CHAPTER 15
MEASUREMENT TECHNIQUES

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INTRODUCTION

Earlier chapters describe equipment used in vibration measurements. For example, detailed information concerning transducers, their characteristics, and how these characteristics are influenced by environmental factors is given in Chap. 12. The various measurement system components and the characteristics which determine their selection are described in Chaps. 13 and 14. The use of such measurement systems in vibration problems may involve only one or two engineers as in monitoring the condition of machinery in a factory (Chap. 16), in some problems in modal testing (Chap. 21), in measurements in building structures (Chap. 24), in measuring torsional vibration in reciprocating and rotating engines (Chap. 38), and in the balancing of rotating machinery (Chap. 39). In contrast, in the aerospace industry, some measurement problems are so complex that teams of engineers and several divisions of the company may be involved. Yet all these examples share certain basic measurement procedures. It is these basic procedures (rather than measurement details, which vary from problem to problem) that are considered here. Thus, this chapter includes a general discussion of (1) planning measurements to achieve stated objectives, (2) selecting the type of measurements which should be made to achieve these objectives, (3) selecting transducers, (4) mounting transducers, (5) mounting cable and wiring (including shielding and grounding), (6) selecting techniques for the field calibration of the overall measurement system, (7) collecting and logging the data obtained, and (8) conducting a measurement error analysis.

The best method of analyzing the vibration measurement data, once they have been acquired, depends on a number of factors, including the quantity of data to be processed, the objectives of the measurements, test criteria, specifications, and the accuracy required. These factors are discussed in Chaps. 14, 20, 22, 23, 27, and 28.

MEASUREMENT PLANNING

Careful pretest planning (and, in the case of a complex measurement program, detailed documentation) can save much time in making measurements and in ensuring that the most useful information is obtained from the test data. In many cases, as in environmental testing, measurement procedures are contained in test specifications to ensure that a specification or legal requirement has been met. In other cases (as in balancing rotating machinery), measurement procedures are outlined in detail in national or international standards. In general, the first step in planning is to define the purpose of the test and to define what is to be measured. Planning should start with a clear definition of the test objectives, including the required accuracy and reliability. The second step is to define those non-equipment-related factors which influence the selection of measurement equipment and measurement techniques. These include availability of trained personnel; cost considerations; length of time available for measurements; scheduling considerations; and available techniques for data analysis, validation, and presentation.

Next, the various factors listed in Table 15.1 should be considered. For example, it is important to have some estimate of the characteristics of the motion to be measured—e.g., its frequency range, amplitude, dynamic range, duration, and principal direction of motion. Such information is needed to provide the basis for the optimum selection of measurement equipment. Yet often very little is known about the characteristics of the motion to be measured. Previous experience may provide a guide in estimating signal characteristics. Where this is not available, preliminary measurements may be carried out to obtain information which serves as a guide for further measurements. For example, suppose preliminary measurements show a frequency spectrum having considerable content in the region of the lowest frequency measured. This would indicate that the instrumentation capability should be extended to a somewhat lower frequency in subsequent measurements. Thus an iterative process often takes place in a shock and vibration measurement program. To speed this process, it is helpful to employ equipment whose characteristics cover a wide range and which has considerable flexibility. Failure to take this feedback process into account can sometimes result in the acquisition of meaningless test results. For example, a measurement program was carried out by one organization over a period of many weeks. The objective was to correlate building vibration data, measured in the organization's own laboratories, with the acceptability of these laboratories as sites for ultrasensitive galvanometers and other motion-sensitive equipment. No correlation was found, and the entire measurement program was a waste of time, for two reasons: (a) The measurements were made with equipment with a frequency limit which was not sufficiently low, so that important spectral components of building vibration could not be measured. (b) Measurements were made only in the vertical direction, whereas it was the horizontal component which was dominant and which made certain laboratory areas unacceptable for the location of vibration-sensitive equipment.

Many of the various factors, listed in Table 15.1, which should be considered in planning instrumentation for shock and vibration measurements are discussed in earlier chapters and are cross-referenced, rather than repeated, here. For example, Chap. 12 discusses the effects of environmental conditions on transducer characteristics; Chap. 13 describes various components which follow the transducer in a measurement system (such as preamplifiers, signal conditioners, filters, analyzers, and recorders). Chapter 14 describes the selection of the appropriate analyzer bandwidth, frequency scale, amplitude scale, selection of data windows, etc.

Before making measurements, it is usually important to establish a measurement protocol—the more complex the measurements to be made, the more formal and detailed the measurement protocol should be. It is also important to make an *error analysis,* i.e., (a) to estimate the error introduced into the data acquisition and analysis by each individual item of equipment, and (b) to determine the total error by calculating the square root of the sum of the squares of the individual errors. For

TABLE 15.1 Factors Which Are Important Considerations in the Selection of Measurement Equipment and Measurement Techniques for Mechanical Shock and Vibration Measurements

Parameter to be measured	
Acceleration	Strain
Velocity	Force
Displacement	Mechanical impedance
Characteristics of motion to be measured	
Frequency range	Direction of motion
Amplitude range	Transient characteristics
Phase	Duration
Environmental conditions	
Temperature (ambient and transient)	Magnetic and radio-frequency fields
Humidity	Corrosive and abrasive media
Ambient pressure	Nuclear radiation
Acoustic noise	Sustained acceleration
Transducer characteristics (see Chap. 12)	
Electrical characteristics (sensitivity, resolution, cross-axis sensitivity, amplitude linearity, dynamic range, frequency response, phase response, effects of environment on the transducer)	
Physical characteristics (e.g., size and mass)	
Self-generating or auxiliary power required	
Electrically grounded to case, or isolated	
Self-contained amplifier	
Transducer mountings and locations of mountings	
Effect of mounting on transducer characteristics	
Effect of mounting on vibratory characteristics of item under test	
Number of measurement locations	
Space availability for measurement locations	
Availability of well-regulated power, free of voltage spikes	
Ease of installation	
Possibility of mounting misalignment with respect to intended direction of measurement	
System components (preamplifiers, signal conditioners, filters, analyzers) (see Chaps. 13 and 14)	
Electrical characteristics (e.g., input and output impedances)	
Power availability	
Noise interference (shielding, avoidance of ground loops)	
Number of channels required for measurement and recording: maximum duration of measurements, tape storage requirements	
Possible requirement for real-time information	
Method of data transmission	
Coaxial cable	
Twisted pair of wires	
Telemetry (channels assigned)	
Optical fiber	
Recording equipment (see Chap. 13)	
Recording-time capability	
Electrical characteristics (e.g., signal-to-noise ratio)	
Portability; power requirements	
Correlation between recorded information and physical phenomena	
Redundancy to minimize the risk of loss of vital information	

TABLE 15.1 Factors Which Are Important Considerations in the Selection of Measurement Equipment and Measurement Techniques for Mechanical Shock and Vibration Measurements (*Continued*)

Field calibration
Transducers Over-all measurement system
Data analysis, presentation, and validation
Manual or automatic (Chap. 14); computer (Chaps. 22, 23, 27, and 28) Type of presentation required

example, such an analysis may discover that an individual item of equipment is primarily responsible for introducing a significant total error, suggesting that perhaps it should be replaced. Furthermore, such a determination will indicate whether the total error is within the bounds of acceptability, thereby avoiding useless measurements.

