhat more elaborate method is necessary for output-impedance tests on transducers, such as dc output transducers, which contain active circuitry between transduction element and output terminals. The substitution method (Figure 4–4) is frequently used for this purpose. In this method the measurand—between 50% and 100% of the transducer's range—is applied and maintained at a constant level. The output voltage is measured with a high-impedance voltmeter. A resistance decade box is then connected across the transducer's output terminals, and the resistance dials are adjusted until the output voltage is reduced to 90% of its open-circuit (no-load) value. This resistance, R_{90}, is used to calculate the output impedence, which is simply $\frac{1}{9} \times R_{90}$. If saturation effects are suspected within the transducer, which may yield an incorrect output-impedance reading, the resistance can be adjusted, instead, to the value R_{99} required to reduce the output voltage to 99% of the open-circuit value. In this case the output impedance is calculated as $\frac{1}{99} \times R_{99}$.

4.1.9 Output Noise Tests

Noise in the output of potentiometric transducers frequently occurs during the stroking action of the wiper on the resistance element and is related to variations in instantaneous contact resistance. It is customary to measure

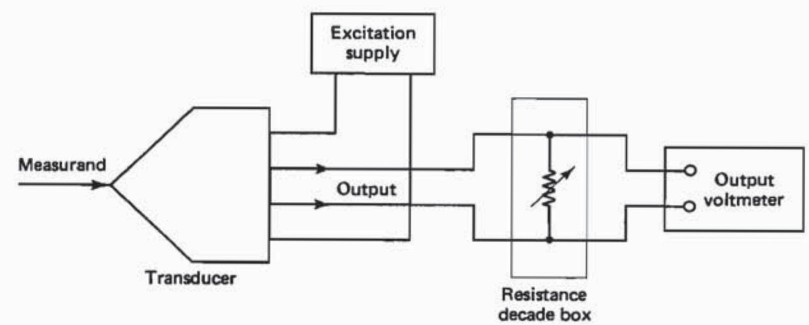

FIGURE 4–4. Output impedance determination by substitution method.

such noise in terms of noise resistance using the test setup illustrated in Figure 4–5. Actuation of the "push-to-calibrate" button results in a calibration deflection on the display device for a noise resistance of 100 ohms. The transducer is then cycled over its full range by suitable variation of the measurand. The noise resistance is monitored on the display device and determined by reference to the 100-ohm calibration deflection. The usual purpose of this test is to determine the maximum noise (resistance). This value can be affected by the transducer cycling rate as well as by environmental conditions such as temperature and (unless the transducer is sealed) humidity. Transducers which have been stored for a long time frequently exhibit abnormally high noise during the first few cycles of such a test. The existence of these various effects point to a need for careful definition of test conditions before starting a noise test on a potentiometric transducer.

Output noise tests on dc output transducers and other types containing active circuitry which can modify the output are considerably simpler. Using the test setup shown in Figure 4–6, the peak-to-peak output noise is read off a calibrated oscilloscope while the measurand, first at 0% and then at 100% of its range, is applied to the transducer. In some cases the use of a low-pass filter can be specified so that noise at higher frequencies is excluded from the measurement. This is specified only when noise at such higher frequencies is expected in the transducer output and the associated measuring system will in no way be adversely affected by it.

4.1.10 Loading-Error Tests

Loading-error tests are performed to determine the effect on the transducer's output of variations in the load impedance either between specified limits or between "infinity" (open circuit) and a specified value. The loading error, when expressed in percent of full-scale output (% FSO), is usually largest at the upper end point, except for potentiometric transducers, where it is maximum at 66% FSO. Figure 4–7 illustrates the loading error, with various

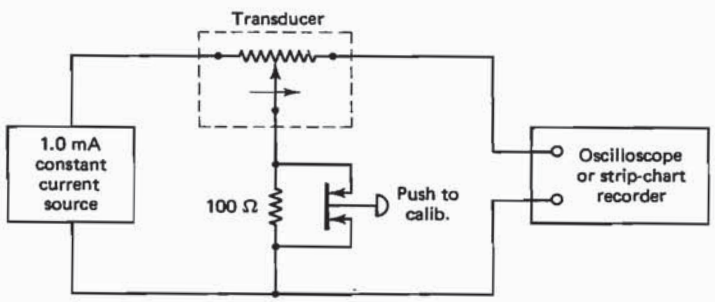

FIGURE 4–5. Output-noise test setup for potentiometric transducers.

