CHAPTER 3
BRIDGE TRANSDUCERS

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1 TERMINOLOGY

A telemetry system responding to a measurand consists of four basic parts—the transducer, the transmitting system, the receiving system, and the data output or display system:

Telemetry. The transmission of information about a measurand.

Measurand. The object of a measurement. The process to be defined.

Transducer. A component in the telemetry system which provides information about a process and, as a by-product, transfers energy from the process. Typical bridge transducers convert physical quantities such as force, pressure, displacement, velocity, acceleration, temperature, and humidity into electrical quantities for input to the transmitting system.

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Transmitting System. The transmitting system typically consists of some or all of the following devices: cable, amplifier, subcarrier oscillator, filter, analog-to-digital (A/D) converter, transmitter, and antenna.

Receiving System. The receiving system typically consists of some or all of the following devices: antenna, preamplifier, multicoupler, receiver, tape or disc recorder, discriminator, decommutator, digital-to-analog (D/A) converter, and output filter.

Data Output and Display System. The data output and display system typically consist of some or all of the following devices: oscilloscope, analog meter, digital meter, graphic display, and digital printer. Either these devices may be connected directly to the output of the receiving system or a computer may process the data from the receiving system before display.

2 FLEXURAL DEVICES IN MEASUREMENT SYSTEMS

Bridge transducers depend on a measurand to directly modify some electrical or magnetic property of a conductive element. For example, the thermal coefficient of impedance can result in a change in impedance of a conductive element proportional to temperature (e.g., resistance thermometer). Similarly, hygroscopic materials can have their impedance change in a deterministic fashion due to humidity (e.g., humidity sensor). Most bridge transducers, however, depend on the displacement of a flexure to vary the impedance of a conductive element, resulting in an electrical signal proportional to the measurand. Advantage is taken of either the strain pattern on the surface of the flexure or the motion of this surface. Among the gamut of flexure elements associated with bridge transducers are cantilever beams, Bourdon tubes, and clamped diaphragms.

2.1 Cantilever Beams

Cantilever beams are routinely designed into bridge transducers. Strain near the clamped end of the beam can be correlated to displacement of the free beam end, force or torque applied to the free beam end, dynamic pressure associated with fluid flow acting over the beam surface, and so on. The compliance of a cantilever beam is defined as

$$\frac{y}{F} = \frac{L^3}{3EI} \tag{1}$$

where y is deflection of the beam free end, F is the force applied to this end, L is the beam length, E is the modulus of elasticity of the beam material, and I is the beam area moment of inertia. A compliant flexure will result in a bridge transducer with a large electrical signal output. Equation (1) indicates a compliant flexure design can be achieved by a long, thin, narrow beam of low-modulus material. The penalty attached to such a design in application could be a transducer which is bulky, displays undesirable response to physical inputs orthogonal to its sensing direction, and has poor dynamic response.

2.2 Bourdon Tubes

Bourdon tubes are one of the most widely used flexures for sensing pressure. The original patent for this device was granted to Eugene Bourdon in 1852. Bourdon tubes are hollow tubes that are twisted or curved along their length. The application of pressure deforms the tube wall which, depending on tube shape, causes it to untwist or unwind. Motion of the

tube is typically used to modify the alternating current (ac) impedance of bridge transducers. Bourdon tubes can be integrated into transducers to achieve extremely high accuracies and have been manufactured from perfectly elastic materials such as quartz.

Transducers employing Bourdon tubes tend to be physically large and easily damaged by environmental inputs such as acceleration. In addition, the tubes themselves afford poor frequency response to time-varying pressure.

2.3 Clamped Diaphragms

Clamped diaphragms are another flexure used to transform a measurand into a strain or displacement proportional to applied pressure. A small, flat, circular diaphragm can be made simply, and it can be placed flush against surfaces whose flow dynamics are being studied. This type of diaphragm is typically designed to deflect in accord with theory associated with clamped circular plates. Corrugated diaphragms provide extensibility over a greater linear operating range than do flat diaphragms. A catenary diaphragm consists of a flexurally weak seal diaphragm bearing against a thin cylinder whose motion is measured. The compliance of a flat, clamped circular diaphragm is defined as

$$\frac{y}{P} = \frac{3R_0^4(1 - \nu^2)}{16t^3E} \tag{2}$$

where y is the deflection of the center of the diaphragm, P is the applied pressure, R_0 is the diaphragm radius, ν is Poisson's ratio, t is the diaphragm thickness, and E is the modulus of elasticity of the diaphragm material. Somewhat analogous to the cantilever beam, a compliant diaphragm will have a large radius, be thin, and be made of a low-modulus material. Equation (2) holds for deflections no greater than t.

Figure 1 shows the radial and tangential strain distribution in a flat, clamped, circular diaphragm. The radial and tangential strains at the center of the diaphragm are identical. The tangential strain decreases to zero at the periphery while the radial strain becomes negative. Figure 2 describes a strain gage pattern designed to take advantage of this strain distribution. The central sensing elements measure the higher tangential strain while the radial sensing elements measure the high radial strains near the periphery. Resistance strain gages are discussed beginning in Section 3.

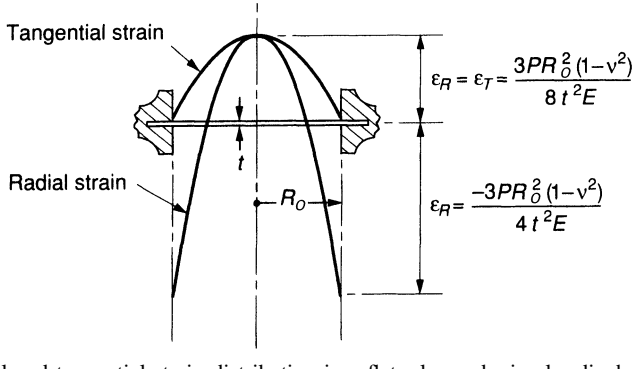


Figure 1 Radial and tangential strain distribution in a flat, clamped, circular diaphragm. (Courtesy of Measurements Group, Inc., Raleigh, NC.)

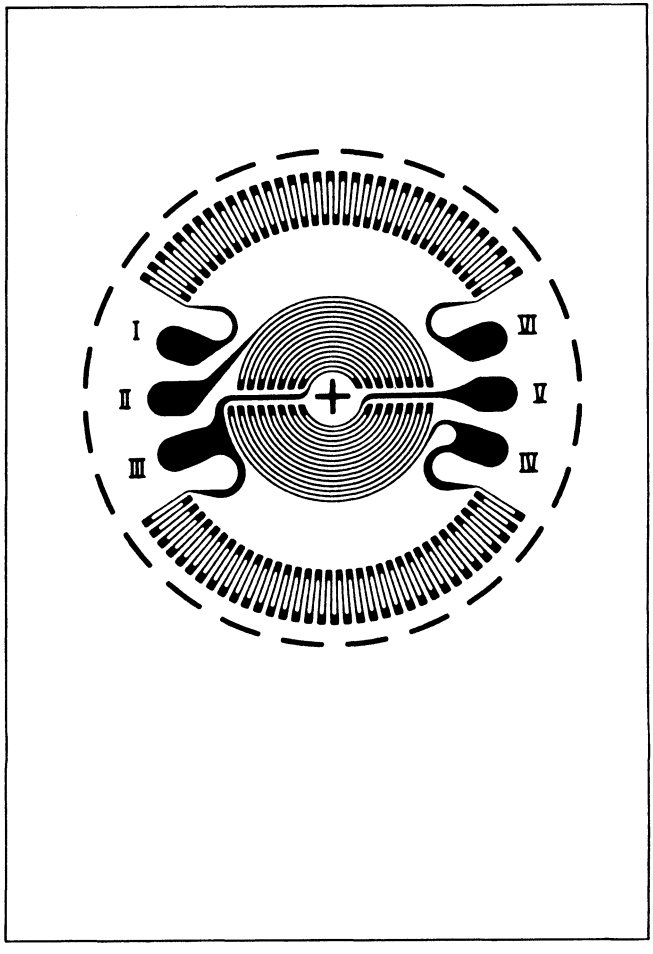


Figure 2 Micro-Measurements' "JB" pattern strain gage for circular diaphragm pressure transducers. (Courtesy of Measurements Group, Inc., Raleigh, NC.)

2.4 Error Contributions from the Flexure Properties

When flexures are designed for bridge transducers, the final transducer may have to possess an accuracy over its operating temperature range of from a few to a fractional percent. Knowledge of the inelasticities and metallurgical behaviors of flexural elements must be considered in transducer design. Metals under a constant load experience a minute deformation with time, called creep. Differences between the loading and unloading curve of a flexure, due to energy absorbed by the material as internal friction, introduce another effect, known as hysteresis. The modulus of elasticity of materials changes with temperature. Corrosion resistance, machinability, magnetics, fatigue effects, thermal conductivity, and thermal expansion are other properties of flexural materials to consider in design application. The 300 series stainless steels are useful flexural materials due to their corrosion resistance, desirable low-temperature properties, and good creep properties at elevated temperatures.

Inconel is a good flexural material in corrosive salt water environments. These materials and others are discussed in an extremely good article on transducer flexures in Chapter 11 of Ref. 1.

3 THE RESISTANCE STRAIN GAGE

Strain gages are used to measure the strain pattern on the surface of the flexure in bridge transducers. In 1938, Simmons, at the California Institute of Technology, and Ruge, at the Massachusetts Institute of Technology, discovered independently that fine wire bonded directly to a surface being studied would respond to surface strain. Ruge's original gage was made by unwinding a constantan wire-wound vitrified resistor, gluing a portion of this wire with Duco cement to a celluloid bar, attaching brass shim stock as terminals, and interfacing the completed assembly to a galvanometer. The first strain gage manufacturer established in the United States was the Baldwin Lima Hamilton (BLH) Corporation (now part of the Vishay Measurements Group). BLH gages operating on the principle discovered by Simmons and Ruge were designated the SR-4 gage to include the initials of both men. The evolution of the bonded resistance wire strain gage occurred during the early 1940s. The first practical bridge transducer load cell was built by Baldwin Lima Hamilton in 1941. By the mid-1950s, Baldwin Lima Hamilton remained the only major strain gage manufacturer and the foil strain gage was beginning to appear. Subsequent work by W. P. Mason and R. N. Thurston (reported in the *Journal of the Acoustical Society of America,* vol. 29, 1957) resulted in the introduction of the commercial semiconductor strain gage. Continued maturation of the bonded resistance strain gage has enabled a transducer industry centered around this technology to develop.

Other sources provide the derivation of all the equations dealing with ensuing topics in this chapter.[2–5]

3.1 Strain Gage Types and Fabrication

Paper-backed wire strain gages typically consist of a grid of resistance wire to which a paper backing has been attached with nitrocellulose cement. The wire is manufactured by drawing the selected alloy through progressive forming dies. To protect it during handling and assembly, the wire is usually sandwiched between two thin layers of paper. Typical grid wires are 0.02 mm in diameter.

Foil strain gages are essentially small printed circuits. Art work for a master gage pattern is first prepared. This pattern is then photographically reduced, and multiple images are placed on a photographic plate. A sheet of foil (typically 0.003–0.005 mm thick) of the appropriate alloy has a light-sensitive emulsion applied, is exposed to the photographic plate, and then undergoes a development process. Chemical etching removes all but the grid material. The resultant grid cross section is square as opposed to round for wire. Advantages inherent in foil gages include better strain transmission due to improved bonding of the grid to the backing, a better thermal path for dissipation of electrically generated heat, and a grid that can more readily be configured to minimize sensitivity to transverse strains.

The total combination of wire and foil gages span grid lengths from 0.2 mm to more than 250 mm. Foil gages satisfy the smaller of these requirements. Both wire and foil gages have associated with them a variety of ohmic values, such as 120, 175, 350, 1000, and so on. Standard values which have historically evolved are 120 and 350 Ω. These values are carry-overs from impedance-matching requirements for galvanometers which were formally used for strain recording. Figure 3 displays numerous configurations of wire and foil strain gages.

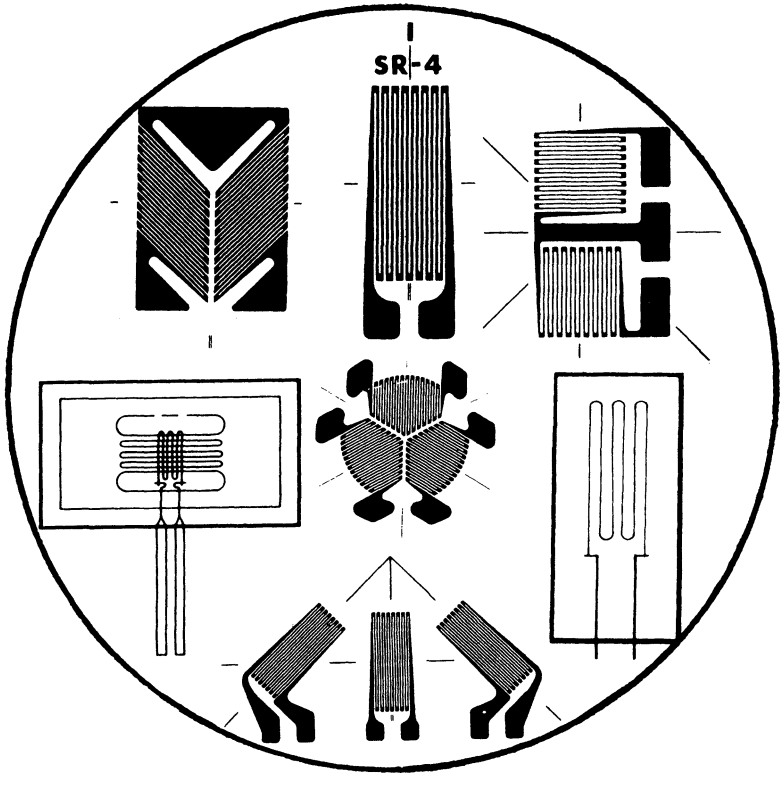


Figure 3 Numerous configurations of wire and foil strain gages—not to scale. (Courtesy of BLH Electronics, now Vishay Measurements Group.)

In the manufacture of bridge transducers using metallic strain gages, vacuum deposition of the gages is an alternate technique to bonding individual gages to the transducer flexure. The flexure is coated with aluminum oxide and then the metal gages are selectively deposited. This process yields the closest match of thermal and electrical characteristics for each bridge element.

The manufacture of semiconductor strain gages starts with a single high-purity silicon crystal. Atoms such as phosphorus (n type) or boron (p type) are doped into the material to lower its resistivity. The parent crystal is sliced into wafers before the dopant is added in a furnace at high temperature (>1000°C). The wafer is masked and etched to produce a suitable grid pattern (usually either a straight element or U-shape). This grid can remain unbacked or can be mounted on a suitable carrier.

Alternately, in diffused semiconductor transducers, the transducer flexure itself may be made of silicon. Its surface can be passivated, etched, and doped to form gage elements integral to the flexure. Similar to vacuum deposition of metal gages, diffused semiconductor transducers offer a more nearly optimum match of thermal and electrical properties for each bridge element. Problems with slippage associated with the bond of a gage carrier or backing are nonexistent.

Bridge transducers using semiconductor gages typically possess poorer thermal and linearity specifications than those using metal gages. However, the sensitivity of semiconductor

gages to surface strain is much greater than metal gages. This allows them to be used in transducers providing more signal output (typically 100–500 mV versus 30 mV) and on stiffer flexures, resulting in smaller transducer size, higher frequency response, and increased ruggedness. Although not strictly correct, by convention it has become equivalent to refer to semiconductor-based transducers as either piezoresistive or solid-state transducers.

3.2 Gage Factor

The gage factor F for a strain gage is defined as

$$F = \frac{\Delta R}{R\epsilon} \tag{3}$$

where R is resistance and ϵ is strain equal to $\Delta l/l$ (Δl is the change in length of l_0). Equation (3) may be redefined as

$$F = 1 + 2\nu + \frac{d\rho}{\rho\epsilon} \tag{4}$$

where ν is Poisson's ratio and ρ is the resistivity of the grid material. Most metal gages have a gage factor between 2 and 4.5. For strain gages made from a semiconductor material, the change in resistivity with applied stress is the dominant factor and values as high as 170 are possible. Table 1 lists properties and gage factors for various grid materials.