SELECTION OF THE PARAMETER TO BE MEASURED

Often, the selection of the parameter to be measured (displacement, velocity, acceleration, or strain) is predetermined by specifications or by standards. When this is not the case, it is often helpful to apply the considerations given in Table 15.2 or to apply the *flattest spectrum rule* described in Chap. 16. According to this rule, the best motion parameter to use is the one whose spectrum is closest to being uniform (i.e., the one having the flattest spectrum). This is important for two reasons: If the spectrum is relatively flat, then (1) an increase at any frequency has a roughly even chance of influencing overall vibration levels, and (2) minimum demands are placed on the required dynamic range of the equipment which follows the transducer. For example, Fig. 16.2 shows two spectra obtained under identical conditions—one a velocity spectrum, the other a displacement spectrum. The spectrum obtained using a velocity transducer is the more uniform of the two; therefore, velocity would be the appropriate motion parameter to select.

SELECTING THE TRANSDUCER

In selecting the transducer best suited for a given measurement, the various factors listed in Table 15.1 must be taken into consideration, particularly those under *Parameter to Be Measured, Characteristics of Motion to Be Measured, Environmental Conditions,* and *Transducer Characteristics.* Each of these factors (as well as cost and availability) influences the selection process. If consideration of different factors leads to recommendations which are in opposition, then the relative importance of each factor must be determined and a decision made on this basis. For example, consider two factors which enter into the selection of a piezoelectric accelerometer, *sensitivity* and *mass.* Sensitivity considerations would suggest that a transducer of large size be selected since transducer sensitivity generally increases with size (and therefore with mass) for an accelerometer of this type. In contrast, mass considerations would suggest that a transducer of small size be selected in order to minimize the mass loading on the test item; a small size is advantageous since, as Eq. (12.13) indi-

TABLE 15.2 A Guide for the Selection of the Parameter to Be Measured

Acceleration measurements
Used at high frequencies where acceleration measurements provide the highest signal outputs
Used where forces, loads, and stresses must be analyzed—where force is proportional to acceleration (which is not always the case)
Used where a transducer of small size and small mass is required, since accelerometers usually are somewhat smaller than velocity or displacement pickups
Velocity measurements
Used where vibration measurements are to be correlated with acoustic measurements since sound pressure is proportional to the velocity of the vibrating surface
Used at intermediate frequencies where displacement measurements yield transducer outputs which may be too small to measure conveniently
Used extensively in measurements on machinery where the velocity spectrum usually is more uniform than either the displacement or acceleration spectra
Used where vibration measurements on resonant structures are to be correlated with modal stress, since modal stress is proportional to modal velocity at resonance frequencies
Displacement measurements
Used where amplitude of displacement is particularly important—e.g., where vibrating parts must not touch or where displacement beyond a given value results in equipment damage
Used where the magnitude of the displacement may be an indication of stresses to be analyzed
Used at low frequencies, where the output of accelerometers or velocity pickups may be too small for useful measurement
Used to measure relative motion between rotating bodies and structure of a machine
Strain measurements
Used where a portion of the specimen being tested undergoes an appreciable variation in strain caused by vibration—usually limited to low frequencies

cates, the natural frequency of a structure is lowered by the addition of mass. Therefore in this case one should choose the most sensitive transducer (and therefore the largest size) which produces no significant mass loading. In special cases, even the smallest transducer may result in an unacceptable load. Then one of the devices described in Chap. 12 which make no contact with the test surface may be selected.

Consider another example. Suppose a specification requires that vibration displacement be measured. It is reasonable to assume that a displacement transducer (such as the one described in Chap. 12) should be chosen since (depending on the frequency spectrum) such a selection could yield the highest signal-to-noise ratio. On the other hand, in many measurement problems it is more convenient and equally satisfactory to select an accelerometer having a wide dynamic range and to employ an electric circuit which obtains displacement by double integration of the signal from the transducer's output.

TRANSDUCER MOUNTINGS

Various methods of mounting a transducer on a test surface include (1) screwing the transducer to the test surface by means of a threaded stud, (2) cementing the transducer to the test surface, (3) mounting the transducer on the test surface by means of a layer of wax, (4) attaching the transducer to a ferromagnetic surface by means of a permanent magnet, (5) mounting the transducer on a bracket which, in turn, is mounted on the test surface, and (6) holding the transducer against the test surface by hand. Several of these mounting techniques are illustrated in Fig. 15.1, and their frequency response characteristics are shown in Fig. 15.2. Two types of mechanical brackets are illustrated in Fig. 15.3.

The method of mounting affects the resonance frequency and, hence, the useful frequency range of the transducer. Therefore it is important to ensure that the frequency response is adequate before measurements are taken. Each of the above methods of mounting has its advantages and disadvantages. The appropriate choice for a given measurement problem depends on a number of factors, including the following:

Effect of the mounting on the useful frequency range of the transducer

Effect of mass loading of the transducer mounting on the test surface

Maximum level of vibration the mounting can withstand

Maximum operating temperature

Measurement accuracy

Repeatability of measurements (Can the transducer be remounted at exactly the same position with the same orientation?)

Stability of the mounting with time

Requirement that the test surface not be damaged by screw holes

Requirement for electrical insulation of the transducer

Time required for preparation of test surface

Time required to prepare mounting

Time required to remove mounting

Difficulty in cleaning the transducer after removal from test surface

Difficulty in cleaning test surface after transducer removed

Skill required to prepare mounting

Cost of mounting

Environmental problems (dirt, dust, oil, moisture)

For example, the above "requirement for electrical insulation of the transducer" would be a major consideration in the selection of a method of mounting if the insulation so obtained would result in the breaking of a ground loop, as explained in a following section.

Stud Mounting. Figure 15.1*A* illustrates a typical stud-mounted transducer; the transducer is fixed to the test surface by means of a threaded metal screw. One method of insulating the stud-mounted transducer from the test surface is shown in Fig. 15.1*B*. The metal stud is replaced with one which is fabricated of insulating material, and a mica washer is inserted between the transducer and the test surface. Other manufacturers employ a threaded, insulated stud with a flange made of the same material; the flange, midway along the length of the stud, serves as the base for the accelerometer. The entire base of the transducer should be in intimate contact with the test surface. The mounting stud must be of the correct length, incorporating a flange to prevent "bottoming" of the stud which may result in strain-induced errors.