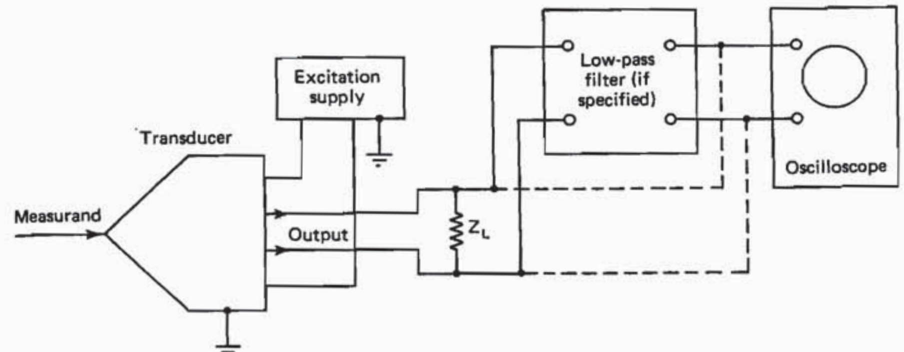

FIGURE 4–6. Output-noise test setup for dc output transducers.

load resistances R_L, of a potentiometric transducer having an element resistance (input impedance) of 7500 ohms. During this test the measurand is applied to the transducer and its level is adjusted so that the transducer's output is at the value where maximum loading error occurs. While the measurand is held constant, the transducer's output is measured first across the maximum, and then across the minimum, specified load impedance.

Since the input impedance of the readout device forms a portion of the

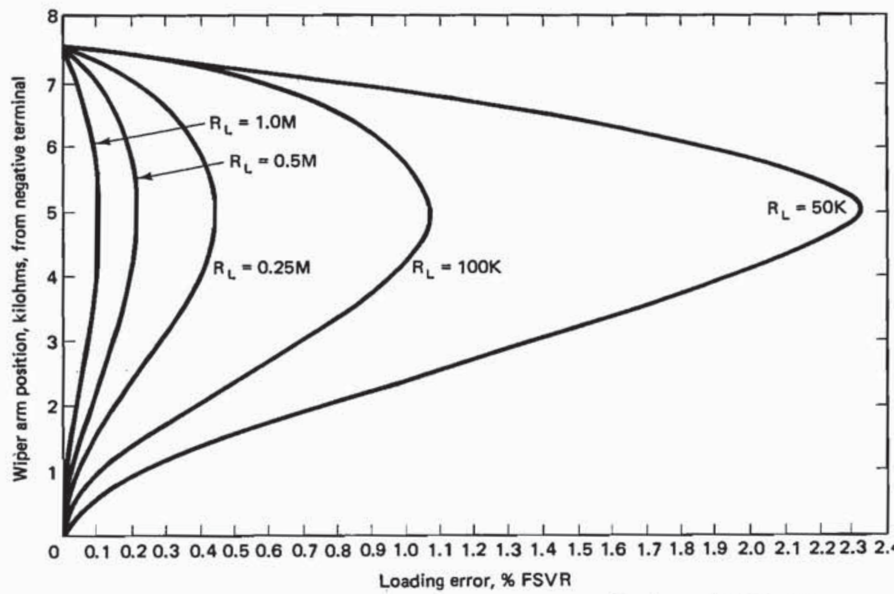

FIGURE 4–7. Loading error for potentiometric transducer with 7500-ohm element resistance.

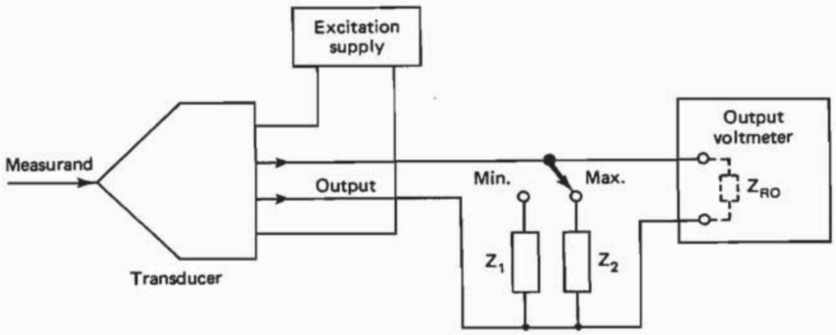

FIGURE 4–8. Loading-error test setup.

load impedance, it must be considered in the determination of test impedance (usually resistance) values. As illustrated in Figure 4–8, the impedance Z_1 necessary to provide the maximum specified load impedance Z_{max} in parallel with the input impedance Z_{RO} of the readout device is

$$Z_1 = \frac{Z_{RO}Z_{max}}{Z_{RO} - Z_{max}}$$

The impedance Z_2 necessary to provide the minimum specified load impedance Z_{min} is

$$Z_2 = \frac{Z_{RO}Z_{min}}{Z_{RO} - Z_{min}}$$

From this test, the loading error is determined as the output reading E_1 (for Z_{max}) minus the output reading E_2 (for Z_{min}). Expressed in percent of full-scale output, the loading error ΔL is then

$$\Delta L = \frac{E_1 - E_2}{E_1} \times 100.$$

4.1.11 Resolution and Threshold Tests

Resolution tests are normally performed only on potentiometric transducers utilizing wire-wound transduction elements. The purpose of this test is to verify the use of a suitable number of turns on the potentiometric winding, as well as the general quality of the winding, but primarily it verifies the absence of grossly uneven spacing between turns, of two or more turns shorting together, and of turns protruding or recessed relative to the nominal outside diameter of the wire-wound resistance element.