3.3 Mechanical Aspects of Gage Operation

To build effective bridge transducers, one must be aware of the interaction between the gage and the surface of the transducer flexure to which it is mounted. Mechanical aspects of this interaction include the influences of temperature, backing material, size, orientation, trans-

Table 1 Grid Material Composition, Trade Name, Properties, and Gage Factor

Composition	Trade Name	Properties	Gage Factor
1. Copper–nickel (57%–43%)	Constantan	Strain sensitivity relatively independent of level and temperature; used to 200°C; high resistivity applicable to small grids; measures strains to 20% in annealed form	2.0
2. Nickel–chromium–iron–molybdenum (36%–8%–55.5%–0.5%)	Isoelastic	High gage factor; high fatigue life; used to 200°C; high temperature coefficient of resistance; nonlinear at strain levels above 5%	3.5
3. Nickel–chromium (80%–20%), Nickel–chromium (75%–20%) plus iron and aluminum	Nichrome V Karma	Good fatigue life; stable; high resistance applicable to small grids; used to 400°C	2.2

Note: Nickel alloy gages are susceptible to magnetic fields.

verse sensitivity, distance from the surface, bonding and installation, and gage frequency response.

Temperature

A qualitative discussion of temperature effects on bonded strain gages indicates the effects to be attributable to three principal causes: (1) The transducer flexure to which the gage is attached expands or contracts, (2) the strain gage resistance changes with temperature, and (3) the strain gage grid expands or contracts. With some gages (particularly semiconductors), the change of gage factor with temperature is also extremely significant. These temperature effects are accounted for by temperature–strain calibration; self-temperature-compensated gages where combined effects 1, 2, and 3 above are minimized over a given temperature range for a given combination of grid and flexure material; and a dummy gage integrated into a bridge circuit (discussed later) to electrically subtract temperature-induced strain.

Backing Material

The purpose of the backing material used in constructing strain gages is to provide support, dimensional stability, and mechanical protection for the grid element. The backing material of the gage element(s) acts as a spring in parallel with the flexure to which it is attached and can potentially modify flexure mechanical behavior. In addition, the temperature operating range of the gage can be constrained by its backing material. Most backings are epoxies or glass fiber–reinforced epoxies. Some gages are encapsulated for chemical and mechanical protection as well as extended fatigue life. For high-temperature applications, some gages have strippable backings for mounting with ceramic adhesives. Still other metal gages can be welded. The frequency response of welded gages, due to uncertainties in dynamic response, is a subject area still requiring investigation.

Size

The major factors to be considered in determining the size of strain gage to use are available space for gage mounting, strain gradient at the test location, and character of the material under test. The strain gage must be small enough to be compatible with mounting location and concentrated strain field. It must be large enough so that, on metals with large grain size, it measures average strain as opposed to local effects. Grid elements greater than 3 mm generally have greater fatigue resistance.

Transverse Sensitivity and Orientation

Strain gage transverse sensitivity and mounting orientation are concurrent considerations. Transverse sensitivity in strain gages is important due to the fact that part of the geometry of the gage grid is oriented in directions other than parallel to the principal gage sensing direction. Values of transverse sensitivities are provided with individual gages but typically vary between fractional and several percent. The position of the strain gage axis relative to the numerically larger principal strain on the surface to which it is mounted will have an influence on indicated strain.

Distance from the Surface

The grid element of a strain gage is separated from the transducer flexure by its backing material and cement. The grid then responds to strain at a location removed from the flexure surface. The strain on flexures such as thin plates in bending can vary considerably from that measured by the strain gage.

Bonding Adhesives

Resistance strain gage performance is entirely dependent on the bond attaching it to the transducer flexure. The grid element must have the strain transmitted to it undiminished by the bonding adhesive. The elimination of this bond is one of the principal advantages of vacuum-deposited metallic and diffused semiconductor bridge transducers. Typical adhesives are as follows:

Epoxy Adhesives. Epoxy adhesives are useful over a temperature range of −270 to +320°C. The two classes are either room-temperature curing or thermal setting type; both are available with various organic fillers to optimize performance for individual test requirements.

Phenolic Adhesives. Bakelite, or phenolic adhesive, requires high bonding pressure and long curing cycles. It is used in some transducer applications because of long-term stability under load. The maximum operating temperature for static loads is 180°C.

Polyimide Adhesives. Polyimide adhesives are used to install gages backed by polyimide carriers or high-temperature epoxies. They are a one-part thermal setting resin and are used from −200 to +400°C.

Ceramic cements (applicable from −270 to +550°C) and welding are other mounting techniques.

Frequency Response

The frequency response of bridge transducers cannot be addressed without considering the frequency response of the strain gage as well. It is assumed that the transducer is used in such a manner that mounting variables do not influence its frequency response.

Piping in front of pressure transducer diaphragms and mounting blocks under accelerometers are two examples of variables which can violate this assumption. Transducers, particularly those which measure force, pressure, and acceleration, typically are dynamically modeled as single-degree-of-freedom systems characterized by a linear second-order differential equation with constant mass, damping, and stiffness coefficients. In reality, transducers possess multiple resonant frequencies associated with their flexure and their case. Figure 4 presents the actual frequency response of a bridge-type accelerometer; The response indicates this single-degree-of-freedom model to be adequate through the first major transducer resonance. Such devices have a frequency response usable (constant within 4% referenced to their dc response) to one-fifth of the value of this major resonance. The strain gage itself acts as a spatial averaging device whose frequency response is a function of both its gage length and the sound velocity of the material on which it is mounted. Reference 6 discusses this relationship from which Fig. 5 is extracted. Figure 5 contains curves for three different length gages. Its abscissa must be multiplied by a specific sound velocity. For most bridge transducers, the structural resonance of the flexure constrains its frequency response.

3.4 Electrical Aspects of Gage Operation

The resistance strain gage, which manifests a change in resistance proportional to strain, must form part of an electrical circuit such that a current passed through the gage transforms this change in resistance into a current, voltage, or power change to be measured. The electrical aspects of gage operation to be considered include current in the gage, resistance to ground, and shielding.

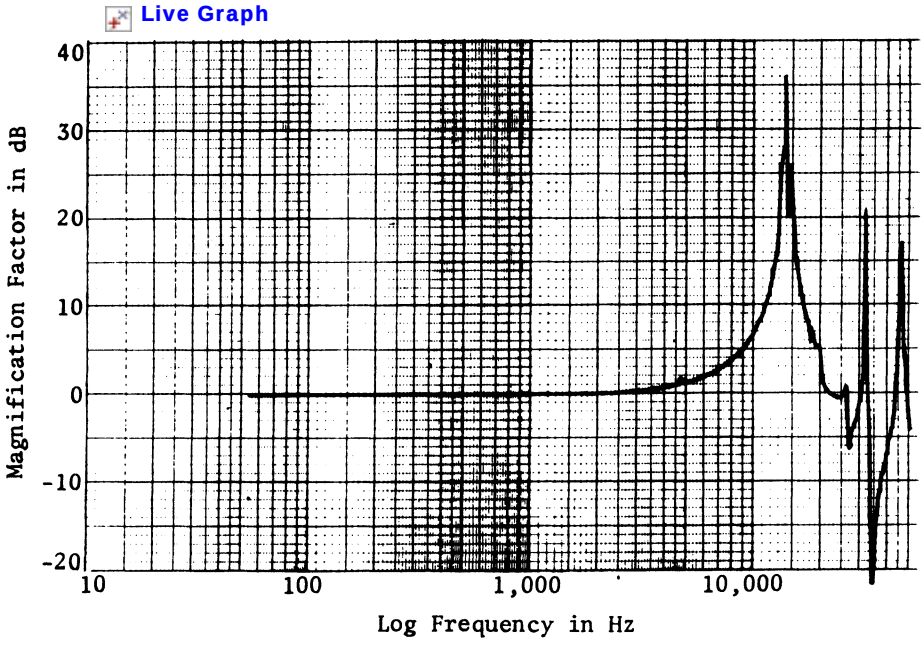


Figure 4 Magnitude of transfer function of piezoresistive accelerometer.

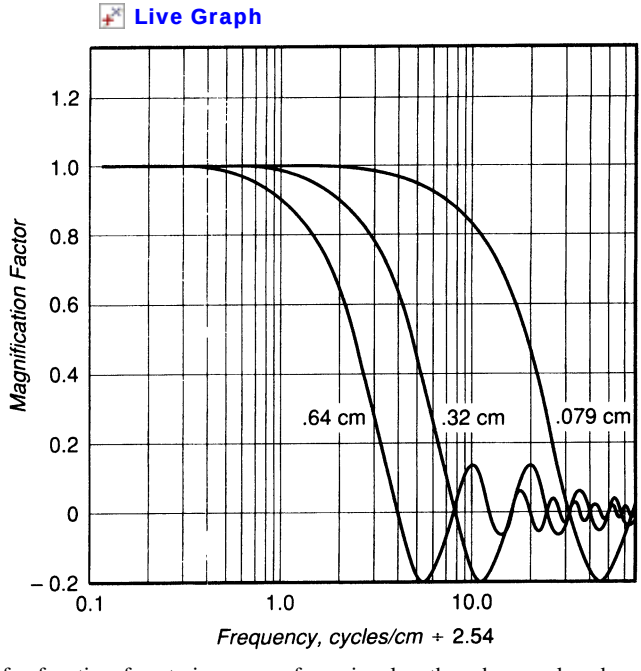


Figure 5 Transfer function for strain gages of varying lengths when analyzed as spatial averaging transducers. (Reprinted with permission from *ISA Transactions,* Vol. 19, Issue 3. Copyright 1980 by the Instrument Society of America.)

Strain gages are seldom damaged by excitation voltages in excess of proper values, but performance degrades. The voltage applied to a strain gage bridge creates a power loss in each arm which must be dissipated in the form of heat. By its basic design, all of the power input to the bridge is dissipated in the bridge with none available to the output circuit. The sensing grid of every strain gage then operates at a higher temperature than the transducer flexure to which it is bonded. The heat generated within the gage must be transferred by conduction to the flexure. Heat flow into the flexure causes a temperature rise which is a function of its heat sink capacity and gage power level. The optimum excitation level for strain gage applications is a function of the strain gage grid area, gage resistance, heat sink properties of the mounting surface, environmental operating temperature range of the gage installation, required operational specifications, and installation and wiring techniques. Rigid operating requirements for precision transducers require performance verification of the optimum excitation level. Zero shift versus load and stability under load at the maximum operating temperature are the performance tests most sensitive to excessive excitation voltage.

Table 2 and Figs. 6–8 allow a first approximation at optimizing bridge excitation levels. Table 2 defines the suitability of various structural materials for providing an adequate heat sink for gage mounting dependent on both accuracy requirements and static or dynamic measurements. Figures 6–8 define the recommended excitation voltage for specific gages as a function of the power density capability of the heat sink and gage grid area.

Resistance to ground is an important parameter in strain gage mounting since insulation leakage paths produce shunting of the gage resistance between the gage and metal structure to which it is bonded, producing false compressive strain readings. The ingress of fluids typically leads to this breakdown in resistance-to-ground value and can also change the

Table 2 Suitability of Various Materails as Heat Sink for Strain Gage Mounting

Accuracy Requirements	Excellent, Heavy Aluminum or Copper Specimen	Good, Thick Steel	Fair, Thin Stainless Steel or Titanium	Poor, Filled Plastic Such as Fiberglass/ Epoxy	Very Poor, Unfilled Plastic Such as Acrylic or Polystyrene
			Static		
High	2–5	1–2	0.5–1	0.1–0.2	0.01–0.02
	3.1–7.8	*1.6–3.1*	*0.78–1.6*	*0.16–0.31*	*0.016–0.031*
Moderate	5–10	2–5	1–2	0.2–0.5	0.02–0.05
	7.8–16	*3.1–7.8*	*1.6–3.1*	*0.31–0.78*	*0.031–0.078*
Low	10–20	5–10	2–5	0.5–1	0.05–0.1
	16–31	*7.8–16*	*3.1–7.8*	*0.78–1.6*	*0.078–0.16*
			Dynamic		
High	5–10	5–10	2–5	0.5–1	0.01–0.05
	7.8–16	*7.8–16*	*3.1–7.8*	*0.78–1.6*	*0.016–0.078*
Moderate	10–20	10–20	5–10	1–2	0.05–0.2
	16–31	*16–31*	*7.8–16*	*1.6–3.1*	*0.078–0.31*
Low	20–50	20–50	10–20	2–5	0.2–0.5
	31–78	*31–78*	*16–31*	*3.1–7.8*	*0.31–0.78*

Note: Units are W/in^2 on top, kW/m^2 in italics underneath. Courtesy of Measurement Group, Inc., Raleigh, NC.

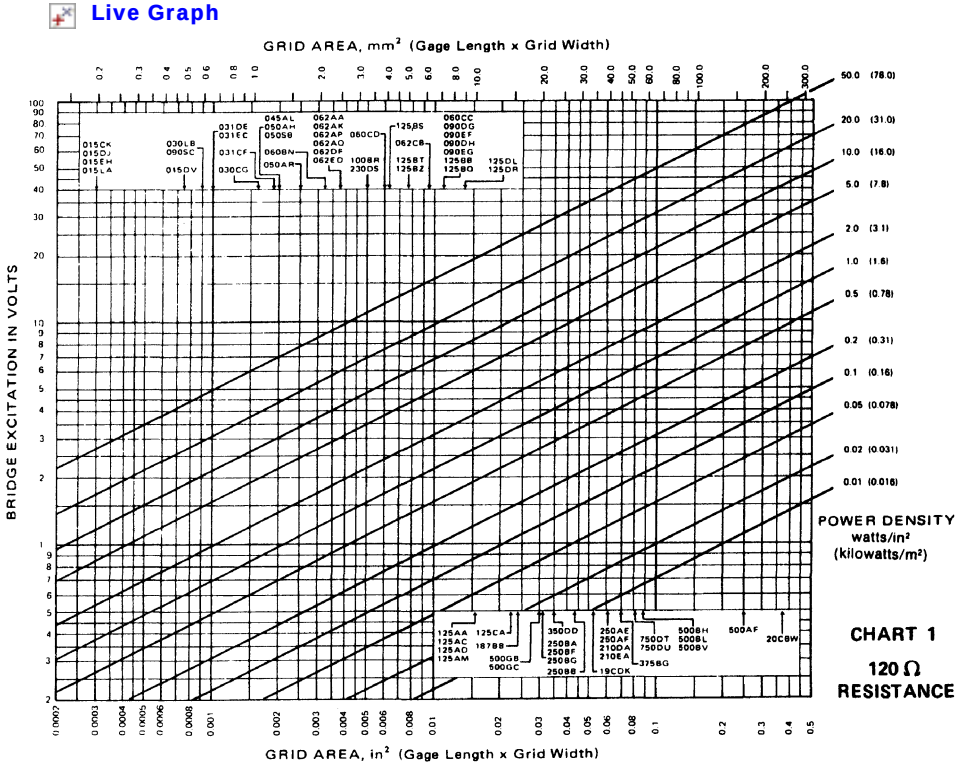


Figure 6 Bridge excitation versus grid area for various power densities and 120-Ω gages. (Courtesy of Measurements Group, Inc., Raleigh, NC.)

mechanical properties of the adhesive. A minimum gage-to-mounting-surface resistance-to-ground value of 50 MΩ is recommended.

Since signals of interest from strain gage bridges are typically on the order of a few millivolts, shielding of the bridge from stray pickup is important. Gage leads should also be shielded and proper grounding procedures followed. Stray pickup may be introduced by 60-Hz line voltage associated with other electronic equipment, electrical noise from motors, radio frequency interference, and so on. Note that shielding materials for electrical fields are different from those for magnetic fields. Nickel alloy strain gages are particularly susceptible to magnetic fields.