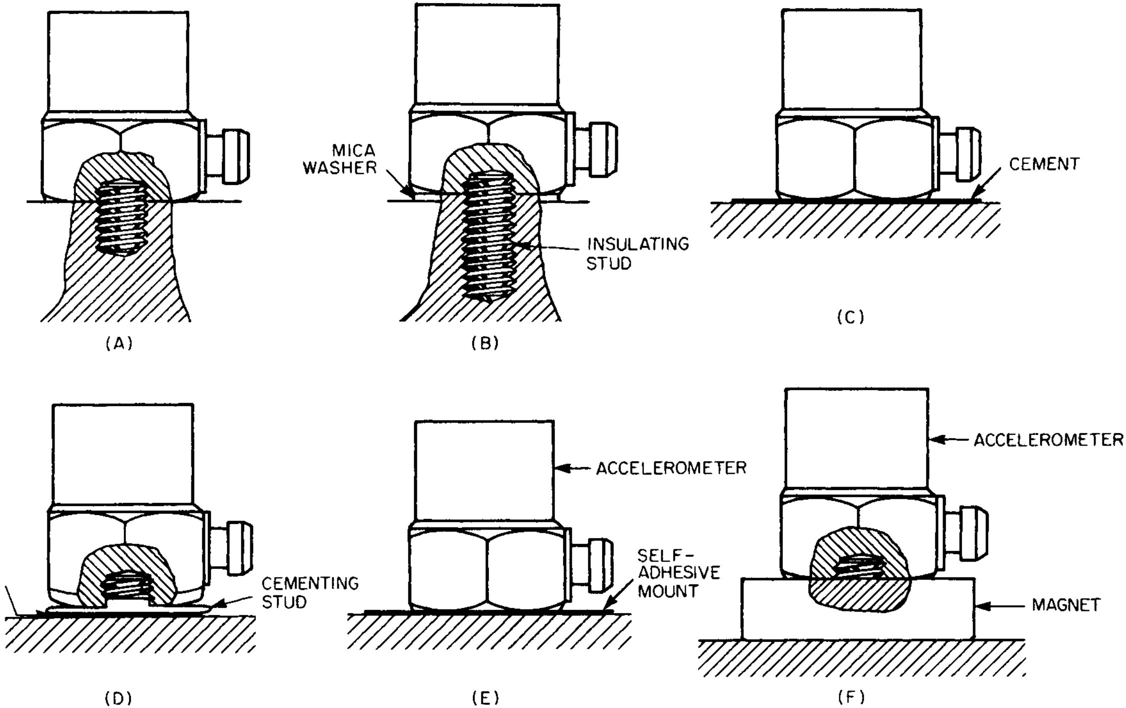

FIGURE 15.1 Various methods of mounting a transducer on a test surface: (*A*) Stud mounting; transducer screws directly to the surface by a threaded stud. (*B*) Same as (*A*) but with a transducer insulated from test surface by use of stud fabricated of insulating material and by a mica washer between the surface and transducer. (*C*) Cement mounting of a transducer; the cement bonds the transducer directly to the surface. (*D*) Similar to (*C*), but here cement bonds the surface to a cementing stud screwed into the transducer. (*E*) Transducer mounted to surface by means of double-sided adhesive tape or disc. (*F*) Transducer mounted to surface by means of a magnet. (*Courtesy of Brüel & Kjaer.*)

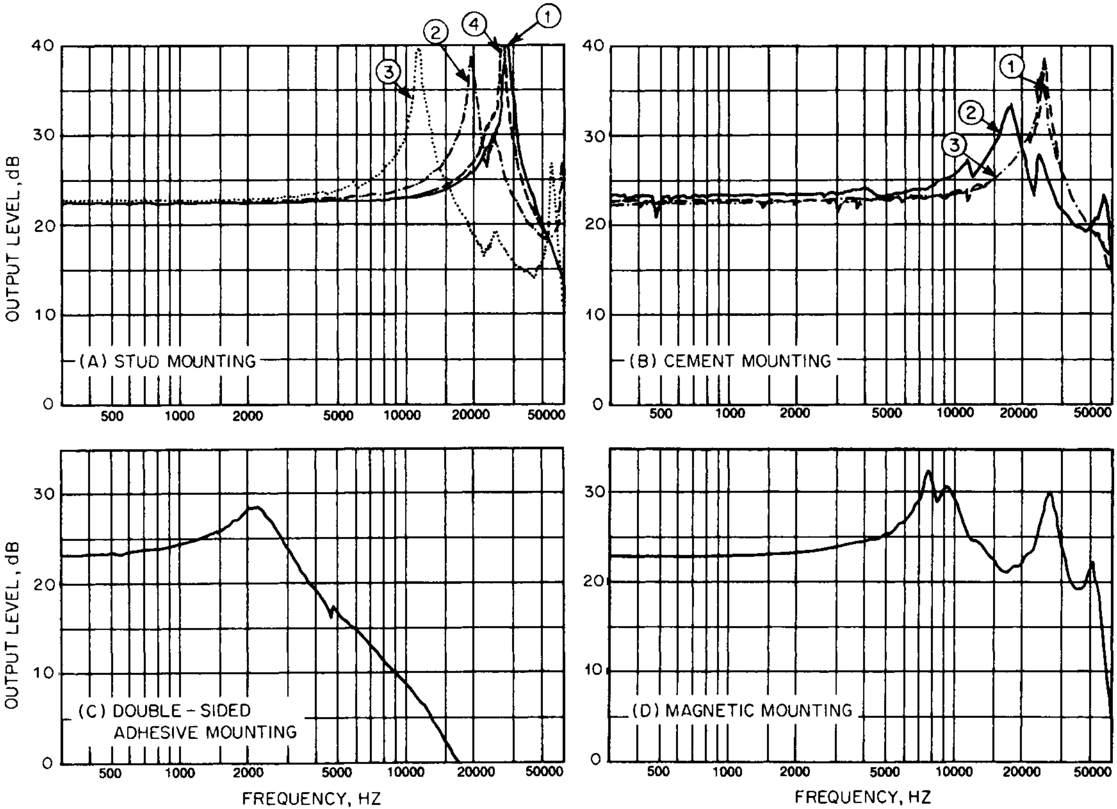

FIGURE 15.2 Frequency-response curves for the same piezoelectric accelerometer mounted by the different methods illustrated in Fig. 15.1: (*A*) stud mounting; (*B*) cement mounting; (*C*) double-sided adhesive mounting; (*D*) magnetic mounting. (*Courtesy of Brüel & Kjaer.*)

Where stud mounting is practical, it is the best type to use for the following reasons:

1. It provides the highest resonance frequency (up to 100 kHz) of any of the mounting techniques and, therefore, the widest possible measurement frequency range (up to 50 kHz).
2. It permits measurements at very high vibration levels without the loosening of the transducer from the test surface.
3. It does not reduce the maximum permissible operating temperature at which measurements can be made.
4. It permits accurate and reproducible results since the measurement position can always be duplicated.

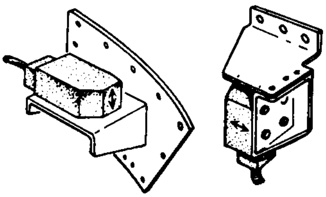

FIGURE 15.3 Two types of mounting brackets. In this example, a velocity-type transducer is shown; the arrows indicate the direction of sensed motion.

In preparing a stud mounting, the test surface must be drilled and tapped. A standard 10-32 thread is widely used. (Also see International Standards Organisation Standard ISO 1101.) Distortion of the transducer as mounted may produce strains that affect the transducer's response. Therefore, it is important (1) to ensure that the test surface is very flat (which can be done by grinding or lapping), (2) to prevent the mounting stud from bottoming in the transducer case—this can lead to strain, and (3) to screw the stud into the hole in the test surface, and then the accelerometer onto the stud using a torque wrench to ensure repeatability in installation of the transducers and to prevent thread damage; use the torque recommended by the transducer's manufacturer. The application of a silicone grease (such as Dow-Corning DC-4) or a light machine oil between the transducer and the test surface usually provides better response at high frequencies—say, above 2000 Hz. The upper temperature limit for the stud mounting of Fig. 15.1*A* is limited only by the accelerometer, but with the mica washer insert shown in Fig. 15.1*B,* the upper limit may be as low as 480°F (250°C).

Figure 15.2*A* shows response curves for a stud-mounted accelerometer for the following conditions: ① spanner tight, which has the highest resonance frequency, ② finger tight, ③ mounted with a mica washer to provide electrical insulation between the transducer and the vibrating surface, and ④ mounted on a somewhat thinner mica washer—which results in a higher resonance frequency than for ③.