The resolution test (Figure 4–9) is usually performed by applying the measurand, varied from the lower to the upper transducer range limit, simultaneously to the test transducer and to a reference transducer which has a continuous-resolution transduction element (e.g., a strain-gage type of transducer). The output of the transducer under test is connected to the "*y*-axis" input of an *x*-*y* plotter, that of the reference transducer to the "*x*-axis" input. The resulting *x*-*y* plot shows the magnitude and number of all steps in the output of the test transducer, provided that the zero and gain setting of the *x*-*y* plotter's amplifiers were properly adjusted. The best results are obtained when the zero setting is shifted several times during the test so that several full-scale plots are obtained, each showing only a selected portion of the test transducer's output but with steps magnified accordingly. The maximum magnitude of any of the output steps (maximum resolution) as well as the average magnitude of all output steps (average resolution) are then determined from examination of the *x*-*y* plot.

Threshold tests are sometimes performed on transducers having continuous-resolution transduction elements. A threshold test is simply the determination of the smallest change in the measurand that will result in a measurable change in transducer output, by use of suitable measurand and output-monitoring equipment. This test may have to be performed at several measurand levels within the transducer's range.

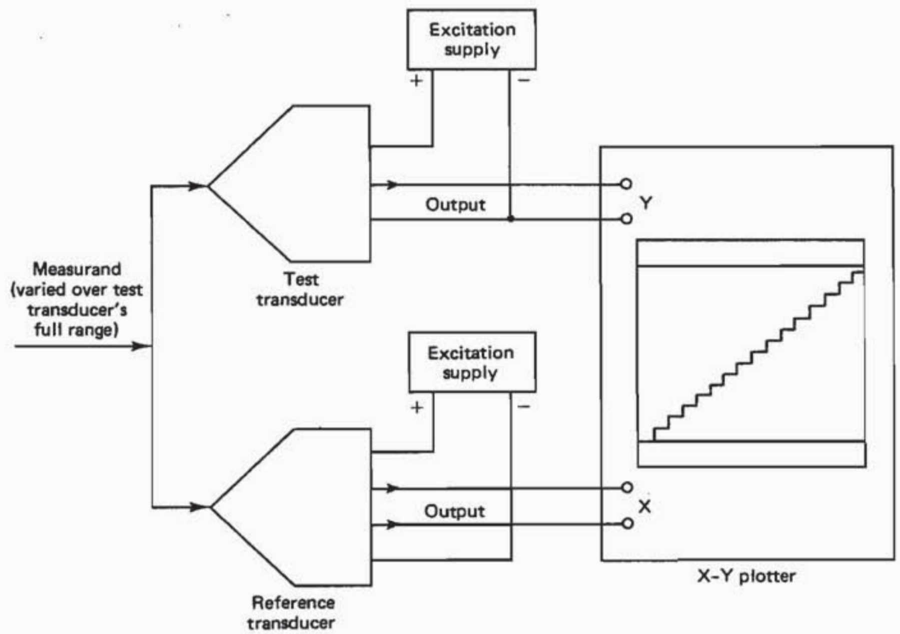

FIGURE 4–9. Resolution test setup.

4.1.12 Excitation Tests

Excitation tests are performed to determine specification compliance of the transducer's excitation ratings and to verify the transducer's susceptibility to field hazards related to excitation.

Tests on transducer designs in which excitation is applied directly to the transduction element are usually limited to power-rating verification. Included here are input-impedance or transduction-element resistance measurements, determination of current drain at rated and maximum excitation voltages, measurements of power dissipation at rated and maximum excitation currents, and verification of proper transducer operation after applications of high-transient pulses of excessive excitation voltage or current.

Additional tests are performed on transducers incorporating excitation-regulation, modification, isolation, or conversion circuitry. Depending on the severity of applicable specification requirements, these may include performance determination at minimum and maximum values of excitation and after excitation polarity reversal, misapplication of excitation to output terminals, and output short-circuiting.

4.1.13 Voltage-Breakdown Test

The voltage-breakdown test, also called the high-potential, dielectric-strength, or dielectric-withstanding-voltage test, is used to verify the adequacy of electrically insulating materials and of the spacing between certain mutually insulated conducting surfaces.

The voltage-breakdown test is performed by applying a specified test voltage between mutually insulated electrical transducer connections or between ungrounded connections and the (grounded) transducer case. The duration of the application (typically 60 s) should be specified, as well as the magnitude and other characteristics of the test voltage (e.g., 500 V ac, rms, 60 Hz). Test failure is evidenced by surface discharge (*flashover*), air discharge (*sparkover*), or puncture discharge (*breakdown*) within the transducer. When limits are also placed on the surge current (measured at initial test voltage application) and on the maximum leakage current (over the entire duration of the test), these currents are measured and recorded.