3.5 Technical Societies and Strain Gage Manufacturers

In concluding a discussion of the resistance strain gage, it is appropriate to identify some of the technical societies dealing with strain gages and some of the manufacturers of strain gages. In 1956, to accelerate the development of the resistance strain gage, BLH Electronics established a users' group to accomplish this purpose and to further the state of the art in strain gage technology in general. This users' group was formed primarily of various aircraft companies in the western United States and is entitled the Western Regional Strain Gage Committee (WRSGC). For 15 years, the WRSGC was an autonomous organization financed by BLH Electronics. Since 1971, WRSGC has operated under the auspices of the Technical

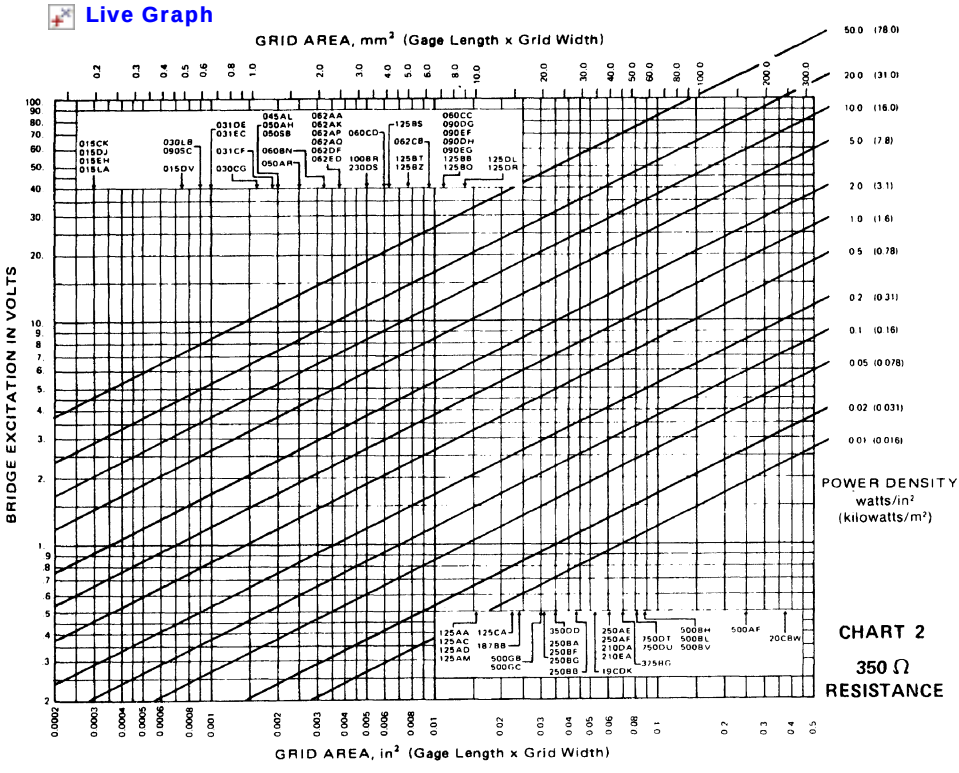


Figure 7 Bridge excitation versus grid area for various power densities and 350-Ω gages. (Courtesy of Measurements Group, Inc., Raleigh, NC.)

Committee on Strain Gages (TCSG) of the Society for Experimental Mechanics (SEM). The SEM is the premier organization in the United States involved with strain gages and experimental mechanics in general. The SEM (formerly Society for Experimental Stress Analysis) was founded by William Murray at the Massachusetts Institute of Technology. Publications of this society include *Experimental Mechanics* and *Experimental Techniques.* A similar European organization is the Joint British Committee for Stress Analysis, whose publication is *The Journal of Strain Analysis for Engineering Design.*

By 2004, essentially the entire strain gage manufacturing capability in the United States was consolidated by Vishay Measurements Group, corporate headquarters at Vishay Intertechnology, Inc., 63 Lincoln Highway, Malvern, Pennsylvania 19355-2120. Its associated website has an extensive array of in-depth articles on strain gage technology.

4 THE WHEATSTONE BRIDGE

Best transducer performance can be achieved by minimizing the strain level in the transducer flexure. Lower strains allow increased safety without mechanical overload protection. Effective overload stops are usually troublesome to design and an added expense to make. Reduced strain levels almost always produce an improvement in linearity accompanied by a reduction in the hysteresis originating in the transducer flexure material.

Live Graph

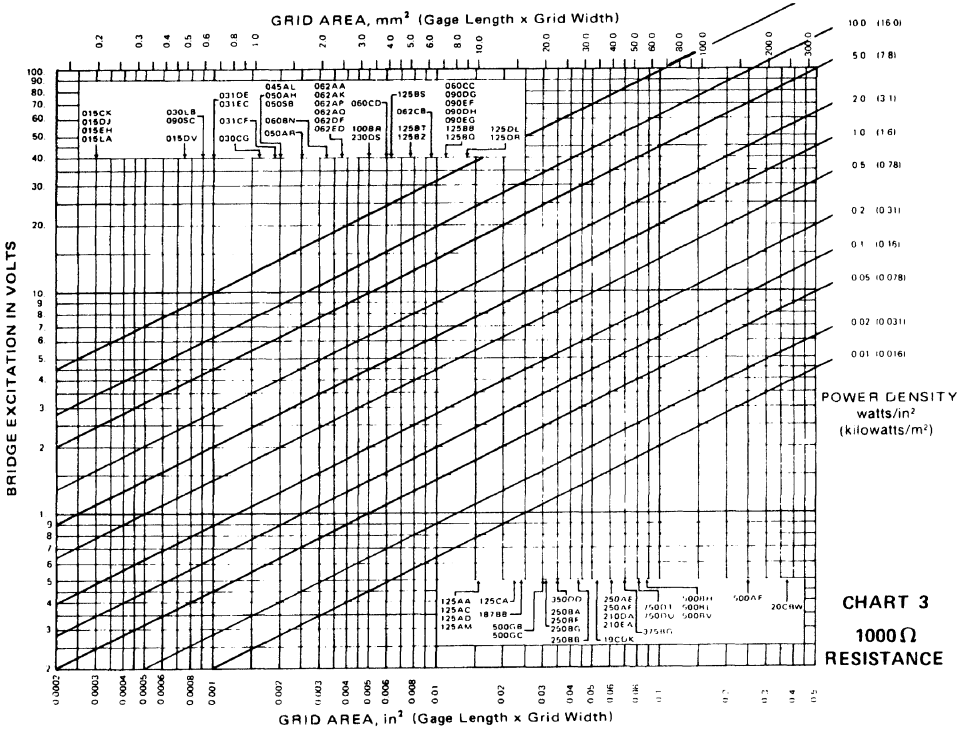


Figure 8 Bridge excitation versus grid area for various power densities and 1000-Ω gages. (Courtesy of Measurements Group, Inc., Raleigh, NC.)

Small strains result in small impedance changes in resistive strain gage elements. Electromechanical transducers use a Wheatstone bridge circuit to detect a small change in impedance to a high degree of accuracy.

4.1 Bridge Equations

The circuit most often used with strain gages is a four-arm bridge with a constant-voltage power supply. Figure 9 shows a basic bridge configuration. The supply voltage E_{ex} can be

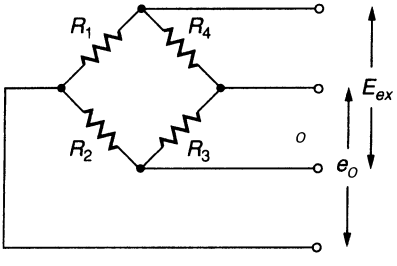


Figure 9 Four-arm bridge with constant-voltage (E_{ex}) power supply.

either ac or dc, but for now we assume it is dc so equations can be written in terms of resistance R rather than a complex impedance. The condition for a balanced bridge with e_o equal to zero is

$$\frac{R_1}{R_2} = \frac{R_4}{R_3} \tag{5}$$

Next, an expression is presented for e_o due to *small* changes in R_1, R_2, R_3, and R_4:

$$e_o = \left[- \frac{R_3\, dR_4}{(R_3 + R_4)^2} + \frac{R_4\, dR_3}{(R_3 + R_4)^2} - \frac{R_1\, dR_2}{(R_1 + R_2)^2} + \frac{R_2\, dR_1}{(R_1 + R_2)^2} \right] E_{\text{ex}} \tag{6}$$

In many cases, the bridge circuit is made up of equal resistances. Substituting for individual resistances, a strain gage resistance R, and using the definition of the gage factor from Eq. (3), Eq. (6) becomes

$$e_o = \frac{FE_{\text{ex}}}{4} (-\epsilon_4 + \epsilon_3 - \epsilon_2 + \epsilon_1) \tag{7}$$

The unbalance of the bridge is seen to be proportional to the sum of the strain (or resistance changes) in opposite arms and to the difference of strain (or resistance changes) in adjacent arms.

Equations (6) and (7) indicate one technique to compensate strain gage circuits to minimize the influence of temperature-induced strain. This was referred to in Section 3 as the dummy gage method.

Assume that we have a bridge circuit with one active arm and arbitrarily let this arm be number 4. Equation (7) becomes

$$e_o = \frac{FE_{\text{ex}}}{4} (-\epsilon_4) \tag{8}$$

Arm 4 responds to the total strain induced in it, which is comprised of both thermal (t) and mechanical (m) strain

$$\epsilon_4 = \epsilon_m + \epsilon_t \tag{9}$$

A problem arises if it is desired to isolate the mechanical strain component. One solution is to take another strain gage (the dummy gage) and mount it on a strain-isolated piece of the same material as that on which gage 4 is mounted. If placed in the same thermal environment as gage 4, the output from the dummy gage becomes simply ϵ_t. If the dummy gage is wired in an adjacent bridge arm to 4 (1 or 3), Eq. (7) becomes

$$e_o = \frac{FE_{\text{ex}}}{4} (-\epsilon_m - \epsilon_t + \epsilon_t) \tag{10}$$

Equation (10) indicates that thermal strain effects are canceled. Similarly, in Fig. 2, four gages were shown mounted on a transducer diaphragm. Equation (7) indicates that thermal strain effects from this circuit should be canceled.

In reality, perfect temperature compensation is not achieved since no two strain gages from a lot track one another identically. However, compensation adequate for many applications can be accomplished.

The biggest thermal problem with bridge transducers occurs in transient situations, such as explosive or combustion environments. Here, due to individual physical locations, gages in a bridge are not in the same time-varying temperature, and compensation cannot be

achieved. The only technique which can be used in this situation is either to cool the transducer by circulating water or gas around it or to delay the thermal transient until the measurement is complete.

The alternating signs in Eq. (7) are useful in isolating various strain components when using bridge circuits containing strain gages. Figure 10 shows a beam flexure used in an accelerometer. Four gages are mounted on the beam—two on the top and two on the bottom. Notches are placed in the beam to intensify the strain field under the gages. Due to symmetry, the tension gages see the same strain as do the compression gages. If the tension gages occupy two adjacent arms of the bridge and the compression gages the other two, Eq. (7) indicates that the net bridge output will be zero. However, if the tension and compression gages are in opposite arms, Eq. (7) indicates that a bending strain signal four times that of an individual gage will be produced with temperature compensation also achieved.

Equation (6) presented the generalized form of the bridge equation for four active arms. If only one arm (e.g., arm 4) is active, this equation becomes

$$e_o = \left[\frac{-R_3 dR_4}{(R_3 + R_4)^2}\right] E_{\text{ex}} \tag{11}$$

This equation was specifically presented for *small* changes in resistance, such as those associated with metallic strain gages. If the change in resistance in arm 4 is large, Eq. (11) is better expressed as

$$e_o = \frac{(R_4 + \Delta R_4)E_{\text{ex}}}{(R_4 + \Delta R_4) + R_3} - \frac{R_4 E_{\text{ex}}}{R_4 + R_3} \tag{12}$$

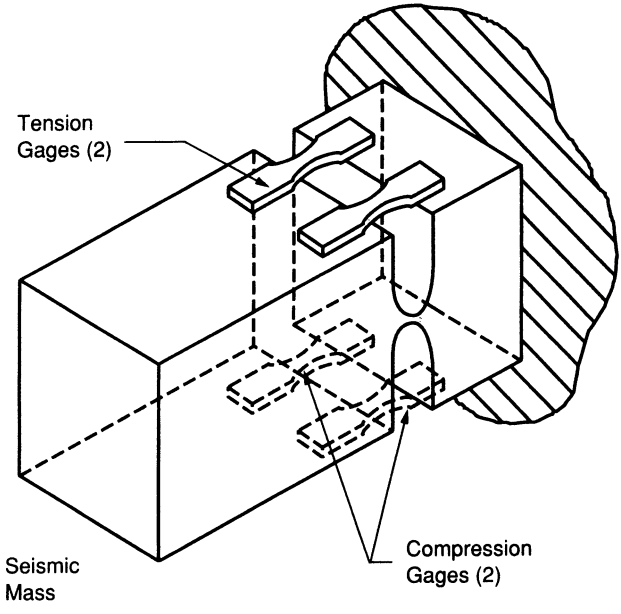


Figure 10 Strain gaged beam flexure used in accelerometer. (Courtesy of Endevco.)

For an equal-arm bridge, this becomes

$$e_o = \frac{\Delta R\ E_{ex}}{4R + 2\ \Delta R} = \frac{FE_{ex}\epsilon}{4 + 2F\epsilon} \tag{13}$$

For an equal-arm bridge, Eq. (11) becomes

$$e_o = \frac{dR\ E_{ex}}{4R} = \frac{FE_{ex}\epsilon}{4} \tag{14}$$

The difference between Eqs. (14) and Eq. (13) is that Eq. (14) describes a linear process while Eq. (13) describes a nonlinear one. Semiconductor gages, because of their large gage factor, require analysis using Eq. (13).

Semiconductor gages may be used in constant-voltage four-arm bridge circuits when two or four gages are used in adjacent arms and strained so that their outputs are additive. Analysis of the bridge equations for this situation will show that if gages in adjacent arms are subjected to equal but opposite values of ΔR, the output signal is doubled and the nonlinearity in the bridge output is eliminated. Another approach to eliminating this nonlinearity is to design a circuit where the current through the strain gage remains constant.

Table 3 provides generalized bridge equations for one, two, and four equal-active-arm bridges of various configurations. The dimensionless bridge output is presented in millivots per volts for a constant-voltage power supply. Strain is presented in microstrain. No small-strain assumption is built into these equations. For large strains with semiconductor gages, F may not be a constant and this correction also has to be built into the equations. In this table, the Poisson gage is one which measures the lateral compressive strain accompanying an axial tension strain. As noted earlier, only for two adjacent active gages with equal and opposite strains or for four active gages with pairs subjected to equal and opposite strains is the bridge output a linear function of strain.

4.2 Lead Wire Effects

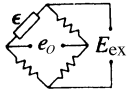
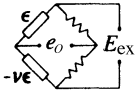
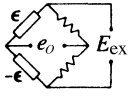
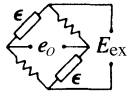
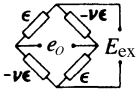
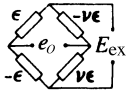
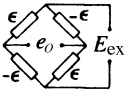
There has been a historical lack of agreement between manufacturers of strain gages as to color codes and wiring designations. This is particularly true in bridge transducers. Figures 11 and 12 are suggested industry standards which have assisted in lessening this confusion. Figure 11 covers the situation where all bridge elements are remote from the power supply, while Fig. 12 covers the situation where only one bridge arm is remote from the power supply. The bridge balance network and shunt calibration are discussed in Sections 5 and 6, respectively. Table 4 presents guidelines for multiconductor strain gage cable.

The previous discussion has assumed that the only resistive elements in the circuits are the gages themselves. Resistance of circuit lead wires also is a consideration.

One possible need for remote recording occurs when the bridge power supply and the readout instrumentation are at one location and the bridge transducer is at a remote location. In this situation, the resistance R_L of each lead wire between the bridge and the power supply or readout must be accounted for. Most readout instruments have very high input impedances, so the effect of R_L in series with them can be ignored. The significant effect of lead-wire resistance is to modify the resistance in series with the power supply from R_{bridge} to $R_{bridge} + 2R_L$. For example, a lead-wire resistance of 3 Ω and a bridge resistance of 120 Ω will produce loading effects which, if not corrected, will result in a 5% error in bridge transducer output.