Cement Mountings. A *cement* is a substance that bonds two surfaces together when the cement hardens; it acts as an adhesive. Where it is not possible to use a stud mounting, a transducer can be bonded to a clean test surface by means of a thin layer of cement (for example, a cyanoacrylate, dental cement, or epoxy cement), as shown in Fig. 15.1*C.* If the test surface is not flat and a miniature accelerometer is used, it is not difficult to build up a layer of dental cement around the accelerometer so as to provide firm attachment for the accelerometer. In mounting the transducer, it should be pressed firmly against the flat, smooth surface to ensure that the adhesive layer is thin; excess adhesive around the perimeter should then be removed immediately.

The cement method of mounting a transducer provides excellent frequency response, as shown in Fig. 15.2*B* for three conditions: ① accelerometer cemented directly to test surface, ② accelerometer cemented with a "soft" adhesive (not recommended), and ③ accelerometer with a cementing stud which is cemented to the surface with a hard cement.

This type of mounting may be used at high levels of vibration if the cementing surfaces are carefully prepared, *following the manufacturer's instructions.* Cement mounting may or may not provide electrical insulation; if insulation is required, the electrical resistance between the transducer and the test surface should be checked with an ohmmeter. The maximum temperature at which measurements can be made is limited by the physical characteristics of the cement employed—usually about 176°F (80°C), although some cements such as 3M Cyanolite 303 have an upper limit as high as 390°F (200°C). At room temperature, it has the best coupling characteristics over a wide frequency range. This type of mounting has good stability with time. Where a transducer has been attached to a surface by the use of a cement, exercise considerable caution in removing the transducer from the surface to avoid damaging it; application of a solvent to soften the cement is strongly recommended.

Methyl cyanoacrylate cements [such as Eastman Kodak 910 (no longer available from Eastman, but obtainable as a somewhat similar generic substitute, often with poorer characteristics), 3M Cyanolite 101, and Permabond 747] dry much more rapidly than epoxy cements and therefore require less time to mount a transducer. They may be removed easily and the surface cleaned with a solvent such as acetone. Removal of epoxy from the test surface and from the transducer may be time-consuming. In fact, the epoxy bond may be so good that the transducer can be damaged in removing it from the test surface. When encased in epoxy, an accelerometer may be subject to considerable strain, which will significantly alter its characteristics. On the other hand, unless the cemented surfaces are very smooth, an epoxy can provide a superior bond since it will fill in a rough surface far better than a cyanoacrylate cement. With either bonding agent, the surfaces must be very clean before application of the cement. This mounting technique is not recommended for conditions of prolonged high humidity or for pyroshock measurements.

Commercial adhesives are obtainable for use in very hot or in very cold environments. For cryogenic applications, a two-component epoxy resin, room-temperature-cured, is available that is effective down to –200ºC and is able to withstand cryogenic thermal shock without cracking. For use at very high temperatures (up to 700ºC) ceramic-based adhesives are available that are effective, but require so high a curing temperature that their use is usually restricted to high-temperature applications. Several epoxy resins are commercially available that are cured at room temperature and can operate at temperatures as high as 260ºC.[2]

Wax Mounting. Beeswax or a petroleum-based petrowax may be used to attach a transducer to a flat test surface. If the bonding layer is thin (say, no greater than 0.2 mm), it is possible to obtain a resonance frequency almost as high as that for the stud mounting, but if the test surface is not smooth, a thicker wax layer is required and the resonance frequency will be reduced. If the mating surfaces are very clean and free from moisture, the transducer can be mounted fairly easily, although some practice may be required. The transducer can be removed rapidly with a naphtha-type solvent. Disadvantages include the possibility of disattachment of the transducer at high vibration levels, a temperature limitation because of the relatively low melting point of wax, and poor long-time stability of the mounting. The maximum temperature at which measurements can be made with this mounting technique is usually about 100°F (40°C).

Adhesive-Tape Mounting. An *adhesive* is a substance used to bond two surfaces together. The adhesive is usually applied to a tape or disc. In such application, this term is often used as a synonym for the word "cement." An adhesive film may be used to mount a small transducer on a flat, clean test surface—usually by means of a double-sided adhesive tape. Double-sided adhesive discs are supplied by some transducer manufacturers. This mounting technique, illustrated in Fig. 15.1*E,* is rapid and easy to apply. Furthermore, such a mounting has the advantage of providing electrical insulation between the transducer and the test surface, and it does not require the drilling of a hole in the test surface; it is particularly applicable for use with a transducer having no tapped hole in its base. Such adhesives can provide secure attachment over a limited temperature range, usually below 200°F (95°C). In preparing an adhesive mounting, it is important to clean both the accelerometer and the test surface so that the adhesive will adhere firmly. When this is done, the frequency response can be fairly good, as illustrated in Fig. 15.2*C,* but not as good as with a wax mounting.

Another method of mounting is to use a cementing stud which is threaded into the transducer; the flat side of the stud is then cemented to the test surface as shown in Fig. 15.1*D.* This is a useful technique where repeated measurements at the same point are required. The transducer may be removed for measurements elsewhere, but the cementing stud is left in place. This provides assurance that future measurements will be made at precisely the same point.

Magnetic Mounting. With magnetic mounting, illustrated in Fig. 15.1*F,* a permanent magnet attaches the transducer to the test surface, which must be ferromagnetic, flat, free from dirt particles, and reasonably smooth. Magnetic mounting is useful in measuring low acceleration levels. The transducer can be attached to the test surface easily and moved quickly from one measurement point to another. For example, in a condition-monitoring system (described in Chap. 16) it can be used to determine a suitable measurement location for a transducer to be mounted permanently on a large rotating machine. In a heavy machine of this type, the added mass of the magnet is not important, but in other problems, the additional mass loading on the test surface may make the use of magnetic mounting unacceptable. Furthermore, if the acceleration levels are sufficiently high, as in impact testing, the magnet may become loosened momentarily. This can result in an inaccurate reading and possibly a slight change in the position of the transducer, which would also change the reading. The frequency response for this type of mounting is fair, as shown in Fig. 15.2*D,* but not as good as with the wax mounting. The magnet, often available from the transducer's manufacturer, usually is attached to the transducer by means of (1) a projecting screw on the magnet, which is threaded into the base of the transducer, or (2) a machine screw, one end of which is threaded into the transducer and the other end into the magnet. Application of a light machine oil or silicone grease usually improves the frequency response above about 2,000 Hz. The maximum temperature at which measurements can be made with this mounting technique is usually about 300°F (150°C). In attaching a magnetically mounted transducer to a test surface, the magnetic force that pulls the assembly toward the surface may sometimes be sufficiently high to result in a high level of mechanical shock at the time of contact, causing damage to the sensing elements or its internal electronics.

Mounting Blocks or Brackets. Physical conditions may make it impractical to mount a transducer by any of the above methods. In such cases, a mounting bracket or block that has been especially prepared for use on the test surface may be employed. For example, if the structural surface is rounded, a solid mounting block can be fabricated which is rounded to this same contour on one side and flat on the other side for mounting the transducer. A mounting block also may be useful where the surface is subject to structural bending; in this case, two accelerometers selected to have the same characteristics may be attached to the mounting block to measure bending-induced rotation. The effect of the mass of the mounting block is considered in Eq. (15.1). Two types of mounting brackets are illustrated in Fig. 15.3. Instead of using a triaxial accelerometer, sometimes it is more convenient to mount three transducers on a single block having sensitivities in three orthogonal directions. Any such mounting must couple the transducer to the test surface so that the transducer accurately follows the motion of the surface to which it is attached. This requires that the effective stiffness of the transducer mounting be high so that the mounting does not deflect under the inertial load of the transducer mass. This is not a problem in many transducer installations.