Most specifications state either the breakdown voltage rating or the insulation resistance (see next). Hence, only one of these two tests is normally performed on a transducer.

4.1.14 Insulation-Resistance Test

The insulation-resistance test is used to measure the resistance offered by the insulating members of a transducer to an impressed dc voltage tending to produce a current leakage either through or on the surface of these members. The insulation-resistance test is commonly used to determine characteristics of the insulation between the transduction element, together with any integral signal-conditioning circuitry, and the external case of the transducer. In some transducers, where excitation-output isolation is required, the test is additionally used to measure the insulation between excitation and output connections.

The importance of this test is given largely by the high impedance circuits frequently used in electronic measuring systems. The operation of the system can be affected severely by "ground loops"—undesirable leakage currents through structural ground planes between components of the system or between excitation-supply and signal-transmission grounds. Excessive leakage currents may also lead to further deterioration of the insulation by heating or electrolysis.

The test is performed by connecting the two voltage-carrying leads from a megohmmeter, megohm-bridge, or insulation-resistance test set to the specified connection points on the transducer (e.g., all insulated receptacle pins, in parallel, and the transducer's case). The test voltage is raised to the specified level (usually 50, 100, or 500 V dc), and the resistance is read on the test-set meter. The reading is taken either when the resistance has stabilized at the value above the minimum specified resistance or after an electrification time of two minutes.

Insulation-resistance measurements are often repeated during and after various environmental tests in order to determine the effects of heat, moisture, dirt, oxidation, and loss of volatile materials on the required insulation characteristics of a transducer.

4.2 CALIBRATIONS

The term "calibration," in its broader sense, includes making adjustments to instruments and making marks on indicating dials and on control knobs. In its narrower sense, however, when applied to transducers (with electrical output), a calibration is purely a test during which known values of measurand are applied to the transducer and the corresponding output readings are recorded. All adjustments, stabilization, and compensation, as well as any interim checks of the operation of the transducer, are considered manufacturing processes, and these all have to be completed before calibration. Only those operations that would normally be performed during use, or just prior to use, of a transducer can be included in the calibration. An example of such a normally performed operation is the short-time, high-temperature "bakeout" of certain vacuum transducers.

Calibration methods differ widely, depending on the measurand. The key issue in a calibration is that the value of the measurand applied to the transducer has to be *known*, which means that the possible errors in that value have to be known. Some calibrations use a reference instrument for this that is of the same general type as the transducer; or a different type can be used, as long as its errors are known and are substantially smaller than those allowed for the transducer. Usually, these reference instruments are periodically compared with a transfer standard. Other calibrations may use a well-understood natural phenomenon as reference; for example, temperature transducers are calibrated by exposing them to a "fixed-point" temperature such as the freezing point of pure water, the boiling point of water, or the freezing or boiling points of other pure materials. Experts in national standards laboratories are usually available for advice on up-to-date acceptable calibration methods. The manner in which output readings are obtained is covered in Section 4.1.

Most transducers are subject to a *static calibration*, which is performed under room conditions and includes letting the measurand stabilize at various values before an output reading is recorded. These values are generally selected at equal increments, with the measurand first increasing and then decreasing. Certain types of transducers that either cannot be calibrated statically or are used primarily for dynamic measurements are subjected to a *dynamic calibration* (see Section 4.3). A few types of transducers whose behavior can be predicted accurately by measuring their output at only one measurand value may be subjected only to a *one-point calibration*.

4.3 DYNAMIC TESTS

Dynamic tests are performed on transducers to verify or determine their dynamic characteristics (see Section 2.5.2). These tests indicate how well the transducer output indicates fluctuations in the amplitude of the measurand. (Fidelity tests on loudspeakers or phonograph cartridges are comparable to this.) The fluctuations can be continuous (e.g., sound or vibration) or occasional (e.g., sudden increases or decreases in temperature, pressure, or flow). Certain categories of transducers are routinely subjected to a *dynamic calibration*, a thorough dynamic test, instead of a static calibration. More categories, however, receive a static calibration as well as a dynamic test; in these cases the dynamic test is generally performed only on transducers subjected to qualification tests, sampling tests, and other non-production tests.

Two types of tests exist for dynamic tests: the sinusoidal response test and the step-function response test. Both tests often (but not always) employ a reference transducer that has a known and faster response (i.e., a wider flat-response frequency range or a shorter time constant) than the transducer to be tested. Connecting both transducers to the same measurand then allows a comparison between the behavior of the test transducer and that of the

reference transducer. When such a test is used as a dynamic calibration, it is called a *comparison calibration*. The amplitude changes that are typically used in the two methods are illustrated in Figure 4–10.