There are at least three simple techniques to eliminate this error source:

Table 3 Equations for One, Two, and Four Equal-Active-Arm Bridges

Bridge/Strain Arrangement	Description	Output Equation $-e_o/E_{ex}$ (mV/V)
	Single active gage in uniaxial tension or compression	$\frac{e_o}{E_{ex}} = \frac{F\epsilon \times 10^{-3}}{4 + 2F\epsilon \times 10^{-6}}$
	Two active gages in uniaxial stress field—one aligned with maximum principal strain, one "Poisson" gage	$\frac{e_o}{E_{ex}} = \frac{F\epsilon(1 + \nu) \times 10^{-3}}{4 + 2F\epsilon(1 - \nu) \times 10^{-6}}$
	Two active gages with equal and opposite strains—typical of bending-beam arrangement	$\frac{e_o}{E_{ex}} = \frac{F\epsilon}{2} \times 10^{-3}$
	Two active gages with equal strains of same sign—used on opposite sides of column with low temperature gradient (e.g., bending cancellation)	$\frac{e_o}{E_{ex}} = \frac{F\epsilon \times 10^{-3}}{2 + F\epsilon \times 10^{-6}}$
	Four active gages in uniaxial stress field—two aligned with maximum principal strain, two "Poisson" gages (column)	$\frac{e_o}{E_{ex}} = \frac{F\epsilon(1 + \nu) \times 10^{-3}}{2 + F\epsilon(1 - \nu) \times 10^{-6}}$
	Four active gages in uniaxial stress field—two aligned with max. principal strain, two "Poisson" gages (beam).	$\frac{e_o}{E_{ex}} = \frac{F\epsilon(1 + \nu) \times 10^{-3}}{2}$
	Four active gages with pairs subjected to equal and opposite strains (beam in bending or shaft in torsion)	$\frac{e_o}{E_{ex}} = F\epsilon \times 10^{-3}$

Courtesy of Measurements Group Inc., Raleigh, NC.

1. The bridge transducer can be calibrated with the long length of cable with which it will operate.
2. The excitation voltage E_{ex} can be measured at the bridge itself instead of at the power supply and appropriate values substituted in Eq. (6) or equivalent versions of it.
3. The bridge voltage E_{ex} can be determined by measuring the current to the bridge (I_{bridge}) and calculating E_{ex} as the product $I_{bridge} \times R_{bridge}$.

Another possible need for remote recording occurs when two gages (either both active or one active and one for temperature compensation) are at the test site. The other two bridge completion resistors are in parallel with the power supply and located adjacent to it. In Fig. 9, assume R_3 and R_4 are the two remote active arms. In Eq. (6), the last two terms would be zero since these arms are not active. In this equation R_3 and R_4 would become respectively $R_3 + R_L$ and $R_4 + R_L$. If the strain gages in both arms are identical, Eq. (6) reduces to

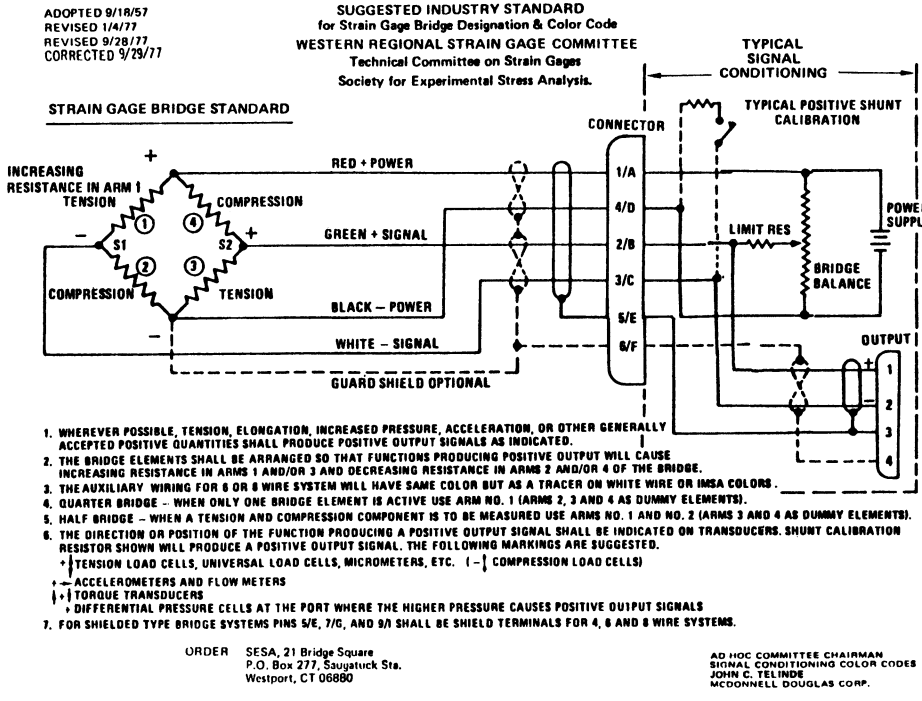


Figure 11 Color code and wiring designation, four-arm bridge. (Courtesy of Western Regional Strain Gage Committee.)

$$e_o = \frac{FE_{ex}R}{4(R + R_L)}(-\epsilon_4 + \epsilon_3) \tag{15}$$

Other situations can be investigated by substituting appropriate values for the resistance in each bridge arm (including lead-wire resistance) in the governing bridge equation. In addition, Section 6 will show that shunt calibration is one technique that can be used to compensate the system for the effects of lead-wire resistance.

4.3 Temperature Compensation

Before leaving the analysis of the Wheatstone bridge circuit, temperature compensation of bridge-type transducers should receive additional discussion. An ideal transducer would yield an output voltage which is a constant calibration factor times its mechanical input, independent of other environmental factors. Ambient temperature variations are one of the major error sources in precision transducers. Even when using self-temperature-compensated strain gages and taking advantage of the ability of the Wheatstone bridge circuit to subtract in the dummy gage method, some residual error remains. These remaining errors are of two types.

First, the transducer zero output can change with temperature. Unequal mechanical expansion of transducer members can cause this effect. Second, the calibration factor, span, or sensitivity also can change with temperature. This can be caused, for example, by a change in the stiffness of the transducer flexure with temperature.

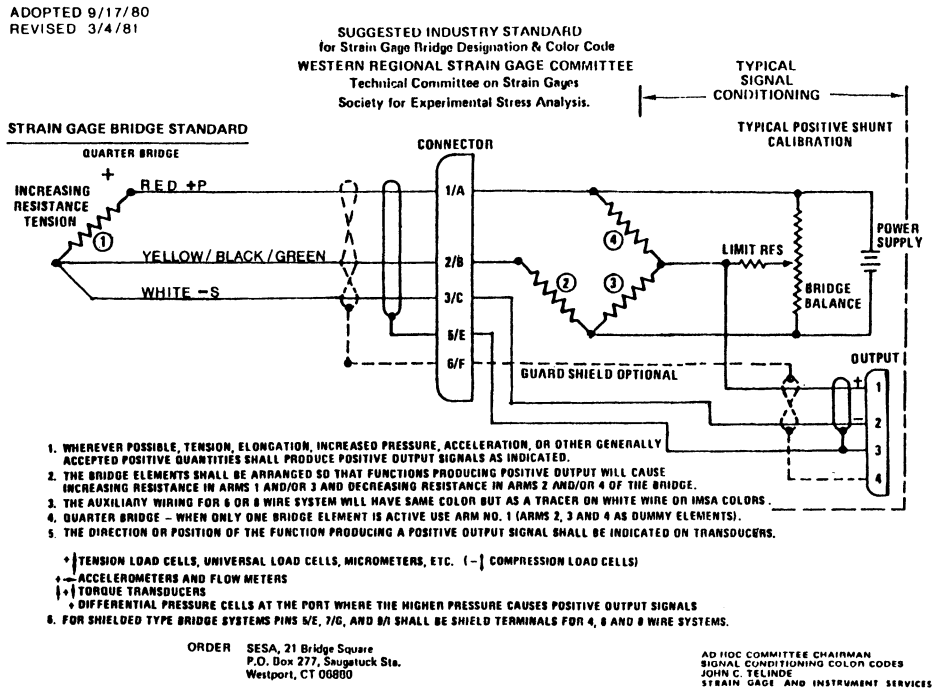


Figure 12 Color code and wiring designation, single-arm bridge. (Courtesy of Western Regional Strain Gage Committee.)

Table 4 Multiconductor Strain Gage Cable Guideline, Western Regional Strain Gage Committee

A need exists for low-millivolt signal levels to be transmitted by better quality multiple conductor cables of considerable length.

I. Conductors	Three through eight twisted, stranded conductors of tinned copper per ASTM-B-174, AWG 20-16/32, or AWG 18-16/30
II. Color code	Jacket: orange, grey, white, or black Conductors: Per ISA-S37.3, ANSI-MC6.2-1975, and WRSGC/SESA 5-6-1960
III. Insulation	Superior to the PVC materials currently in use. The dielectric material should be nonhygroscopic and approach zero water absorption and zero water permeability. Target jacket thickness of .016 in. or less and conductor insulation of .012 in. or less. Target resistance values should be constant as practical humid and wet environments and as high as possible (target value of 500 Ω per 1000 ft). The breakdown level of the dielectric materials shall be greater than 150 V dc.
IV. Construction	The cable shield shall be aluminized polyester tape with 100% coverage of all conductors. A 22-AWG drain wire shall be in intimate contact with the shield throughout the entire cable length. The cable shall have as a small a diameter as practical and be flexible enough to have a bend radius less than six cable diameters. Overall cable strength sufficiently high to be pulled through conduits.

Courtesy of Society for Experimental Mechanics.

The following discussion provides one compensation scheme for each type (metallic and semiconductor) of bridge transducer. References 7 and 8 are sources of more detailed information. An equal-arm bridge transducer operating with a constant-voltage supply is assumed. Metallic strain gages are discussed first.

Figure 13 shows one scheme for compensating for transducer zero shift. A corner of the bridge is brought out to terminals, and a temperature-sensitive resistor, r, is placed in one side of the bridge. Typically, a wire resistor such as Balco, nickel, or copper with a positive temperature coefficient is used.

The transducer must first be temperature calibrated and the change in zero reading for a given temperature range determined. This can be characterized in volts of output change per volt of input. Definitions are

b = output voltage change per degree per input volt
a = temperature coefficient of resistance of r
R = bridge arm resistance
T = temperature change from reference temperature

If the bridge supply voltage is E_{ex} and R is changed a small amount by the addition of r, the bridge output is

$$e_o = \frac{E_{ex} r}{4R} \tag{16}$$

Equation (16) can further be expressed as

$$e_o = \frac{E_{ex} r_0 (1 + aT)}{4R} \tag{17}$$

or

$$e_o = \text{const} + E_{ex} bT \tag{18}$$

where r_0 is the value of r at the reference temperature. The effect of the constant term is eliminated by a temperature-insensitive trim resistor in an adjacent arm. The above equations indicate that at the reference temperature r_0 should be selected equal to $4\,Rb/a$. If the transducer is properly designed, b is very small compared to a, keeping the compensating resistor small in value. The compensating resistor should be located in an arm causing a voltage change of opposite sign to the zero drift with increasing temperature.

After zero shift is compensated, the calibration or span factor remains to be compensated. Most metal strain gage transducers give larger outputs with increasing temperature, so the temperature coefficient of the calibration scale factor, K, is positive. The trick in span compensation is to hold the transducer supply voltage constant while automatically varying

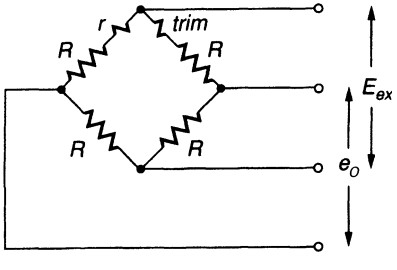


Figure 13 Transducer bridge compensation for zero shift, metal gages.

the bridge current, causing it to decrease with increasing temperature. In this discussion, r is identified to be a positive series resistor (Fig. 14). Definitions are

$r = r_0(1 + aT)$
a = positive temperature coefficient of r
T = temperature difference from reference temperature
c = temperature coefficient of the calibration factor K, so $K = K_0(1 + cT)$
E_{ex} = transducer supply voltage

The voltage on the transducer at the reference temperature is $RE_{ex}/(R + r_0)$ and at temperature T is $RE_{ex}/(R + r)$. The ratio by which it changes is $(R + r_0)/(R + r)$, which is used to correct for the variation in K. This variation is corrected for when $K_0(1 + cT)(R + r_0)/[R + r_0(1 + aT)]$ = constant. The value of r_0 which satisfies this requirement can be shown to be

$$r_0 = \frac{cR}{a - c} \tag{19}$$

Note that in span and zero compensation as discussed thus far, the compensating resistors must be at the same temperature as the transducer. Usually, this is accomplished by mounting the resistors inside the transducer.

Figure 15 shows one technique for correcting for zero shift due to the temperature in semiconductor bridges. Temperature compensation is performed by adding non-temperature-sensitive resistors in series and parallel to the gage having the highest resistance change with temperature. The objective of this method is to achieve both zero balance and temperature compensation together. Since the compensation resistors are non–temperature sensitive, they can be added wherever convenient in the circuit.

The bridge is first balanced using a series resistor at ambient room temperature. Next, the transducer is cycled over the temperature extremes. A parallel resistor is installed across the gage having the greatest resistance change. The bridge is then rebalanced and the procedure repeated until satisfactory performance is achieved.

Semiconductor bridge transducers are typically compensated for calibration or span factor with a circuit as in Fig. 14. However, r for this situation is a non-temperature-sensitive resistor. For p-type silicon gages, the strain sensitivity drops with temperature while the resistance rises. The increase in resistance occurs at a greater rate than does the decrease in sensitivity. Figure 14 shows that the effect of an increase in resistance R, with r constant, is to increase the voltage applied to the bridge, offsetting the decrease in strain sensitivity. Alternately, in Fig. 14, r can be replaced by a thermistor instead of a fixed dropping resistor. The thermistor is generally a more efficient method of compensation but must be in the same thermal environment as the bridge network.

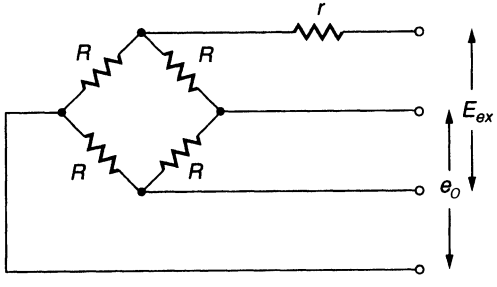


Figure 14 Transducer bridge compensation for span, metal gages.

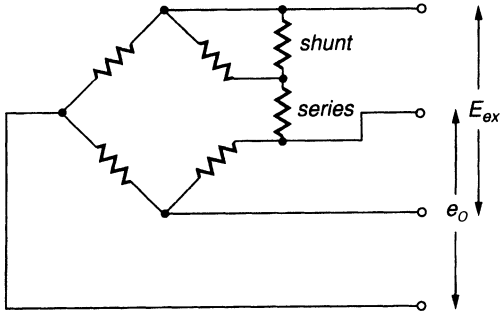


Figure 15 Transducer bridge compensation for zero shift, semiconductor gages.

When balancing Wheatstone bridges, it must be determined that the balancing circuit does not significantly alter the thermal compensation network. Balancing methods are discussed next.

5 RESISTANCE BRIDGE BALANCE METHODS

Even when a best attempt is made at matching resistors, the output from a bridge transducer with zero measurand applied is always something other than zero volts. With microprocessors and scanners, this is of little consequence. The initial bridge output can be acquired and stored in the memory of the microprocessor and then subtracted from all subsequent readings. Frequently, however, it is desired to initialize a bridge circuit such that a zero value of measurand corresponds to zero voltage. For example, assume it is desired to acquire a vibration measurement on a space vehicle using a bridge transducer. Assume the channel is to be calibrated for $\pm 20g$ and the accelerometer has a sensitivity of 1 mV/g (g = standard acceleration of gravity). If the data channel range were ± 20 mV, and the accelerometer acquiring the measurement had a zero offset of 5 mV, the channel could transmit only in the range of $+15g$ to $-25g$ as opposed to $\pm 20g$. Balancing the bridge would solve this problem.

Equation (5) presented the requirement for a balanced bridge. Basically, the resistance ratio of any two adjacent bridge arms must be equal to the resistance ratio of the other two arms. Any bridge-balancing network must then have as its objective the satisfying of this criterion. The two main types of zero balancing methods are those which manipulate one arm of a transducer bridge to bring its output to the desired condition and those which manipulate two adjacent arms of the transducer bridge.

Figure 16 presents the most common circuit for manipulating a single bridge arm. A variable resistor R_B is placed across one of the resistors (say R_4) whose value needs to be

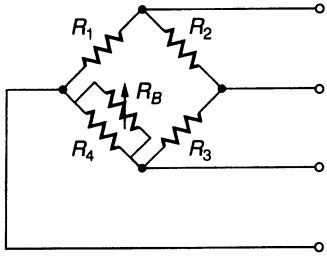


Figure 16 Circuit for manipulating a single bridge arm.

lessened such that $R_1/R_4 = R_2/R_3$. The effect of R_B in parallel with R_4 is to lessen the value of the bridge arm from R_4 to some new value R_T.