Mounting brackets may have resonance frequencies which are below 2,000 Hz and have little damping. Under such conditions, their use may result in significant measurement error as a result of resonant amplification or because of attenuation of vibration in the mounting. This is illustrated in Fig. 15.4, which shows the frequency response of a transducer mounted on brackets which are identical in geometry but which are fabricated from different materials. Note that a change in material from (*A*) steel to (*B*) a phenolic plastic halves the resonance frequency of the mounting. A change in the method of attachment, from (*B*) screw mounting to (*C*) an epoxy resin adhesive bond, significantly increases the frequency of the mounting resonance. Although these results are not of a general nature, they show that such minor variations in the transducer mounting may produce significant changes in the output characteristics of the transducer. It is good practice to calibrate an accelerometer in combination with its mounting block.

Hand-held Transducer. A transducer which is held against the test surface by hand provides the poorest performance of any of the techniques described here, but it sometimes can be useful in making a rapid survey of a test surface because the measurement location can be changed more rapidly than with any other method of mounting. Usually, a rod (called a *probe*), which is threaded at one end, is screwed into the transducer; the other end has a tip that is pressed against the test surface.

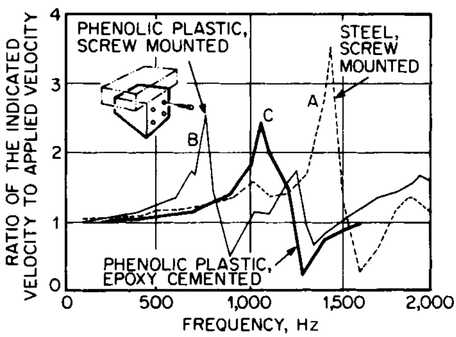

FIGURE 15.4 Relative frequency response of a velocity transducer mounted on three brackets which have identical geometry but are fabricated of different materials: (*A*) steel bracket, screw mounted, (*B*) cloth-reinforced phenolic plastic bracket, screw mounted, and (*C*) same as (*B*) but attached with epoxy resin adhesive.

The frequency response is highly restricted—about 20 to 1,000 Hz; furthermore this technique should not be employed for accelerations greater than 1*g*. Thus, this technique is used when measurement accuracy is not essential, e.g., in finding the nodal points on a vibrating surface.

Mass-Loading. The effect of the mounting on the accuracy of measurement can be estimated roughly if it is assumed that the combination of the transducer (having a mass m) and the mounting (having a stiffness k) behaves as a simple spring-mass system driven at the spring end of the system. Then the acceleration of the transducer $\ddot{x}$ is given by

$$\ddot{x} = \ddot{u} \frac{k}{k + m(2\pi f)^2} \tag{15.1}$$

where $\ddot{u}$ is the acceleration of the test item, and f is its frequency of vibration. If the acceleration of the transducer is to be within 10 percent of the acceleration of the test item, then from Eq. (15.1), k must have a value at least 10 times greater than the term $m(2\pi f)^2$. Since the undamped natural frequency f_n of the transducer-mounting system is given by $f_n = ½\pi(k/m)^{1/2}$, the value of the natural frequency of the system must be at least 10 times the frequency of vibration of the test item—especially for the measurement of transients.

Alternatively, the unloaded dynamic environment at the mounting point can be calculated from the measured dynamic environment using the mechanical impedance ratio given by Eq. (3.4) of Ref. 2.

FIELD CALIBRATION TECHNIQUES

TRANSDUCERS

Various methods of calibrating transducers are described in Chap. 18. If a transducer is to be used under unusual temperature conditions, it is important to perform the calibration in the temperature range in which it will operate. Of these, the following are particularly convenient for use in the field.

Comparison Method. This is a rapid and convenient method of obtaining the sensitivity of a transducer. It is one of the most commonly used calibration techniques. Calibration is obtained by a direct comparison of the output generated when the transducer is attached to a vibration exciter with the output generated by a secondary standard transducer which is attached to the same vibration exciter and which is subject to precisely the same motion. The two transducers are mounted back to back, as illustrated in Fig. 18.3. Calibration by this method is limited to the frequency and amplitude ranges for which the secondary standard has been calibrated and for which the vibration exciter has adequate rectilinear motion. The secondary standard accelerometer should be calibrated against a National Institute of Standards and Technology (NIST) traceable reference, at least once a year, in compliance with MIL-STD-45662A.

Free-fall Calibration Method. The gravimetric free-fall calibration method (sometimes called a *drop test*) is a simple and rapid method of calibrating motion and force sensors. The transducer under test is allowed to fall freely for an instant of time under the influence of gravity; the peak signal then is measured for an acceleration of gravity having a value of 1*g*. This technique is illustrated in Fig. 18.5.

Earth's Gravitational Field Method. In the following technique (sometimes called the "*inversion method*" of calibration), the sensitive axis of the transducer is first aligned vertically in one direction of the earth's gravitational field, as shown in Fig. 15.5*A*. Then it is inverted so that its sensitive axis is aligned in the opposite direction, as shown in Fig. 15.5*B*. The transducer output is observed for a 2*g* change in acceleration, as shown in Fig. 15.5*C*. This method is limited in application to accelerometers having sensitivity down to 0 Hz; it is not recommended for calibration of accelerometers having significant transverse sensitivity.

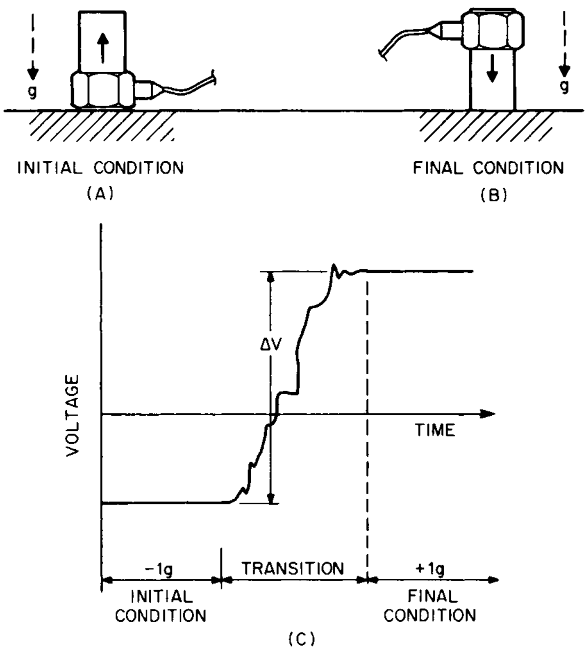

FIGURE 15.5 Gravitational field method (inversion test) for calibrating an accelerometer having useful sensitivity down to 0 Hz. Inversion of the accelerometer, initially aligned in one direction, as in (*A*), to the opposite direction, as in (*B*), produces a change in acceleration of 2*g*. The transducer output for this change is measured in (*C*). (*Courtesy of Quixote Measurement Dynamics, Inc.*)

OVERALL SYSTEM

Calibration of a complete vibration measurement system usually is referred to as *overall calibration* or *end-to-end calibration*. It is good practice to perform such a calibration at periodic intervals—particularly both before and after an extensive series of measurements. In such a calibration, the amplitude characteristics, phase characteristics, and linearity of the overall system are determined when the transducer is subject to a known acceleration, velocity, or displacement, for example, by means of a *field calibrator.*

Field Calibrator. This is a portable device on which a transducer can be mounted and subjected to a known acceleration, velocity, or displacement at a fixed frequency. Such an instrument (essentially a small, portable, battery-powered shaker) provides a convenient means for calibrating a transducer in the field and/or calibrating the overall vibration measurement system. For example, the hand-held device shown in Fig. 15.6 can be used to calibrate a transducer weighing up to 85 grams at a frequency of 79.6 Hz. This device is furnished with an internal oscillator and a stable, built-in reference accelerometer in a feedback loop controlling the electrodynamic exciter; the exciter subjects the transducer under test to a constant rms acceleration amplitude of 1*g*.