The *sinusoidal response test* can be performed on only a limited number of different types of transducers, primarily because of test equipment design problems. During this test, the measurand applied to the transducer is caused to undergo precisely controlled sinusoidal variations in its level. The frequency of the sinusoidal variations is increased, either continuously (*frequency sweep*) or in steps, and the transducer output is recorded continuously or for each step, respectively. The amplitude of the sinusoidal measurand fluctuation is held constant throughout the test. Typical test amplitudes are 20, 10, and 1% (the latter two are preferred) of the transducer range, peak to peak, within the lower or middle portion of the range.

The *step-function response test* can be performed on most types of transducers. It consists of recording the transducer output while the measurand applied to the transducer is caused to undergo a step change in its level. Step changes from 45% to 55% or from 10% to 90% of the transducer range are commonly used. The equipment used to create this step change must be capable of minimizing the rise time of the step, as seen by the

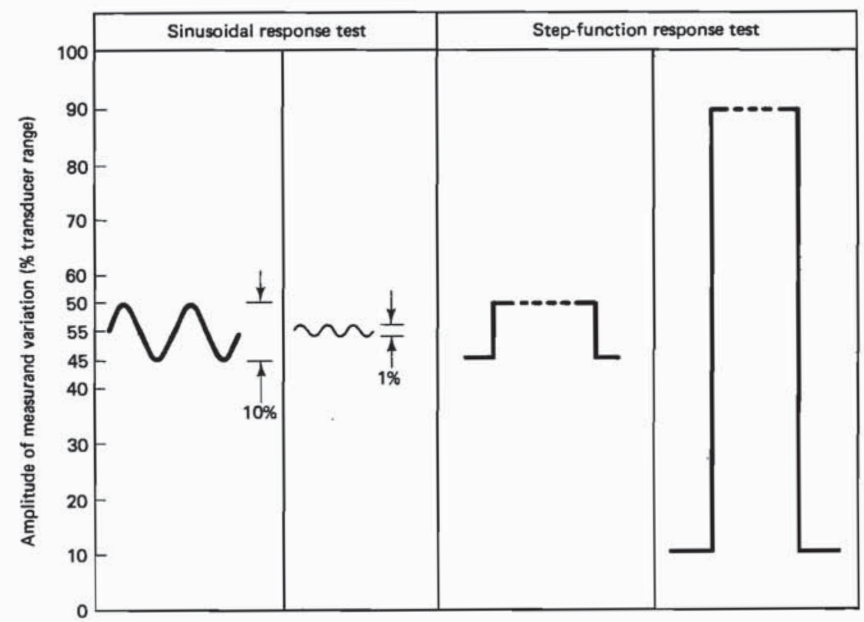

FIGURE 4–10. Types and amplitudes of measurand variations in dynamic response tests.

transducer, so that a true step function and not a ramp function is applied to it. The equipment must also be capable of maintaining the final level of the measurand for a time long enough to yield valid output data.

Frequency response is best determined by use of the sinusoidal response test, but equipment limitations may make this test difficult or impossible to administer. In this case the frequency response may be inferred from calculations based on results obtained from a step-function response test in combination with a knowledge of the transducer's mechanical properties or geometry; it should then be identified as a *calculated frequency response*. The step-function response test can be used for determining not only a transducer's time constant, rise time, or response time, but also its natural frequency, ringing period, damping ratio, and overshoot.

4.4 ENVIRONMENTAL TESTS

Most transducers are used in applications where one or more environmental conditions exceed those defined as room conditions, the ambient conditions prevailing during calibration. Unless otherwise specified, *room conditions* are generally a temperature of 25 ± 10°C, a relative humidity of 90% or less, a barometric pressure of 88 and 108 kPa (26 to 32 in Hg), and an absence of vibration and acceleration (unless one of these is the measurand). When transducers are to be exposed to more severe environments during their intended use (see Section 2.5.3), they can be expected to have performance errors greater than those indicated on their calibration record. Under these conditions they can also take a shift in their calibration curve, and they can even be damaged and stop operating entirely. When environmental conditions more severe than room conditions are specified for a transducer (usually together with widened performance tolerances under such conditions), environmental tests must be performed to verify that the transducer performs as specified. Such environmental tests are normally performed only as part of a qualification or sampling test; however, some critical applications may require at least some partial environmental testing on a 100% basis.

There are two categories of environmental tests: *operating tests*, during and after which the transducer must perform within specified tolerances; and *nonoperating tests*, during which no performance tolerances apply but after which the transducer must again perform as specified.

It rarely happens that the person responsible for transducer selection and use is also responsible for running the environmental tests. Most commonly the tests are performed by a different department in a company or facility, or by the transducer manufacturer, or by an outside laboratory. Therefore, it is best to have a written test procedure that both parties agree to before any tests are begun. This procedure should establish the test sequence, test methods, and test setups and equipment to be used, and it should

show when and how test data, test results, and any additional observations will be recorded. A set of general ground rules should also be followed for all environmental tests. These can only be reflected partly in the written procedure, but can be verified by inspection and observation as well as by discussions with test personnel:

1. The transducer, and especially its electrical, mechanical, hydraulic, and pneumatic connections, must not affect the environment.
2. The transducer must be exposed to no other environments than that specified for the test.
3. The calibration equipment, especially the measurand-level sensor or indicator, must be isolated from the environment.
4. The environment should not affect the measurand seen by the transducer.
5. The level of the environment actually seen by the transducer should be monitored throughout the test.
6. At least a partial calibration, at room conditions, should always be performed right after an environmental test has been completed, to determine any latent or permanent effects of the environment on the transducer.