The overall combination of R_B in parallel with R_4 must be variable over a range at least equal to the maximum possible initial unbalance of the bridge. Selecting this range, other than by trial and error, requires knowledge of the strain gage resistance R, its tolerance in percentage m, and the number of active gages n in the bridge. The range of the balancing circuit should be

$$\frac{2Rmn}{100} \tag{20}$$

Note that the presence of the variable resistor R_B desensitizes the bridge network since $\Delta R_4/R_4$ is not equal to $\Delta R_T/R_T$. If the strain gages are initially closely matched, the influence of this effect is small since R_B will remain large and R_T will closely approximate R_4. For optimum precision, the best method to minimize the influence of the variable resistor is to calibrate the transducer once the bridge is balanced. Of course, if less than four arms of the bridge are active and balancing is performed across a dummy completion resistor, no desensitizing of the bridge occurs.

Two techniques are available to manipulate two adjacent arms in a bridge. Again, the rationale for this manipulation is to satisfy Eq. (5). The first technique is series manipulation, which assumes the bridge is open such that the variable resistance may be inserted in series with two arms of the bridge. This technique is not applicable to a closed bridge.

Figure 17 shows a variable series resistor R_S inserted in one corner of the bridge. The insertion of R_S, which is typically quite small, allows adjustment of the ratio of R_2 to R_3 to achieve balance. Reference 2 provides the best discussion of bridge balance networks and indicates that minimum bridge desensitization occurs when bridge power is applied across the vertical terminals of Fig. 17 as opposed to the horizontal.

The second technique discussed (and the one typically used) is parallel manipulation of two adjacent bridge arms. Figure 18 illustrates this technique. The parallel variable resistor R_B allows the ratio of R_2/R_3 to be adjusted. A pad resistor, R_{PAD}, serves simply to keep the individual bridge arms from being shorted out at the end of travel of R_B. Again, the secret is to keep the combination of R_B and R_{PAD} as high as possible to avoid bridge desensitization. If no other guidance is available, start out with a pad resistor about 100 times the bridge resistance and a variable resistor about 20 times the bridge resistance. Again, maximum accuracy is achieved when the bridge transducer is calibrated with the balance network with which it will be used.

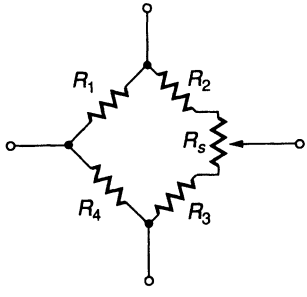


Figure 17 Circuit for series manipulation of two adjacent bridge arms.

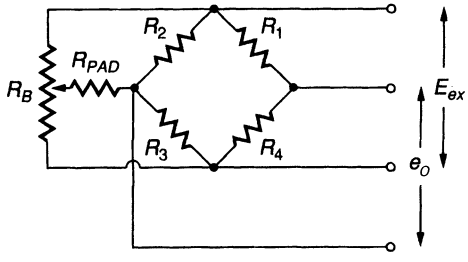


Figure 18 Circuit for parallel manipulation of two adjacent bridge arms.

As alluded to earlier, the addition of a balance network to a bridge transducer may react unfavorably with temperature compensation resistors placed in the transducer's circuitry by its manufacturer. Temperature compensation can be severely modified by the presence of this balancing network. The prerequisite to insertion of a balance network should be an exact knowledge of the circuit of the transducer. For this reason, and for reasons associated with desensitization of the transducer, balance networks should be avoided unless required.

6 RESISTANCE BRIDGE TRANSDUCER MEASUREMENT SYSTEM CALIBRATION

A basic component in any measurement system is the transducer. The measurement system can be as simple as a transducer, a cable from the transducer, and a recorder. Alternately, the measuring system can contain many more of the elements of the transmitting and receiving system defined in Section 1. Cables, amplifiers, filters, digitizers, tape recorders, and so on all have the capability, when inserted into a measurement system, to modify both the amplitude and spectral content of the signal from the transducer defining the measurand. The response of these components may also drift with time.

To obtain measurements of the highest possible quality, one must accurately and carefully calibrate the entire measurement system as near to the time of actual measurement as possible. The calibrations may be conducted prior to, immediately after, or even during the time of actual measurement. Such calibration of an entire measurement system is referred to as ''end-to-end'' calibration. This calibration ordinarily does not replace the evaluation of individual components of the measurement system.

One group concerned with ''end-to-end'' calibration of measurement systems is the Telemetry Group/Range Commanders Council whose Secretariat is headquartered at White Sands Missile Range, New Mexico. The Transducer Committee of the Telemetry Group coordinated the writing of Chapter 2 of Ref. 9, entitled ''Test Methods for Transducer-Based System Calibrations.'' The following information is largely extracted from that chapter, which also deals with piezoelectric transducers, servo transducers, capacitive and inductive transducers, and thermoelectric transducers.

A preferred calibration procedure is one in which a known value of the measurand is applied directly to the transducer in the measurement system (transmitting, receiving, and display) in which it will be used. This procedure permits the output display to be read directly in terms of units of the measurand.

6.1 Static Calibration

The basic equipment for the static calibration of transducer systems consists of a measurand source supplying accurately known and precisely repeatable values of the measurand and an output-indicating or recording system. The combined errors or uncertainties of the calibration system should be sufficiently smaller than the permissible tolerance of the system performance characteristic under evaluation so as to result in meaningful calibration values. All calibration system components should be periodically checked against standards. Environmental conditions during calibrations should be constant and specified to permit corrections to the data, as required.

The procedures which will be specified are based on the assumption that the measuring system is linear. For systems that will ultimately measure dynamic data, linearity is a prerequisite.

The static calibration sequence consists of the following steps:

1. Zero-measurand output verification
2. Sensitivity verification
3. Linearity and hysteresis verification
4. Repeatability verification

Zero-measurand output verification starts with a measurement of system output with zero measurand applied to the transducer. Zero measurand is an important measurement for several reasons:

1. In many measurement systems, the transducers are exposed to zero measurand before the test begins.
2. For many transducers, zero measurand means that no external input to the transducer is required, thus greatly simplifying the test procedure.
3. Measurement system malfunctions, including drift, will frequently appear when the system output is monitored over some reasonable time period with zero measurand applied.
4. In some measurement systems with no external measurand input, the ambient environment will furnish an important reference point for the system calibration. For example, for an absolute-pressure-measuring system, the ambient atmospheric pressure provides this reference. Similarly, for certain accelerometer systems, the measurable attitude of the test vehicle prior to launch represents a known component of the earth's gravitational field as input to the accelerometer.

For a measurement system with a linear response, the slope of the line characterizing the input measurand versus system output represents the sensitivity of the system. There are a number of straight lines which may be chosen to provide this sensitivity verification. These include the following:

1. Endpoint line—The straight line between the outputs at the specified upper and lower limits of the range.
2. Best straight line—The line midway between the two parallel straight lines closest together that enclose all output versus measurand values on a calibration curve.
3. Terminal line—The straight line for which the endpoints are 0 and 100% of both measurand and output.
4. Theoretical slope line—The straight line connecting the specified points between which a specified theoretical curve has been established.
5. Least-squares line—The straight line for which the sum of the squares of the residuals is minimized for all calibration points.

Procedures used in the verification of sensitivity will depend on specific accuracy, calibration time, and expense trade-off choices for each system. For unidirectional transducers, it is typical to calibrate from zero to full scale and back again in 10% of full-scale increments (21 points). For bidirectional transducers, a 21-point calibration cycles the transducer from negative full scale to positive full scale and back again in 20% of full-scale increments.

Data extracted from these calibrations are typically linearity and hysteresis. Linearity is the closeness of a calibration curve to the specified straight line, expressed as the maximum deviation of any calibration point from that line during any one calibration cycle. Hysteresis is the maximum difference in output at any measured value within the specified range when the value is approached first with increasing and then with decreasing measurand.

The reference straight line selected is often the linear least-squares line. This line is based on the following principle: The most probable value of an observed quantity is such that the sum of the squares of the deviations of the observations from this value is a minimum. This is based on the fact that most measurements of physical quantities show a normal distribution with both positive and negative deviations from the mean probable and very large deviations less likely than small deviations. The line can be defined unequivocally in terms of the quantities measured. The line also is statistically significant, and standard deviations can be assigned to estimates of the slope, intercept, and other parameters derived from it.

An additional parameter describing the performance of the measurement system is obtained by repeating the static calibration of the system. A minimum of two, but preferably three, consecutive static calibrations yield data from which the ''repeatability'' of the system is verified. Repeatability is the ability of the measurement system 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 corresponding values from at least two consecutive calibrations. Although there is no universal agreement as to the particular values selected, a value close to full-scale output is commonly used.

If the bridge transducer will be used to acquire time-varying measurements, the measuring system must be both dynamically and statically calibrated. The dynamic response of any system is described by a frequency response function which is a complex function of frequency. The frequency response function relates system output to system input in the frequency domain. For measurement systems, this frequency response function is typically represented by Bode plots which are log amplitude and phase versus log frequency.

6.2 Dynamic Calibration

Dynamic calibrations are inherently more difficult to perform than are static calibrations and usually require specialized equipment. Dynamic calibrations can be performed using several types of well-defined input signals, such as applications of sinusoids, transients, or broadband noise. The principal requirement that the input must satisfy is that it must contain significant energy at frequencies over the range of the frequency response function of interest.

The dynamic calibration sequence consists of the following steps:

1. Dynamic sensitivity determination
2. Dynamic amplitude linearity determination
3. Amplitude–frequency verification
4. Phase–frequency verification

If the measuring system does not have zero frequency response, its end-to-end calibration is of necessity made by dynamic methods. The simplest approach to dynamically determining system sensitivity is the application of a sinusoidally varying measurand to the transducer. The amplitude of the measurand should be equal to the range of the transducer. For unidirectional transducers, this test involves biasing the transducer to its half-range point. At the test frequency, it is possible to relate the peak amplitude of the system response to the amplitude of the measurand and determine system dynamic sensitivity.

It is further desired to acquire dynamic amplitude linearity by performing tests equivalent to dynamic sensitivity determination at several levels of the measurand (usually levels of 25, 50, 75, and 100% of full scale are adequate). This testing should be performed at several different frequencies over the range of the frequency response function of interest.

If the measurement system cannot be verified to be linear, it should not be used to acquire time-varying measurements.

The concept of a measuring system having a unique amplitude–frequency and phase–frequency response is only meaningful for systems which have been verified to be dynamically linear. Amplitude–frequency response tests consist essentially of a series of dynamic sensitivity determinations at a number of frequencies within the bandwidth of the system. Three is the *minimum* number of test frequencies. One test should be performed close to the upper limit of the frequency band where the response has not been affected by the high-frequency roll-off characteristic of the system. The second frequency should be sufficiently higher than the first to provide some indication of the roll-off rate of the system. The third frequency should be about halfway between zero frequency and the first test frequency to verify a flat response to the upper band edge. More improved definition obviously can be provided by increasing the number of test frequencies.

Phase–frequency response characteristics of a measuring system can often be acquired simultaneously with the amplitude–frequency response. An output recording device is required with two identically responding channels. The system output is recorded on one channel. The second channel records the measurand, which is typically acquired by a previously calibrated monitoring transducer whose amplitude–frequency and phase–frequency response characteristics are well established. A time correlation between the system output and this monitoring transducer can establish measuring system phase–frequency response. For systems measuring signals whose time history is important, a linear phase response with frequency is required. For those signals about which only statistical information is to be acquired (e.g., random vibration), phase response is not an important system characteristic.

With today's technology, frequency response functions can also be characterized by transient or random system excitation. Dual-channel spectrum analyzers can ratio input-to-output measuring system Fourier transforms in near-real time. Recall that the system input stimulus must contain significant signal content at all frequencies of interest.

6.3 Electrical Substitution Techniques

If actual values of the measurand cannot be used to calibrate resistance bridge transducers, electrical substitution techniques can be used. Test equipment required includes a precision voltage source, precision resistors or decade box, and a signal generator. The techniques include shunt calibration, series calibration, and bridge substitution. Shunt calibration techniques are discussed first.

Inserting a resistor of known value in parallel with one arm of a strain gage bridge is single-shunt calibration. The calibration resistor is inserted across the arm opposite the strain gage conditioning system. The conditioning system may contain a balance potentiometer, a limit or pad resistor, modulus resistors, and temperature compensation resistors. Standard practice is to insert the shunt resistor between the negative input (excitation) and the negative output (Fig. 19). This reduces errors caused by shunting some of the bridge-conditioning resistors.

The value of the shunt resistor R_c is determined by first applying a value of the measurand to the transducer and monitoring the voltage change at the transducer output terminals (Fig. 19). With the measurand removed, a decade box is substituted for R_c and its resistance adjusted until a voltage change results with a magnitude equal to that caused by the measurand. For subsequent calibrations, a fixed resistor R_c can be substituted for the decade box. When the switch in series with R_c is closed, it will produce a step voltage through the measuring system of amplitude equal to that produced by the measurand. When shunting one arm of the bridge, the resistance change produced in that arm is $-R^2/(R_c + R)$.

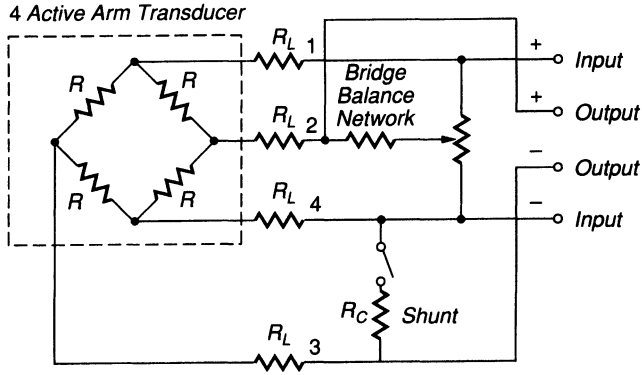


Figure 19 Single-shunt calibration of bridge transducer.

In the calibration laboratory, the small lead length associated with the transducer introduces no error in establishing R_c. The application of the bridge transducer in the field can require significant lengths of cable with significant transmission line resistance. Figure 20 illustrates the situation where R_c must be applied remotely. If R_c were applied directly at the bridge, loading errors introduced by transmission lines would be accounted for. If (as in Fig. 20) R_c is applied at a remote location, the effect of the transmission line resistance $2R_L$ in series with R_c must be considered.

Bipolar shunting is used when the physical loading creates both positive- and negative-going signals and it is desired to create positive and negative calibration outputs. The calibration resistor is alternately inserted across the two arms opposite the bridge-conditioning network. If line resistance is significant, it must be considered as in Fig. 21.

Series calibration of bridge transducers is considerably different from shunt calibration. Figure 22 describes this process. Series calibration consists of two distinct calibration phases.

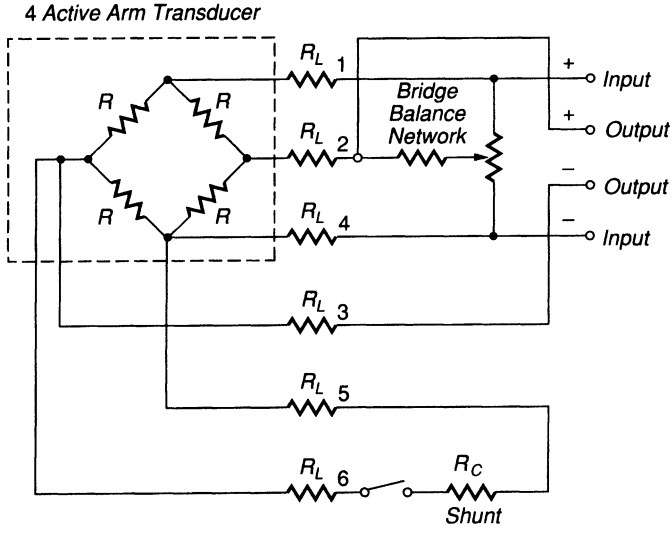


Figure 20 Remote-location single-shunt calibration of bridge transducer.