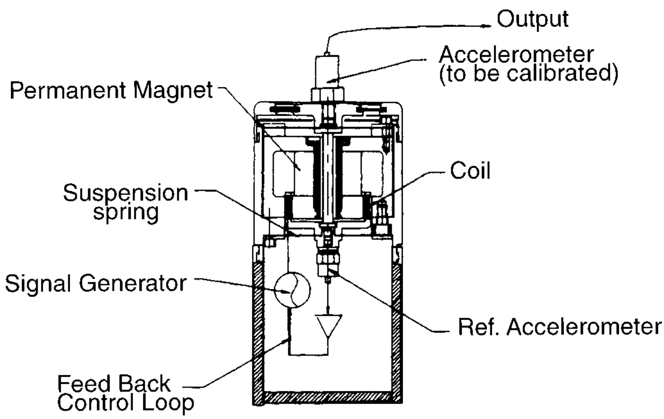

FIGURE 15.6 A hand-held vibration calibrator especially designed for field application. (*Courtesy PCB Piezotronics, Inc.*)

Combining Characteristics of Individual Components. When it is not possible to subject the transducer to a known acceleration, velocity, or displacement, the overall characteristics sometimes are determined by combining the characteristics of the individual components of the system, as described below, or the system is calibrated employing a simulated transducer output [see *Voltage Substitution Method of Calibration* below, and *Calibration of Auxiliary Circuits* (Chap. 18)].

There may be a significant electrical signal at the output of a measurement system though no signal is supplied by the transducer to the input; such electrical signals, which represent noise, (1) may result from a coupling between circuits in the measurement system with power circuits, (2) may be generated by vibration-sensitive elements (such as cable) other than the transducer, or (3) may be the result of improper selection of system components, or the improper setting of one or more of these components, so that the signal-to-noise ratio that the overall system is capable of attaining is not achieved.

Where a single component of a measurement system is the source of noise, it can sometimes be located by using an oscilloscope which is first connected to the transducer output with no vibration applied. Then the oscilloscope connection is moved, component by component, through the measurement system until the noise is observed. Another approach is to short-circuit the signal path at various points in the system (where this is practical), one at a time, until the system electrical noise disappears. Usually this pinpoints the source as the component next nearest the transducer from the last short circuit.

Spurious mechanical sources and acoustic noise sources must be eliminated or controlled if they result in noise in the measurement system. Spurious resonances in the response of the overall system may result from improper seating of the transducer on the test surface or from resonances in the transducer mounting. It is often very useful to excite the transducer-mounting system by giving it a blow and then to observe the transducer's output—look for resonances other than the resonance frequency of the transducer. The other resonance frequencies which appear may be due to (1) resonances in the test specimen or (2) resonances in the transducer mounting. Loose mountings usually produce "noisy" signals and may produce audible buzzing sounds. Often it is difficult to determine the difference between resonances in the mounting and resonances in the item under test. If serious doubt exists, the test should be repeated with a different mounting or a different measurement location for the transducer. If the resonance frequencies are identical for the new mounting, the resonances are probably due to the test specimen, and the original mounting probably was satisfactory.

Combining Calibration Characteristics of a Measurement System's Components. An overall system can be calibrated by combining the measured electrical characteristics of all components in the measurement system from one end to the other. Obtaining a system calibration in this way circumvents the difficulties of precise field calibration, but it requires that each element in the system be calibrated in the laboratory with extreme care and that the effects of the source and load impedances be completely accounted for. Thus, a system calibration is subject to the sum of the experimental errors introduced by the calibration of each element, in addition to any errors resulting from improper simulation of, or accounting for, loading effects. In general, the calibration of each element is performed before the system is assembled, and so this method is subject to error resulting from (1) undetected damage to components between calibration and use and/or (2) improper connections, misidentifications, or confusion in polarity.

Voltage Substitution Method of Calibration. A suitable simulated transducer for use in field checkout must duplicate the electrical outputs of the actual transducer for the various vibration conditions to be simulated. The simulated transducer must either (1) reproduce the electrical voltage- or current-generating characteristics of the actual transducer and have the same output impedance or (2) duplicate the electrical quantity generated by the actual transducer when connected to its load. Failure to meet these conditions will result in a different loading of the actual and simulated transducers and will probably cause calibration errors. It is important that the simulated transducer have the same electrical grounding configuration as the actual transducer; otherwise, electric-circuit noise and cross talk* will not be represented accurately when the simulated transducer is in use.

Typical examples of circuits which simulate transducers are shown in Fig. 15.7. The simulated transducer introduces an electrical signal into the measurement system, thereby simulating the response of the actual transducer.

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*_Cross talk_ is the output of one measurement channel when a signal is applied to another measurement channel. Cross talk can be distinguished from other electrical disturbances because it is a function of the applied signal in the other measurement channel and disappears when this applied signal is removed.