4.4.1 Temperature Tests

The primary environmental equipment used for these tests is the *temperature chamber*, typically a double-walled, well-insulated metal box with a removable door and with a number of small holes or ports, either in the door or the box, or both, as feed-throughs for electrical, mechanical, and hydraulic or pneumatic connections to the transducer. A mounting bracket for the test specimen is often attached to the inside of the door. The transducer to be tested can then be mounted to that bracket, all connections to it made through holes in the door, and the door, carrying the entire setup, reinstalled on the chamber.

Heating as well as cooling elements are installed between the inner and outer walls. The heating elements are electrical resistance heaters, and the cooling elements are made of tubing that will circulate an externally supplied coolant between the chamber walls. Many chambers also provide a compartment that can be filled with dry ice. A small blower in the chamber improves convective heat transfer and prevents thermal stratification. The internal chamber temperature can be preset, whereupon it will remain thermostatically controlled. Some chambers provide for fine control, using a continuous-type temperature sensor and a controller (which can be proportional) in a closed control loop. A temperature sensor is attached to the transducer case, its leads are connected to an external temperature indicator, and the actual temperature of the transducer can then be monitored and stabilization at the desired temperature can be determined. Performance verification tests are carried out either after stabilization at the specified temperature or after an additional specified period ("temperature soak").

4.4.2 Temperature Shock and Temperature Gradient Tests

Even though both the temperature shock and the temperature gradient test involve a rapid change in the temperature seen by the transducer, the first is usually a nonoperating test and the second is usually an operating test.

The temperature shock test is used to determine whether a change in ambient temperature between two specified levels and at a specified rapid rate (e.g., 5° per min) causes subsequently detectable damage or intolerable performance changes. This test usually simulates a shipping or other pre-use condition such as transportation in an unpressurized aircraft cargo compartment. Some temperature chambers can provide the desired rate of temperature change, while others require the use of a simpler but more severe test method. The transducer, with all required connections, is first stabilized in a chamber maintained at one temperature and then removed and inserted in a second chamber that is precooled or preheated to a different temperature.

A performance test (including at least a partial calibration) after subsequent stabilization of the transducer at room conditions demonstrates any permanent effects of temperature shock on the transducer.

A temperature gradient test is performed on some types of transducers to determine their temperature gradient error (see Section 2.5.3). The test is performed on a bench rather than in a temperature chamber, and its objective is to create a sudden difference in temperature between the sensing element and the case while the transducer output is being recorded continuously. One of these two temperatures is usually room temperature.

Some methods involve keeping the sensing element at room temperature while the case of the transducer is rapidly immersed into a hot or cold liquid bath. If the test specimen is a pressure transducer, for example, a short piece of tubing can be connected to its pressure port, and the assembly can be held by the tubing while the transducer case is immersed. When the sensing element is exposed, as in a flush-diaphragm pressure transducer, the sensing element can be immersed in a hot or cold bath without the transducer case being immersed in it, or the sensing element can be exposed to a step increase in temperature by setting off a flashbulb in front of it or suddenly directing hot air from a blower at it.

4.4.3 Acceleration Tests

Acceleration tests are performed on transducers to determine their performance while they are subjected to quasi-steady-state or slowly varying acceleration (as opposed to vibratory accelerations; see Section 4.4.4). A rotary accelerator (*centrifuge*) is most commonly used to simulate an environment in which acceleration is present. The acceleration acting on a transducer mounted to a turntable near its perimeter can be calculated very accurately from a knowledge of the radius arm (distance between the centerline of the transducer and the center of the turntable) and the angular speed (in r/min) of the turntable.

When the axes of the transducer have been properly identified (see Figure 2–29), the transducer can be mounted in various orientations so that the acceleration will act along its x-, y- or z-axis, in a positive or negative direction. Most acceleration specifications call for acceleration tests along each of these three axes in both directions, although not necessarily at the same acceleration levels. This means mounting the transducer on the centrifuge six times and performing an acceleration test each time. For each acceleration test, the measurand is applied to the transducer and usually held at a fixed level. The difference in transducer output readings taken just before starting the centrifuge and while it is running is the acceleration error. Acceleration tests are quite short; 30 to 60 s is usually long enough to obtain a valid output reading with acceleration applied. Remounting the transducer for each test makes the tests more time consuming.