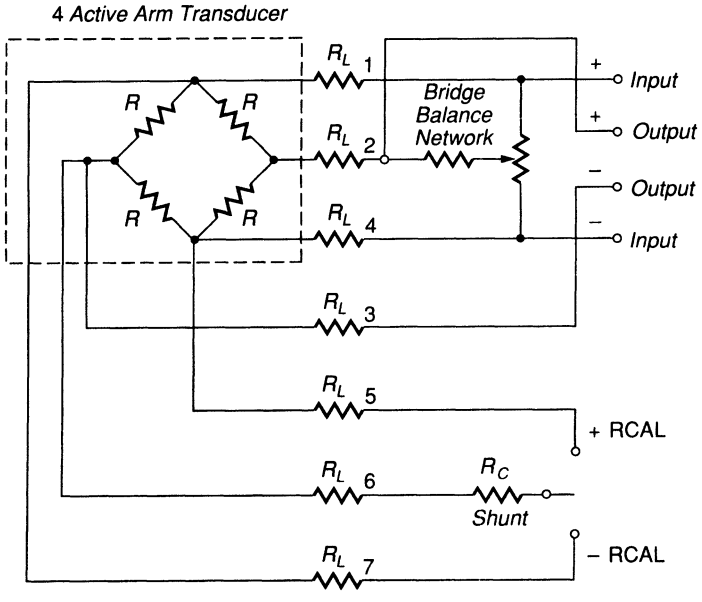


Figure 21 Remote-location double-shunt calibration of bridge transducer.

In the zero calibration phase the Zero Cal switch is moved downward so excitation is removed from the bridge. The sensitivity resistor (R_{SENS}) is concurrently placed across the bridge input terminals, simulating the power supply impedance to result in the same overall system impedance encountered in the data circuit. Zero bridge transducer output is recorded.

The next calibration phase is the series phase. In the series calibration mode the two switches in Fig. 22 are closed with the Zero Cal switch back in its original position, introducing R_{c1} and R_{c2} into the circuit. This removes power from one corner of the bridge and puts a calibration resistor R_{c1} in series with the sensitivity resistor and one side of the bridge output. The second calibration resistor becomes intermediate between the R_{SENS}-to-R_{c1} connection and excitation return. This second resistor, R_{c2}, is selected to maintain the approximate equivalent bridge impedance across the excitation. The calibration circuit then electrically simulates the bridge transducer. The value of R_{c1} is determined experimentally, corresponding to some measurand equivalent.

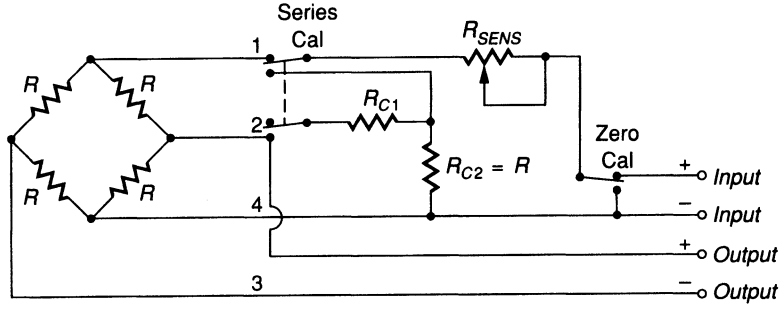


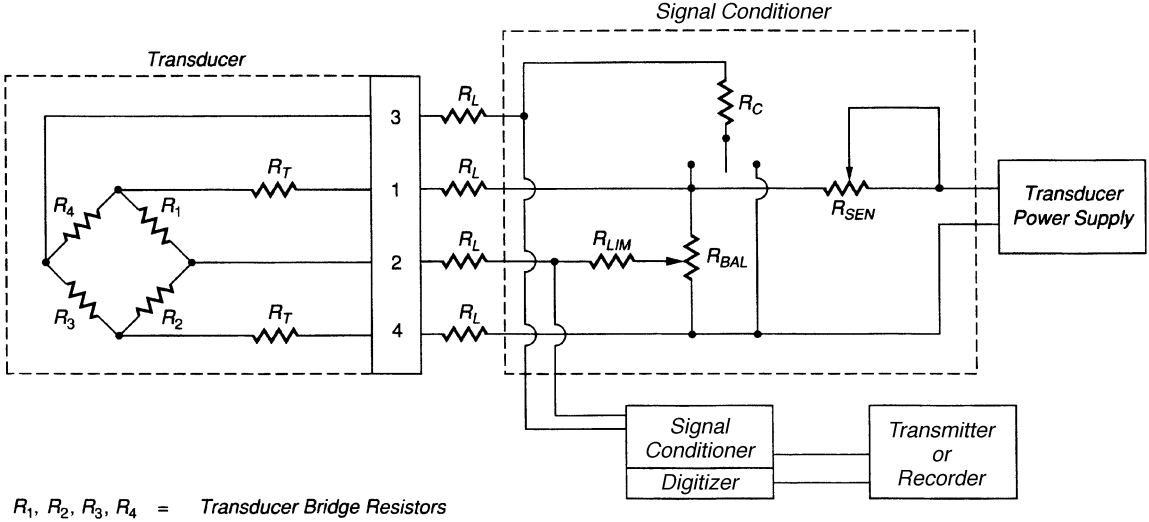
Figure 22 Series calibration of bridge transducer.

Series calibration overcomes a serious shortcoming of shunt calibration. During application of a shunt resistor, the transducer can still respond to mechanical input. The calibration step is superimposed upon any mechanically induced signal present. If the mechanical input is static and of sufficient magnitude, overranging will invalidate the calibration step. If the mechanical input is dynamic, it may be impossible to accurately measure the magnitude of the calibration step. The magnitude of the series calibration step is significantly more independent of this mechanical input. As in all calibration, transmission line resistance must be considered where significant. Similarly, a change in sensitivity resistance modifies the effect of the series calibration resistance. However, the typical error incurred is negligible.

The final electrical substitution technique discussed is bridge substitution. This technique involves substitution of a model for the bridge transducer itself. Figure 23 represents a typical low-level bridge system.

An accurate bridge transducer model has the same terminal impedance as the transducer and provides a fast and simple method of generating a static and dynamic output equivalent to that generated by the transducer for a given physical load. It also provides a convenient method for verifying the calibration resistor's measurand equivalency for shunt and series systems. The two types of bridge transducer models employed for system calibrations are the shunt resistor adapter and the shunt resistor bridge.

Figure 24 describes the shunt resistor adapter, which is simple, inexpensive to construct, and an exact model since it is used in conjunction with the actual transducer. The adapter is inserted between the transducer and the rest of the measurement system. It performs three primary functions.



R_1, R_2, R_3, R_4 = *Transducer Bridge Resistors*
R_T = *Transducer Temperature Compensation Resistor*
R_L = *Line Resistance*
R_{LIM} = *Balance Potentiometer Limiting Resistor*
R_{BAL} = *Balance Potentiometer*
R_C = *Shunt Calibration Resistor*
R_{SEN} = *Sensitivity Resistor*

Figure 23 Typical low-level bridge system.

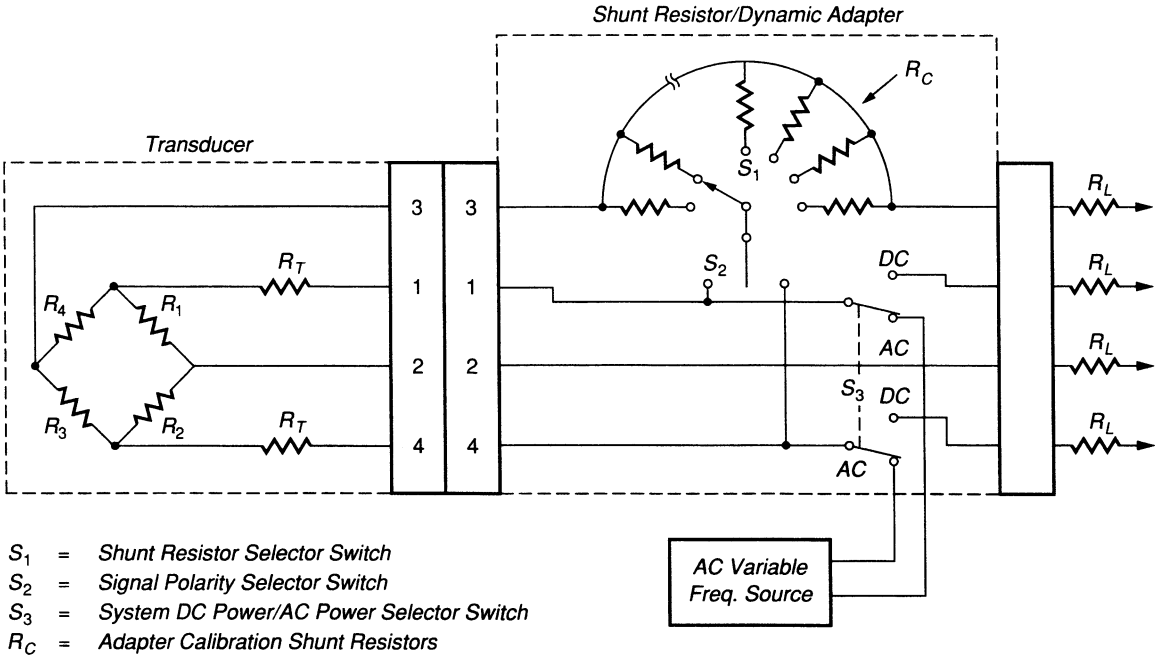


Figure 24 Shunt resistor adapter.

1. It supplies the stimulus for performance of system end-to-end calibrations. Shunting the arms of a transducer bridge with the appropriate resistors produces an unbalance in the bridge equivalent to that produced by a given measurand. The adapter provides a convenient method of applying these shunt resistors directly to the bridge with negligible line loss (S_1 and S_2).
2. It performs a system frequency response test. A convenient system frequency response can be performed by selecting the appropriate shunt resistor and sweeping the adapter's ac power supply over the desired range. Figure 25 shows a typical oscillograph display of the results.
3. It provides a convenient check of the system's calibration resistors (R_c) and equivalents. The system's R_c equivalent will differ from the values established by the laboratory calibration as a function of line resistance, calibration resistor tolerance, and so on. Since the adapter shunt resistors are precision resistors that are applied directly to the bridge, the equivalency of the adapter shunt resistors will not be affected by lead resistance and other variables.

Although the shunt resistor adapter model is a very powerful and simple calibration tool, it has two undesirable characteristics. The least desirable characteristic is that the system calibration and calibration resistor equivalents generated by the adapter are incremental values superimposed on the transducer output resulting from the physical stimulus acting at the time of the test. Also, the adapter does not provide a fixed independent reference since it is used in conjunction with the transducer.

The undesirable features of the shunt resistor adapter can be eliminated by replacing the actual transducer with a bridge model (Fig. 26). Since the shunt resistor bridge (bridge

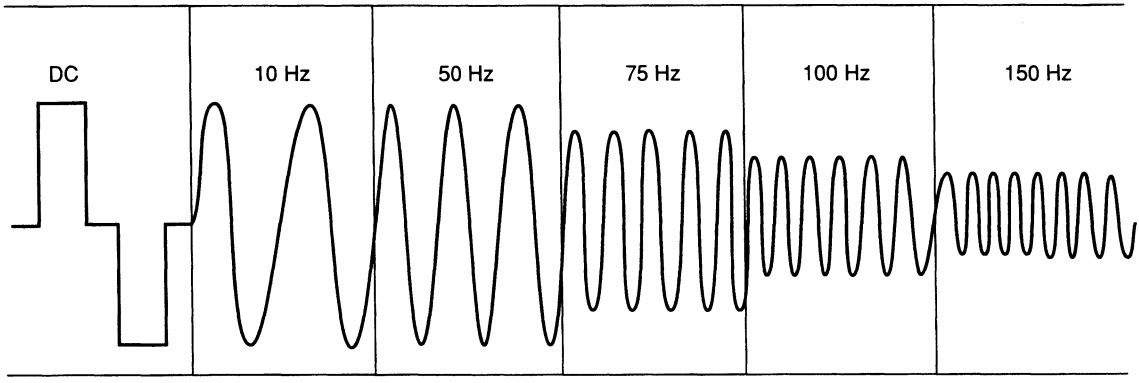


Figure 25 Oscillograph frequency response display.

model plus shunt resistor adapter) is a stable, complete model of the transducer, it can be used to perform an absolute end-to-end system calibration and can be a valuable tool in troubleshooting.

Several disadvantages are encountered when using the shunt resistor bridge as a calibration tool. Since some transducers are hard to model, it is difficult to ensure that the bridge is a representative model of the transducer under all conditions. Furthermore, a different bridge model is required for each major transducer design.

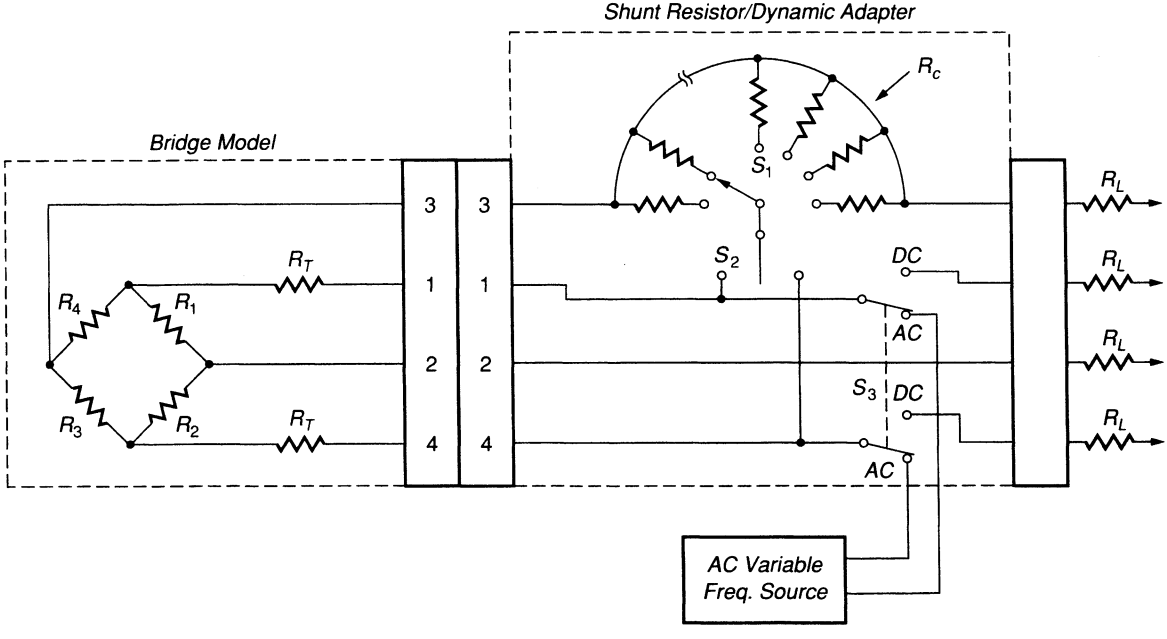


Figure 26 Shunt resistor bridge.

As a final note, remember that the resistance of semiconductor bridge transducers is strongly a function of temperature. When using shunt or series calibration techniques on semiconductor bridges, ambient-temperature changes should be taken into account.

7 RESISTANCE BRIDGE TRANSDUCER MEASUREMENT SYSTEM CONSIDERATIONS

7.1 Bridge Excitation

When amplifiers and power supplies were formally designed around vacuum tubes, component drift was a problem in bridge transducer measurement systems. Alternating-current power supplies in bridge circuits eliminated many of these problems by operating at frequencies above dc. Most bridge transducer power supplies today are dc. When comparing dc supplies with ac, the following advantages are associated with dc:

1. Simpler circuitry
2. Wider resultant instrumentation system frequency response
3. No cable capacitive or inductive effects due to the excitation
4. Simpler shunt calibration and bridge balance circuitry

Independent of type of supply, the power level selected has to take account of all variables which affect the measurement. These include gage resistance, gage grid area, thermal conductivity of flexure to which gage is mounted, flexure mass, ambient test temperature, whether used on a static or dynamic test, accuracy requirements, and long- or short-term measurement. These variables account for the fact that a strain gage is a resistance which has to dissipate heat when current passes through it. Most of the heat is conducted away from the gage grid to the transducer flexure. The result of inadequate heat conduction is gage drift.

For transient measurements, a steady transducer zero reference is not as important as for static measurements. Bridge power can be significantly elevated to increase measurement system signal-to-noise ratio.

The following specifications define key performance parameters of dc output instrumentation power supplies. Input supply can be either ac or dc.