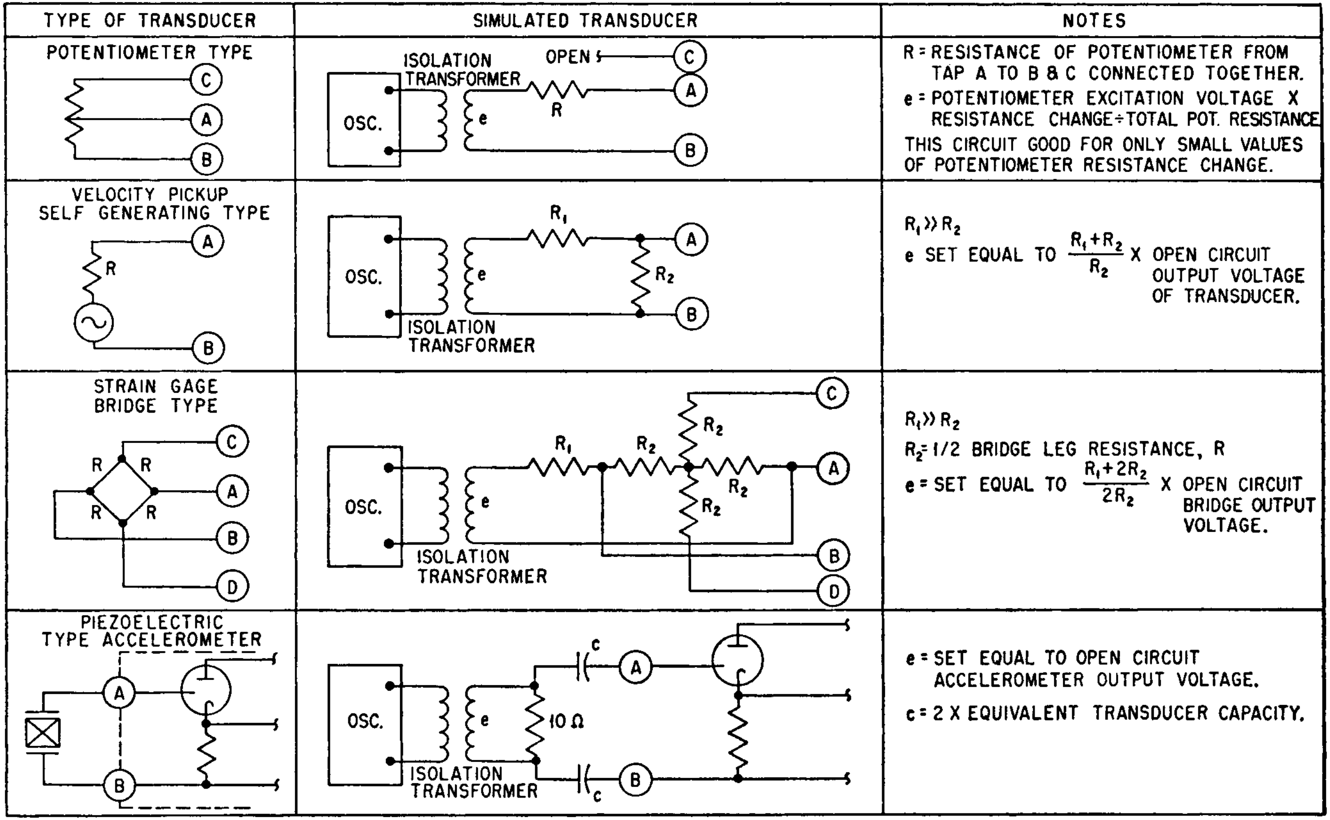

FIGURE 15.7 Electrical schematic diagrams of some common types of transducers and typical circuits used to simulate them during field calibration. Terminals labeled *A* and *B* are the signal lead connections to which either the transducer or the simulated transducer is connected.

CABLE AND WIRING CONSIDERATIONS

The method of data transmission between a transducer and the electronic instrumentation which follows it depends on the complexity of the problem. In general, cable is used for most problems, but the aerospace industry often relies on telemetry for data transmission. Many types of cable are available. The choice of a suitable cable depends primarily on the particular application, the transducer, the cable length, whether the transducer is followed by a voltage amplifier or charge amplifier, and environmental conditions. For example, cable jackets may be made of silicone rubber having a useful temperature range from –100 to 500°F (–73 to 260°C), of polyvinylchloride having a useful range from –65 to 175°F (–54 to 79°C), or of fused Teflon having a useful range from –450 to 500°F (–268 to 260°C). Special-purpose cables are available that can be used at much higher temperatures. In general, cable should be as light and flexible as possible—consistent with other requirements. The effect of the shunt capacitance of the cable following the transducer on the sensitivity of the transducer depends on the type of amplifier connected to the cable. If a voltage amplifier is used, there is a reduction in sensitivity of the transducer, given by Eq. (12.17). In contrast, when a charge amplifier is used, the effect of the shunt capacitance of the cable in reducing the sensitivity of the transducer is negligible, as shown in Eq. (13.2) (although the noise pickup in the high-impedance circuit increases with cable length).

In the audio-frequency range, the series inductance L and the shunt leakage G of short, good-quality cables are negligibly small in comparison with other parameters and may be neglected. Figure 15.8*A* shows the equivalent low-frequency representation of a cable with distributed constants. For most purposes the simpler lumped-constant configuration of Fig. 15.8*B* is a sufficiently accurate representation. The quantities R_c and C_c are the total resistance of the conductors and the total capacitance between them, respectively. Values for a typical coaxial cable having a Teflon dielectric are R_c = 0.01 ohm/ft (0.03 ohm/m) and C_c = 29 pF/ft (88 pF/m).

The normal characteristic impedance of about 50 ohms for such cable has no significance in most measurement problems, where cables usually are relatively short. The open-circuit input impedance of the cable is almost exclusively capacitative. When terminated, it takes on the impedance of the load, modified by the series and shunt parameters.

In general, cables should be treated with the same care given transducers in shock and vibration measurement systems. The following are based on recommendations given in Ref. 1; they represent good engineering practice.

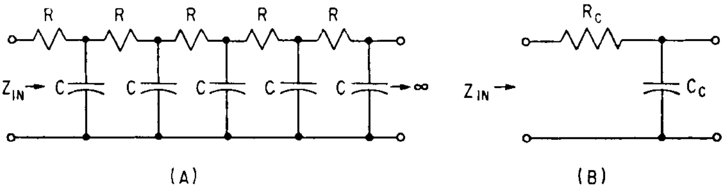

FIGURE 15.8 Successive approximations in the representation of a short, high-quality transmission line at audio frequencies. (*A*) Distributed constant configuration neglecting series inductance and shunt leakage. (*B*) Lumped-constant configuration.

1. Attach a coaxial cable to a transducer by turning the connector nut onto the threads of the transducer (not vice versa) to avoid damage to the pins.
2. Avoid cable whip by tying down the cable at a point near the transducer and at regular intervals to avoid induced cable noise.
3. Screw the cable connection to the tightness specified by the manufacturer.
4. Loop the cable near the connector in a high-humidity environment, to allow condensation to drip off before reaching the connector.
5. Clean the cable connector before use (e.g., acetone or chlorothene) to remove contamination as a result of handling; the contamination can create a low impedance between the signal path and ground.
6. Check electrical continuity of cable conductors and shield if intermittent signals are observed. Then, flex the cable—especially near the connector—and observe if the signal is affected by flexing.
7. Select cables that are light and flexible enough to avoid loading the transducer and/or the structure under test, or exerting a force on the transducer.
8. Avoid twisting the cable when it is connected to the transducer.
9. Move the cable back and forth to determine if such movement generates unacceptable electrical noise; if so, tie the cable more securely or replace the cable.

CABLE NOISE GENERATION

When two dissimilar substances are rubbed together, they become oppositely charged—a phenomenon known as *triboelectricity,* illustrated in Fig. 15.9. Thus a charge may be generated when a cable is flexed, bent, struck, squeezed, or otherwise distorted, for then such friction takes place between the dielectric and the outer shield or between the dielectric and the center conductor.[3] A charge is generated across the cable capacitance so that a voltage appears across the termination of the cable.

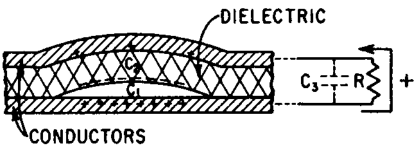

FIGURE 15.9 A section of cable during distortion, showing how separation of triboelectric charge leads to the production of cable noise across the termination resistance. (*After T. T. Perls.*[3])

Another mechanism by which noise may be induced in the cable results from the change in capacitance of the cable when it is flexed. If the transducer produces a charge across the cable, the change in capacitance results in a voltage change across the output of the cable, appearing as noise at the input of a voltage amplifier; it will not produce a similar change if a charge amplifier is used.