Special fittings and fixtures are often required to apply a given measurand to the transducer while the turntable is in motion. Pressure can be applied through a rotary-seal swivel fitting in the turntable shaft. Displacement transducers can have their shaft clamped in a fixed position, while temperature transducers can be immersed in a specially designed constant-temperature bath mounted on the centrifuge turntable, with care taken to keep the acceleration from affecting the temperature of the bath during each of the short tests. Electrical connections are always made by use of slip-ring contacts in the centrifuge shaft.

4.4.4 Vibration Tests

Vibration tests are performed to determine the effects of (linear) vibratory acceleration on the transducer's performance. A *vibration exciter* (*shaker*) is used to apply vibration to a mounting fixture on which the transducer is installed. The axis along which the vibration is applied is determined by the orientation of the transducer's axes, as explained in the previous section for acceleration tests. Since vibration is bidirectional, it is only necessary to install the transducer in three different orientations, whereas six such orientations and associated remountings are necessary for performing a complete triaxial acceleration test. Electromagnetic shakers are normally used for vibration testing; their operating principle is similar to that of dynamic loudspeakers such as are used in many automobile radios.

The mounting fixture for the transducer requires careful design, followed by a "dry run" on the shaker while it is instrumented, so as to assure that there are no mechanical resonances and no "cross talk" in the fixture; "cross talk" refers to vibration induced in axes other than the test axis. As illustrated in the typical set-up diagram (Figure 4–11), three monitoring accelerometers are installed on the fixture in close proximity to the transducer to be tested, in order to monitor vibration along three mutually orthogonal axes—the test axis and the two transverse axes. An additional accelerometer, the *drive* (control) accelerometer, is mounted so that it measures the applied vibration. The drive is connected in a feedback circuit to the shaker control console so as to maintain closed-loop control of vibration at preselected levels. As during acceleration tests, the measurand can be applied to the transducer from external sources (as illustrated), or it can be generated and maintained locally (on the transducer, on the mounting fixture, or in the environment immediately ambient to the mounting fixture).

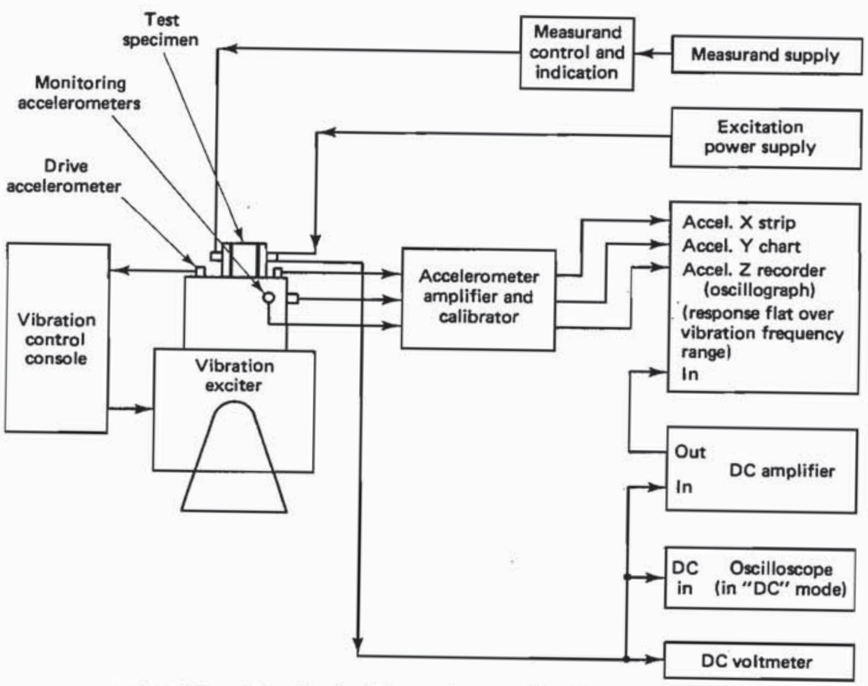

FIGURE 4–11. Typical transducer vibration test setup.

By use of appropriate control, filtering, and power-amplifying equipment, vibration is applied to the transducer in accordance with a predetermined vibration program stated in tabular or graphical form. Such a program usually describes vibration levels in terms of vertical displacement (for low frequencies) or acceleration (for higher frequencies) vs. vibration frequencies, and vibration frequency vs. elapsed test time.

Two types of vibration can be generated and applied to a transducer, either individually or simultaneously (combined): sinusoidal vibration, whose source is usually an audio oscillator; and random vibration, whose signal emanates from a noise source and passes through a number of narrow band-pass filters (equalization controls), allowing the power spectral density of the applied vibration to be adjusted for each narrow band of vibration frequencies. Sinusoidal vibration is periodic in nature. Random vibration is nonperiodic, described only in statistical terms, and characterized by an amplitude distribution which essentially follows a Gaussian distribution ("normal error curve"). The test duration time must be specified, unless the random vibration is combined with a sinusoidal vibration program including a frequency-vs.-time program.