1. *Warmup Time.* The time necessary for the power supply to deliver nominal output voltage at full-rated load. It is usually specified over the range of operating temperatures.
2. *Line Regulation.* The change in steady-state dc output voltage resulting from an input voltage change over the specified range.
3. *Load Regulation.* The change in steady-state dc output voltage resulting from a full-range load change.
4. *Efficiency.* The ratio of the output power to the input power.
5. *Load Transient Recovery.* The time required for the output dc voltage to recover and stay within a specified band following a step change in load.
6. *Periodic and Random Deviation.* The ac ripple and the noise of the dc output voltage over a specified bandwidth with all other parameters held constant.
7. *Stability* (*Drift*). The deviation in the dc output voltage from dc to an upper limit which coincides with the lower limit as specified above in 6.

8. *Temperature Coefficient.* The change in output voltage per degree change in ambient temperature.

Reference 10 defines test procedures for these specifications.

7.2 Signal Amplification

In addition to providing a precision power source to bridge transducers, the resultant millivolt signals from these transducers often require amplification. This amplification is usually performed by a differential dc amplifier. A differential dc amplifier is an electronic circuit whose input lines are conductively isolated from the output lines, power, and chassis ground and whose output voltage is proportional to the differential input signal voltage. Ideally, both input lines have equal impedance and transfer characteristics with respect to the amplifier ground structure. The amplifier has a frequency response from 0 Hz to a value determined by the bandwidth of the amplifier.

Selecting amplifiers can be difficult because specification terminology is not universally standardized. Amplifier specifications are either referred to input (RTI) or referred to output (RTO). Discussing these specifications can lead to an understanding of the amplifiers themselves.

1. *Input Impedance.* The minimum impedance the amplifier will present when operated within its specification. It is the impedance seen between the two ungrounded input lines of the amplifier.
2. *Source Current.* The bias current flowing through the circuit comprised of the amplifier input terminals closed through the source resistance. The amplifier input transistors act as constant-current generators in series with the input terminals. This current can result in both offset voltage and common-mode voltage.
3. *Common Mode Rejection.* The measure of the conversion of common-mode voltage to normal differential signal. The common-mode input voltage is the voltage common with both inputs to the amplifier. A common-mode rejection of 60 dB implies that a 10-V signal applied simultaneously to both inputs produces an error signal RTI of 10 mV.
4. *Linearity.* The maximum deviation from the least-squares straight line established through the output voltage versus differential input voltage characteristic. In evaluating linearity, it is usually sufficient to test at the highest and lowest gains, since linearity will be worst at these settings.
5. *Gain Range.* The slope of the least-squares straight line established through the output voltage versus the differential input voltage characteristic of the amplifier. The gain range is the maximum and minimum values of gain available from the amplifier without causing any degradation in performance beyond the limits of the specification.
6. *Gain Stability with Temperature.* The change in amplifier gain as a function of ambient temperature for any gain in the specified gain range.
7. *Zero Stability with Temperature.* The change in output voltage with temperature. It must be specified as RTI or RTO, and this test is typically performed with the amplifier input leads terminated with the maximum source impedance and no signal applied. A warm-up period is usually specified for both this test and gain stability with temperature.

8. *Frequency Response.* The minimum frequency range over which the amplifier gain is within ±3 dB of the dc level for all specified gains for any output signal amplitude within the linear output voltage range. In writing specifications, it is not uncommon for a user to also specify the desired phase characteristics over the frequency range of interest and the number of filter poles.
9. *Slew Rate.* The maximum rate at which the amplifier can change output voltage from the minimum to the maximum limit of linear output voltage range. It is expressed in volts per microsecond with a large-amplitude step voltage applied to the input of the amplifier and the amplifier driving a specified capacitive load. The usual source of slew rate difficulty is current limiting, and this specification (a nonlinear process) should not be confused with rise time (a linear process).
10. *Settling Time.* The time following the application of a step voltage input for the amplifier output voltage to settle to within a specified percentage of its final value.
11. *Overload Recovery.* The time required for the amplifier to recover from a specified differential input signal overload. It is specified as the number of microseconds from the end of the input overload to the time that the amplifier dc output voltage recovers to within the linear output voltage range. Amplifier gain must be specified.
12. *Noise.* Noise is divided into two components: RTI and RTO. RTI noise is that component of noise that varies directly with gain. It is measured with the amplifier input leads terminated in the maximum source impedance and no signal applied. The RTO noise is that component of noise which remains fixed with gain.
13. *Harmonic Distortion.* The maximum harmonic content for any amplifier frequency or output amplitude within the specified limits.
14. *Output Impedance.* The maximum impedance the amplifier will present when it is operated anywhere within its specification. This specification is important in resistive loading ratings or in determining the amount of capacitance which can be connected across the output without causing instability.

Reference 10 describes test procedures for these specifications and discusses them further. Figure 27 presents the basic dc amplifier circuit. Reference 11 provides additional discussion directed toward understanding dc instrumentation amplifiers.

7.3 Slip Rings

In many measurement applications, it is necessary to acquire data from rotating machinery. Turbines, rate tables, and centrifuges are examples of such machinery. If it is necessary to

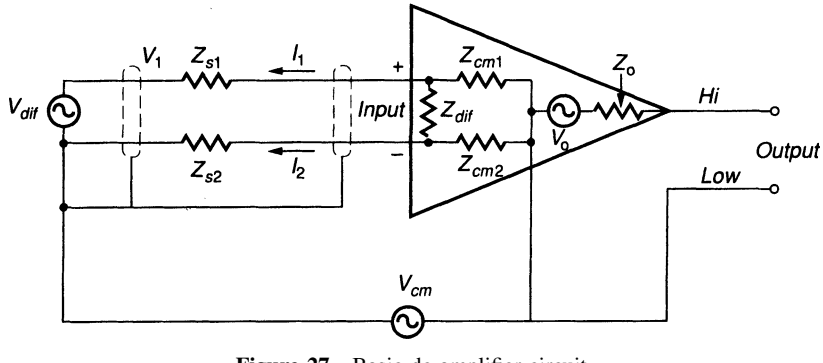


Figure 27 Basic dc amplifier circuit.

measure strain, pressure, torque, force, and so on on the rotating machine component, signals from bridge transducers must be coupled from this component to a stationary instrumentation system. Instrumentation slip rings accomplish this function.

In their simplest form, slip rings consist of a metal ring on the rotating machine component against which a brush attached to the stationary machine portion is spring loaded to make ohmic contact. Precious metals are generally used for mating surfaces to minimize contact resistance.

Slip rings came into existence in the 1940s with initial application in the aircraft industry. In the 1950s, mercury slip rings came into existence. These latter rings, which first found application at Rolls Royce in England, use mercury as the signal transfer medium. The mercury is entrapped between the rotor and the stator of the ring assembly. Today, slip rings are capable of operating from very low RPM to tens of thousands of RPM.

Noise induced in slip rings is of the ohmic contact type, that is, it is roughly proportional to current. A high brush pressure reduces noise at the expense of increased brush wear. Brush wear is a function of the brush pressure, material, finish (usually microinch), and flatness. One technique for lowering contact noise is to mount several brushes in parallel on the same ring.

Because ohmic changes in the slip rings can be of the same order of magnitude as resistance changes in the bridge transducer, full bridges are almost always used on the rotating part to avoid inserting slip rings within the bridge itself. Slip rings in the output circuits of bridge transducers using voltage monitoring do not create significant problems because any small resistance changes in the rings are in series with the large input impedance of the voltage-measuring device and are effectively ignored. Slip rings in the input circuits of bridge transducers operating from a constant-voltage source can create problems if they cause fluctuating voltage drops in series with the transducer. For this reason, constant-current sources are preferred when using slip rings.

Other techniques for extracting data from rotating machinery have evolved over the years. These include rotary transformers, light modulation, and radio frequency (RF) telemetry. Of these schemes, RF telemetry has displayed the most promise with commercially available low-power transmitters capable of operating up to 30,000g.

7.4 Noise Considerations

Many other sources besides slip rings can induce unwanted spurious signals in these transducers. Since the unamplified output from bridge transducers is typically ones or tens of millivolts and never more than a few hundred, they are easily influenced by noise sources. The following discussion defines noise, documents how to verify its existence (or hopefully nonexistence), and provides some hints as to how to suppress noise in bridge transducer measuring systems. Reference 12 provides a basis for this discussion.

The output of measuring system components represents combinations of responses to environments. These environments can be divided into two categories: desired and all others (undesired). For example, consider a bridge pressure transducer in a hostile explosive environment. Its desired environment is pressure. Other undesired environments it encounters are temperature, acceleration, ionized gas, and so on. Ideally, the transducer would respond to pressure alone. In practice, an additional response is elicited from the transducer due to the other environments; usually, but not always, the response is small compared to the pressure response.

Two response types exist for a bridge transducer: self-generating and non-self-generating. Non-self-generating responses are due to changes in the material properties or geometries within a transducer. Power has to be applied to the transducer to elicit a non-

self-generating response. For example, pressure applied to the diaphragm of a pressure transducer with bridge electrical power supplied modifies the impedance of the strain gage circuit and results in a millivolt output (non-self-generating). Self-generating responses are those attributable to various measurands applied to bridge transducers without electrical power supplied. Examples of these responses include thermoelectric-, photoelectric-, pyroelectric-, and magnetoelectric-induced voltages within the bridge circuit. Thus, there exist four environment–response combinations in bridge transducers. The non-self-generating response to the desired environment is defined as signal. The non-self-generating response to the undesired environment, as well as the self-generating response to both the desired and undesired environment, is noise. Figure 28 illustrates the paths associated with these four combinations with path 4 being signal and paths 1, 2, and 3 being noise.

The quantifications of paths 1–4 can be accomplished by switching. If at some time during the test bridge power is switched off, Fig. 28 indicates that only paths 1 and 3 will exist. Since these paths are both noise, the bridge transducer response ideally should approach zero. Similarly, if the desired environment can be switched off for some time period, only paths 1 and 2 remain. If path 1 was verified as being noise free when bridge power was removed, path 2 also becomes quantified. If paths 1, 2, and 3 are all shown to provide negligible signal level, transducer output becomes attributable to path 4, which has been defined as signal. In summary:

Remove bridge power: Document paths 1 and 3.

Reapply power and remove desired environment: Document paths 1 and 2.

If the documented signal paths are of sufficiently small magnitude to be considered inconsequential during test, the non-self-generating response to the desired environment (signal) is recorded.

Some question may arise as to how to implement these procedures, particularly in transient measurement situations. For example, assume a bridge accelerometer is to be used to measure a transient acceleration event. Three accelerometers can be fielded in close physical

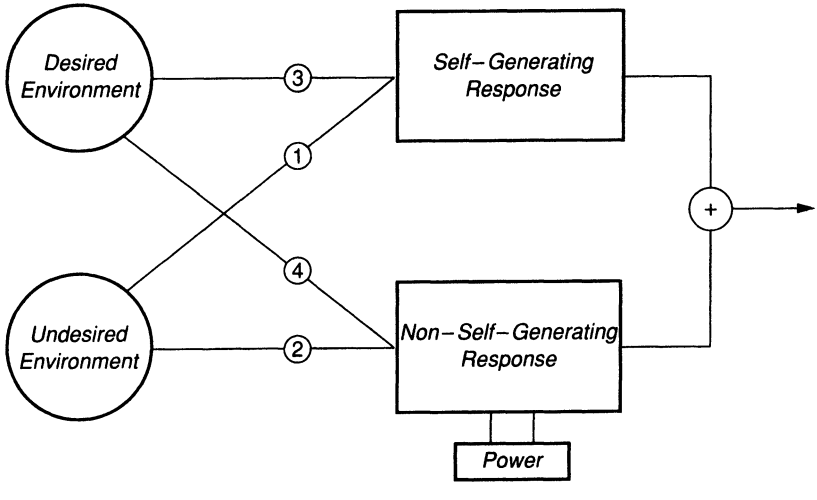


Figure 28 Bridge transducer model for noise hunting and documentation. (Adapted with permission from "Information as a 'Noise Suppression' Method," by Peter Stein, Stein Engineering Services, Inc., Phoenix, AZ, LR/MSE Publ. 66, 1975.)

proximity. The first can be mounted without power applied to document paths 1 and 3. The second can have power applied but be mounted in a piece of foam to isolate it from the acceleration environment, resulting in documentation of paths 1 and 2. The third can be powered and properly mounted to measure the acceleration environment. If the first two accelerometers produce no output, then the output from the third is the noise-free signal.

If noise is present in measuring systems containing bridge transducers, noise control efforts are dictated by the specific noise type. Electric and magnetic fields can be shielded, noise components at specific frequencies can be filtered, thermal transient effects can be absorbed or delayed, steady-state temperature effects can be compensated, and so on. The prerequisite to any noise control is documentation of its presence.

As noted earlier, most modern resistance bridge transducers use dc power supplies as opposed to ac power supplies. However, ac power supplies still have an important role to play with resistance bridge transducers. The ac power supplies accomplish noise suppression by separating the self-generating responses from the non-self-generating responses in a trans-

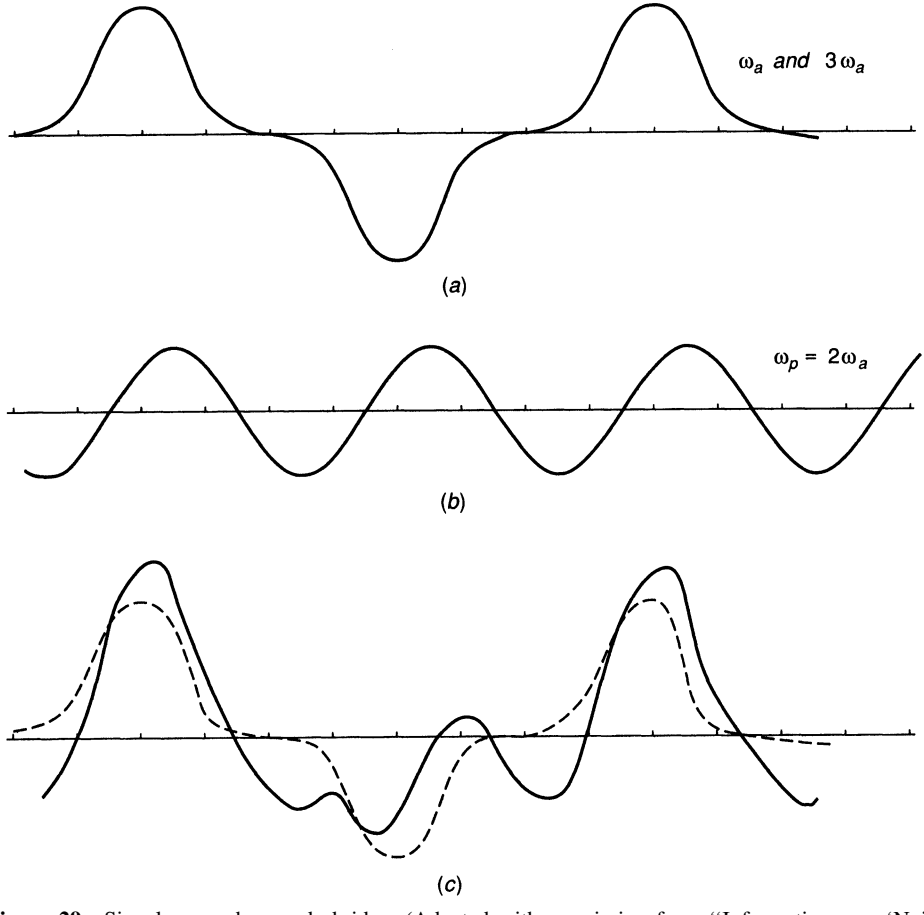


Figure 29 Signal wave shapes, dc bridge. (Adapted with permission from ''Information as a 'Noise Suppression' Method,'' by Peter Stein, Stein Engineering Services, Inc., Phoenix, AZ, LR/MSE Publ. 66, 1975.)

ducer by moving the frequency content of a signal into some new range of the frequency spectrum. This procedure is known as amplitude modulation. Reference 13 forms the basis for the following discussion.

Referring to Fig. 28, amplitude modulation can eliminate paths 1 and 3 (noise) from the net output signal. Thus, self-generating electromotive force (emf), such as thermoelectric and electromagnetic ones, can be separated from emf attributable to resistance changes in a bridge transducer.