Suppose the dielectric surfaces within the cable are coated so that an electrical leakage path is provided along the dielectric surface. Then if the cable shield is separated from the outer surface of the dielectric, the charges flow along the surface to the nearest point of contact of the dielectric and shield; without this leakage path, the charges would flow to the terminating impedance, where they would give rise to a noise signal. Such coatings are provided in low-noise cables which are available commercially. Cables of this type are capable of withstanding considerable abuse before becoming noisy. Usually they are tested by the manufacturer continuously along their lengths to assure meeting the low-noise characteristics. It is important in fitting such a cable with a connector, or in splicing such a cable, that no conducting material be allowed to form a leakage path between the conductors. Carbon tetrachloride and xylene are satisfactory solvents and cleaning agents.

NOISE-SUPPRESSION TECHNIQUES

Under certain conditions of use and environment, spurious signals (noise) may be induced in wiring and cables in a measurement system. Then there will be signals at the termination of the system that were not present in the transducer output.

Electrical noise may be generated by motion of some parts of the wiring because of variation in contact resistance in connectors, because of changes in geometry of the wiring, or because of voltages induced by motion through, or changes in, the electrostatic fields or magnetic fields which may be present. No cable should carry wiring *both* for data transmission and for electrical power; all electrical power wiring should be twisted pair. In general, such electrical noise will be reduced if the cable is securely fastened to the structure at frequent intervals and if connectors are provided with mechanical locks and strain-relief loops in their cables. Precautions taken to avoid interference usually include the use of shielding, cables which are only as long as necessary, and proper grounding. Cable jackets must be selected that will not deteriorate under the measurement environment. In addition, the use of a transducer containing an internal amplifier (described in Chap. 12) can provide advantages in noise suppression.

Shielding. A change in the electric field or a change in the magnetic field around a circuit or cable may induce a voltage within it and thus be a source of electrical noise. Such electrical interference can be avoided by completely surrounding the circuit or cable with a conductive surface which keeps the space within it free of external electrostatic or magnetic fields. This is called *shielding.* Protection against changes in each type of field is different.

Electrostatic Shields. Electrostatic shields provide a conducting surface for the termination of electrostatic lines of flux. Stranded braid, mesh, and screens of good electrical conductors such as copper or aluminum are good electrostatic shields. Most shielded cables use copper braid as the outer conductor and electrostatic shield. A good magnetic shield is also a good electrostatic shield, but the converse is not true. For installations where cable lengths are especially long, where impedances are high, or where noise interference is highly objectionable, double-shielded cable is sometimes used. In this type of cable, a second shielding braid is woven over the cable jacket, electrically insulating it from the inner shield; the inner braid furnishes additional shielding against electrostatic fields which penetrate the first shield. The shields should be connected to ground at one point only, as explained below under *Grounding; Avoiding Ground Loops.*

Magnetic Shields. Magnetic shields are effective partly because of the short circuiting of magnetic lines of flux by low-reluctance paths and partly because of the cancellation resulting from opposing fields set up by eddy currents. Accordingly, they are made from high-permeability materials such as Permalloy, are as thick as possible, and contain a minimum of joints, holes, etc.

Magnetic fields associated with current-carrying power lines, electronic equipment, and power transformers are among the most troublesome sources of magnetic interference in instrumentation setups—chiefly at the frequency of the power line and its harmonics. Since these fields attenuate rapidly with distance from the source, the most practical solution for this type of interference usually is to keep the signal cables as far from the power source as possible.

Grounding; Avoiding Ground Loops. A circuit is said to be grounded when one terminal of the circuit is connected to the "earth." Grounding removes the potential difference between that side of the circuit and earth, and the variable stray capacitances which tend to induce voltages in "floating" (i.e., ungrounded) systems. Water pipes make good ground connections because of their intimate contact with the earth.

Ground loops are formed when a common connection in a system is grounded at more than one point, as illustrated in Fig. 15.10, where the cable shield is grounded at both ends. Since it is unlikely that the two grounds will be at a common potential, their potential difference, e_{gnd}, will be the source of circulating currents in the ground loop. Then a signal produced by the transducer will be modulated by the potential e_{gnd}, thereby introducing noise in the measurement system. Such a condition may occur when one end of a cable is connected to one side of the electrical output of a transducer that has been grounded to the transducer's housing and the other end of the cable is connected to a voltage amplifier or signal conditioner which is also grounded (usually to the case of the instrument). Then, a ground loop will be formed. *Such a condition must be avoided by grounding the circuit at only*

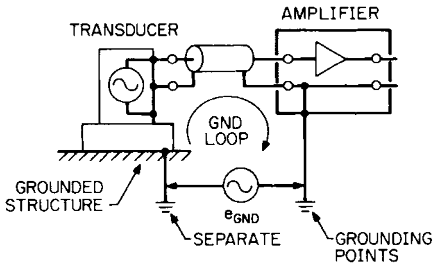

FIGURE 15.10 Ground loop in a system as a result of grounding the cable shield at two points. Then, the input signal e_1 is modulated by the potential difference e_{gnd} which develops between these two points.

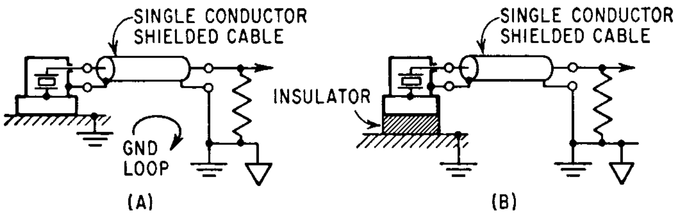

FIGURE 15.11 (*A*) A ground loop formed when the "low" sides of both the transducer and the amplifier are connected to their respective cases, which are grounded. (*B*) The ground loop shown in (*A*) is broken by isolating the case of the transducer from ground.

one point. Thus the circuit shown in Fig. 15.11*A* will result in noise because of the ground loop, but by insulating the transducer as shown in Fig. 15.11*B* the ground loop has been broken.

DATA SHEETS FOR LOGGING TEST INFORMATION

When data are acquired in the field, measurement conditions may be far from ideal; environmental conditions may be unfavorable, and the time available for measurements may be extremely limited. Therefore it is good practice to prepare data sheets that are relatively simple and that require a minimum amount of writing; for example, use multiple-choice entries. The data sheets should include sufficient information so that someone else, at a later time, could duplicate the measurement setup on the basis of information supplied by the data sheets. If there are any anomalies that occur during the test, they should be duly noted. In general, the following information should be included:

Basic data concerning the test measurements:

- Date, times, and duration of test.
- Identification of test by test number.
- Identification of equipment, machine, or device under test.
- Conditions of operation during the measurement.
- Any anomalies in operation and their times of occurrence.
- Location of test, using diagram where appropriate.
- Environmental conditions during test; note anomalies where appropriate.
- Persons participating in the test.

Equipment, including transducers, cables, signal conditions, data recorders, telemeter:

- Type.
- Manufacturer, model number, and serial number.
- Transducer sensitivity, exact location, orientation, and type of mounting.
- Signal conditioner and amplifier gain and attenuator settings; note any changes in these settings during the test.
- Filter settings, if any.
- Recorder speed, number of tracks, tape speed, gain settings; note any changes in these settings during the test.

Calibration information:

- Transducer calibration.
- Overall system (end-to-end) calibration of system.
- Phase of output signal relative to input signal.
- Any changes in calibration between pretest and posttest conditions.

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3. Perls, T. A.: *J. Appl. Phys.,* **23**(6):674 (1952).