Vibration effects on transducers, as determined during such tests, can usually be classified into three categories: permanent damage (mechanical failure), output variations corresponding to applied vibration levels, and output variation due to *resonances*—amplified vibrations of internal components, within narrow frequency bands, related to the resonant frequencies of these components and excited by the applied vibration when at those frequencies.

More than most other tests, vibration tests call for the talents of an experienced test engineer, one who is capable of determining the validity and possible origins of an apparent test failure as soon as it occurs. Failures ascribed to a transducer are frequently caused by loose or improper mechanical, pneumatic, or electrical connections to the transducer, by resonances or cross talk within the fixture, by insufficient tightening of the fixture or transducer mounting hardware, by inadvertent variations in the applied measurand, by incorrect settings on the control console or on an accelerometer calibrator, by improper grounding of the various interconnected pieces of test equipment, or even by unfiltered transients in the power-line voltage.

4.4.5 Shock Tests

Shock tests are normally performed on transducers to determine their performance after (rather than during) exposure to mechanical shocks. Various types of shock-test machines are available for conducting such tests. They are all capable of applying shocks having acceleration amplitudes over 10 000g with time durations from less than 200 μs to over 100 ms. The shape of the shock pulse can be half-sine (upper or lower half of a sine wave), sawtooth (terminal peak sawtooth), or trapezoidal. Shock pulses can be defined either by shape, amplitude (of acceleration), and time duration, or by their frequency spectrum. Some shock-test machines are simple mechanical devices, such as a pendulous hammer swinging against a vertical surface or a weight dropping in free fall from a given height guided by vertical rails or rods. Other, more complex machines are hydraulic; these can often be programmed more accurately for a large variety of shock pulses.

Most transducer test specifications call for a total of six equal shocks to be applied to the test specimen while it is installed and connected as intended during its actual use. By mounting the transducer on different surfaces of a test fixture, shock is applied sequentially in both directions along each of the transducer's three (x-, y-, and z-) axes.

In rare cases, the performance of a transducer is also monitored during the shock applications, usually by means of an oscilloscope or oscillograph connected to the transducer's output.

4.4.6 Atmospheric Environmental Tests

The category of atmospheric environmental tests includes all those tests required to verify that the transducer can withstand a variety of chemical and physical effects in the atmosphere (or vacuum, or liquid) it is intended to be used in. Some such tests may also verify that there are no harmful interactions between the transducer and its ambient environment. Most of these tests apply to the housing (case) of the transducer, its material and finish, and its sealing qualities.

The tests are typically nonoperating tests, although excitation power may need to be applied to the transducer for some of the tests. Requirements for these tests usually stem from industrial codes and civilian or military government specifications, which also contain detailed test procedures.

Included among these tests are ambient-pressure tests (for effects of low pressures encountered at high altitudes, vacuum encountered in space, and high pressures acting on an underwater transducer); sunshine and ozone tests; salt-spray and salt-atmosphere tests; fungus, rain, and humidity tests; liquid-immersion tests; explosive-atmosphere tests; and sand and dust tests. Some of these tests may be waived if other evidence exists that the transducer case is hermetically sealed and corrosion resistant.

4.4.7 Special Environmental Tests

Certain transducer applications require that maximum levels and spectra of additional environments be established, and that analyses of the transducer's ability to operate in such environments be supplemented by tests. Some

such typical special environments contain high sound-pressure levels (for which "acoustic tests" are performed), nuclear radiation, or strong electromagnetic or electrostatic fields.

4.4.8 Combined Environmental Tests

In most transducer applications two or more different types of environments act upon the transducer simultaneously, each at various levels at various times. When prediction of the transducer's behavior under such conditions, based on individual environmental tests, is not deemed adequate, combined environmental tests may have to be performed. Examples of these are temperature-vibration, thermal-vacuum, and temperature-altitude-humidity tests, as well as shock tests performed at cryogenic temperatures.

Since such tests typically require complex test setups, their cost effectiveness should be carefully considered before they are called for. Thorough analyses, combined with expert knowledge of transducer design, construction, materials, piece parts, and processes, may lessen the need for having these tests performed.

4.5 LIFE TESTS

Operating life tests are hardly ever performed, because specifications for operating life tend 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 verified and documented that at least one transducer of the same design, taken randomly from a production lot, has operated maintenance free and within specified tolerances in its end-use application for a certain number of years. Another substitute is the accelerated life test, which calls for continuous operation of the transducer at conditions more severe than normal, but only for periods on the order of days or weeks.

Cycling life tests are usually performed as part of a qualification test when a transducer specification calls for full-range or partial-range cycling life. Equipment has been designed for rapid and automatic cycling of many categories of transducers. A calibration is performed at the beginning and end of such a test, and sometimes also at one or more intermediate intervals. When a cycling test is performed automatically and unattended, provisions should be made to stop the test (and the cycle counter) when a catastrophic transducer failure occurs.