A design procedure is presented for an ac-powered bridge where the signal input to the self-generating response extends to frequency ω_1 and the input to the non-self-generating response extends to ω_2. Power supplied is at frequency ω_3. The design method developed requires a knowledge of these frequencies. A procedure to determine these frequencies involves the following:

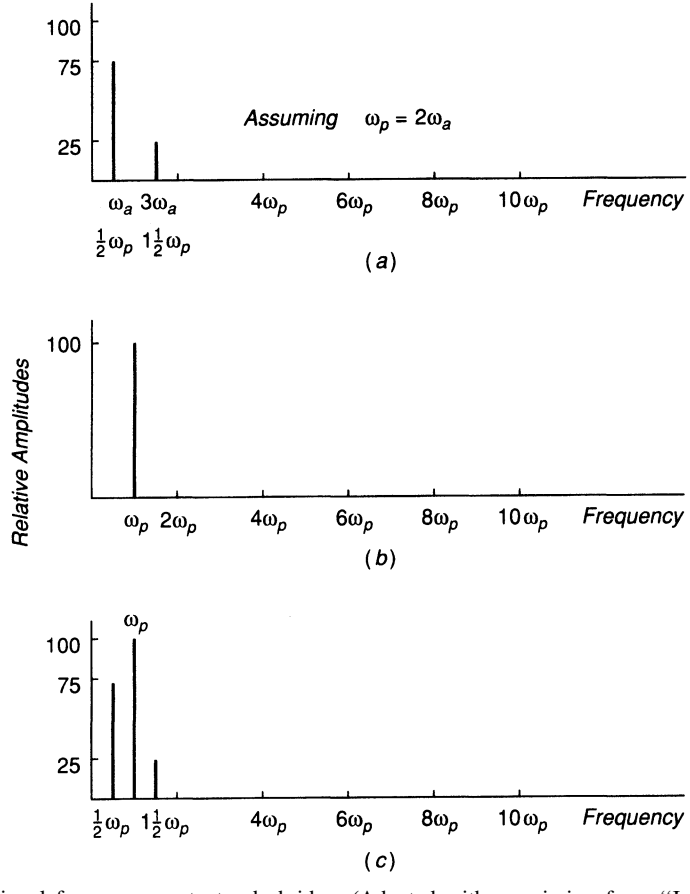


Figure 30 Signal frequency contents, dc bridge. (Adapted with permission from "Information as a 'Noise Suppression' Method," by Peter Stein, Stein Engineering Services, Inc., Phoeniz, AZ, LR/MSE Publ. 66, 1975.)

1. Performing a frequency analysis of the signal recorded with no power supplied to determine ω_1
2. Applying power under normal operating conditions and comparing signal frequency content to the results of 1 to determine ω_2

An example follows where noise is present as a self-generating response and the bridge is powered first by a dc supply and then by an ac supply.

In this example, the non-self-generating response (signal) occurs at frequency ω_p and the self-generating response (noise) occurs at two frequencies bracketing ω_p ($\omega_a = \omega_p/2$ and $3\omega_a$). Figure 29 illustrates the wave shapes assumed for the self-generating and non-self-generating responses with dc power supplied ($\omega_3 = 0$). Figure 29*a* represents both self-generating response input and output, Fig. 29*b* represents non-self-generating response input and output, and Fig. 29*c* represents the total transducer output (summation of 29*a* and 29*b*). It is seen that the two responses are hopelessly intermingled and that the signal cannot be separated from the noise. Figure 30 shows the frequency content of the wave shapes, with Fig. 30*a* corresponding to 29*a*, Fig. 30*b* corresponding to 29*b*, and Fig. 30*c* corresponding to 29*c*. The ac-powered bridge will be presented as a solution to measurement problems such as this. Frequency ω_3 is typically selected as 10 times ω_p.

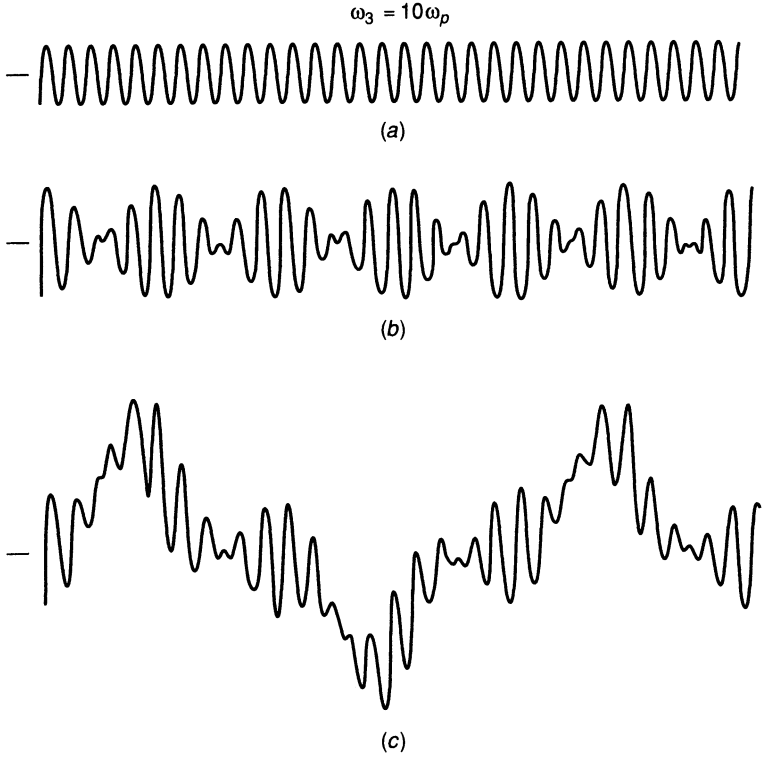


Figure 31 Signal wave shapes, ac bridge. (Adapted with permission from "Information as a 'Noise Suppression' Method," by Peter Stein, Stein Engineering Services, Inc., Phoeniz, AZ, LR/MSE Publ. 66, 1975.)

Figure 31 describes this situation for the ac bridge. Figure 31*a* describes bridge power. Figure 31*b* describes the output from the non-self-generating response which now contains frequencies at $\omega_c - \omega_p$ and $\omega_c + \omega_p$. Here ω_c is defined to be the carrier frequency, ω_3. Figure 31*c* describes the net transducer output, which is a summation of Fig. 29*a* and Fig. 3l*b*. Figure 32 describes the frequency content associated with Fig. 31 respectively. The frequency content in Fig. 32*c* associated with the time history of Fig. 3l*c* shows conclusively that the non-self-generating information has been moved from its original frequency, ω_p, to occupy a new frequency range, $\omega_c - \omega_p$ to $\omega_c + \omega_p$, while the self-generating response is left at ω_a and $3\omega_a$. The non-self-generating response is then in that part of the frequency spectrum where no appreciable noise exists and can be separated by bandpass filtering.

After bandpassing, a problem still remains in phase sensing. Figure 33 describes this problem. Figure 33 illustrates an amplitude-modulated signal after bandpassing to remove the effects of any self-generating response which may be present. This amplitude-modulated signal is ambiguous in that it could correspond to any of the lower four signal inputs to the non-self-generating response. The problem of phase sensing associated with a modulated signal is that of determining which portion of the modulated wave shape is positive and which is negative.

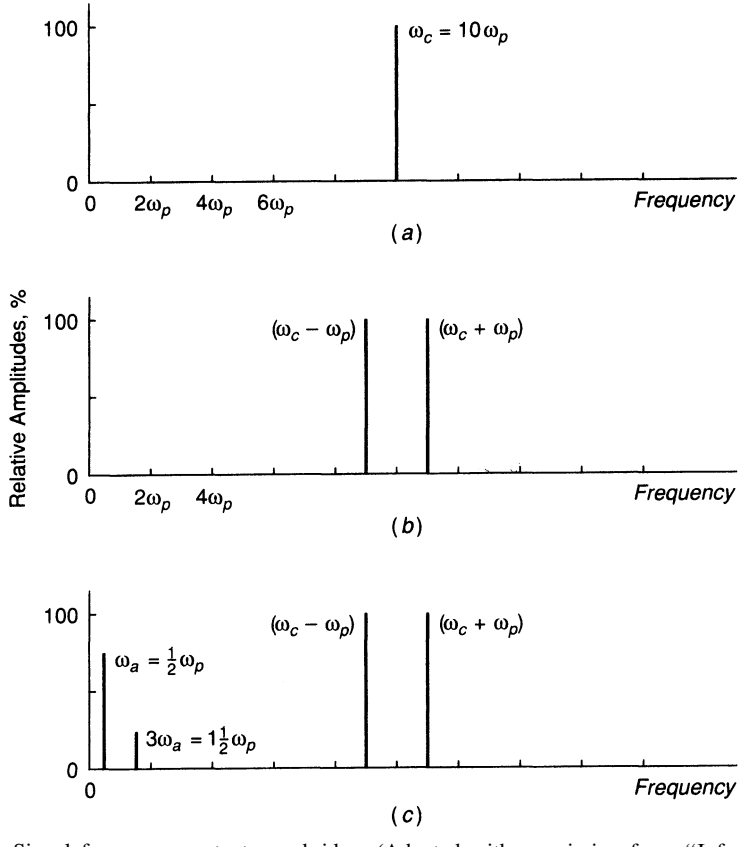


Figure 32 Signal frequency contents, ac bridge. (Adapted with permission from "Information as a 'Noise Suppression' Method," by Peter Stein, Stein Engineering Services, Inc., Phoeniz, AZ, LR/MSE Publ. 66, 1975.)

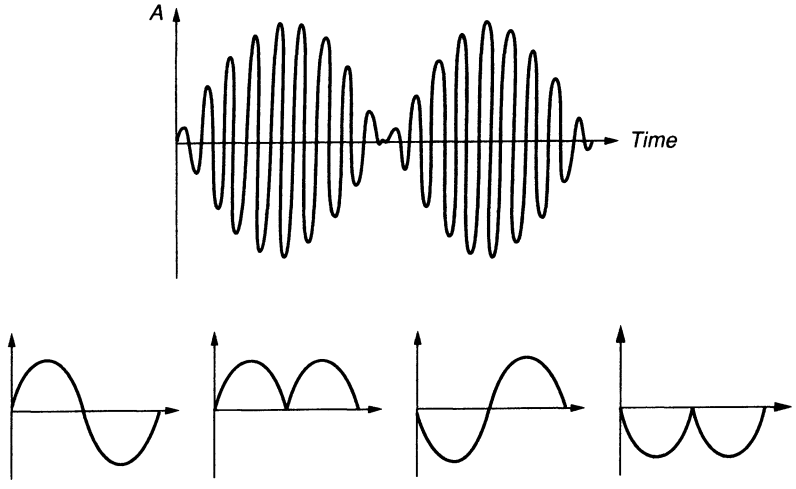


Figure 33 Problems of phase sensing. (Adapted with permission from "Information as a 'Noise Suppression' Method," by Peter Stein, Stein Engineering Services, Inc., Phoeniz, AZ, LR/MSE Publ. 66, 1975.)

If a modulated signal emerges from a measuring system which is initially balanced (zero output for zero input), phase sensing must be done in a phase-sensitive manner. The general principle for all phase sensors is as follows:

> If the system output is of the same sign at the same time as the time-varying supply power, the measurand must have been positive. If the signs are opposite, the measurand must have been negative.

Phase sensing is accomplished by a phase-sensitive demodulator. A reference signal is fed from the bridge supply power to the phase-sensitive demodulator. This signal is compared with the amplitude-modulated signal for phase determination. A half-wave rectifier with transformer coupled reference and amplitude-modulated signals forms one basis for a demodulator.

After phase sensing, a low-pass filter is required to separate the non-self-generating analog signal proportional to the measurand from the other frequencies which appear as sidebands around harmonics of power supply frequency. Final selection of a power supply frequency is a trade-off between the maximum frequency content in the measurand and the low-pass filter roll-off characteristics. While a 10:1 ratio is typical, the power supply frequency may vary between 3 and 20 times the maximum nonself-generating signal frequency.

Note that introduction of an ac power supply requires a bridge-balancing network incorporating complex impedance in the balance controls.

8 AC IMPEDANCE BRIDGE TRANSDUCERS

Having discussed bridge transducers that use resistive sensing elements and ac power supplies (amplitude modulation), a logical question is whether bridge transducer sensing elements can be capacitive or inductive. In practice, many bridge transducers do employ

capacitive or inductive elements. While resistance bridge-type transducers typically possess resonant frequencies in the tens or hundreds of kilohertz range, ac impedance bridge transducers typically possess resonant frequencies of less than 10 kHz. The larger physical size of ac impedance bridge transducers makes them environmentally more fragile but improves their performance by increasing their sensitivity to low-level measurands.

8.1 Inductive Bridges

Figure 34 shows an example of how variable-reluctance sensing elements can be incorporated into an ac bridge transducer. A differential pressure transducer containing a magnetically permeable stainless steel diaphragm as the mechanical flexure is portrayed. This diaphragm

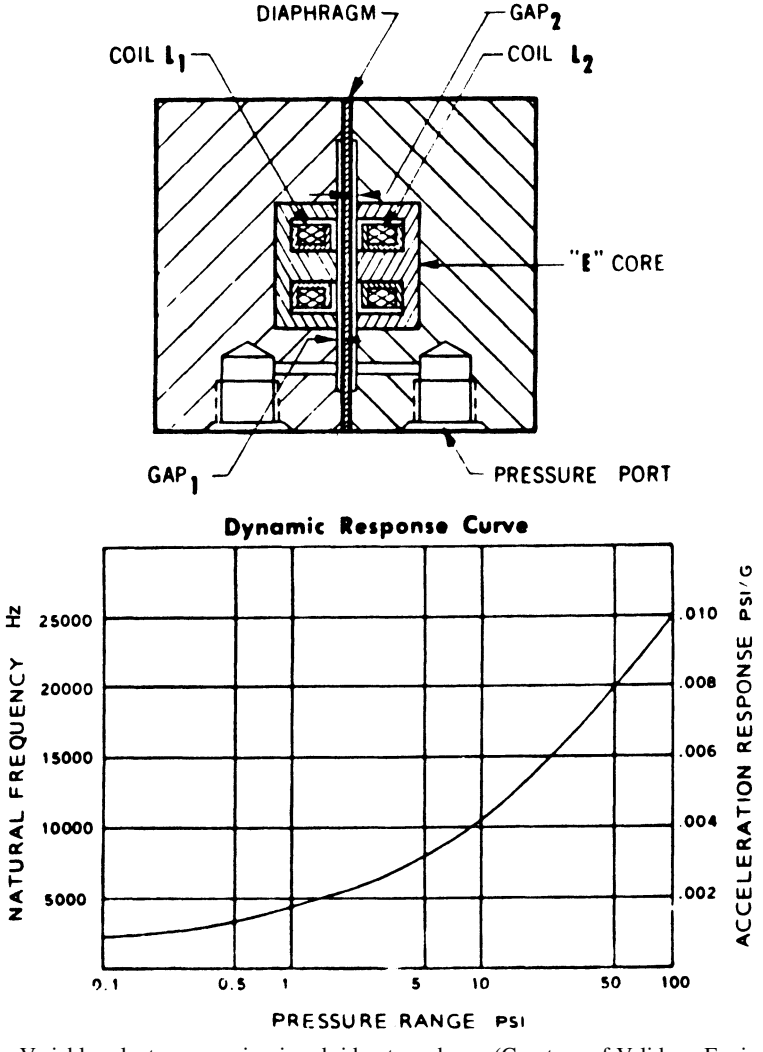


Figure 34 Variable reluctance sensing in a bridge transducer. (Courtesy of Validyne Engineering Corporation.)

is clamped between two blocks and deflects when a pressure difference is created across it through the two ports shown. An E-core and coil assembly is embedded in each block. A small gap exists in front of each E-core. When the diaphragm is undeflected, a condition of equal inductance exists in each coil. When the diaphragm does deflect, an increase of gap in the magnetic flux path of one core occurs, with a resultant decrease in the gap in the magnetic flux path of the other. Magnetic reluctance varies with gap, determining the inductance value. The diaphragm motion then changes the inductance of the two coils, one increasing and one decreasing. These two coils can be placed in adjacent arms of an ac-powered bridge. Resistive elements can be used to complete the bridge. Once the bridge is balanced, an amplitude-modulated signal results when a differential pressure is applied across the ports of the transducer. When the resultant signal is properly demodulated, the applied pressure can be quantified.

Eddy current inductive displacement-measuring systems are another example of the use of impedance as opposed to resistive bridges. Placing a coil with an ac flowing in it a nominal distance from a metal target induces a current flow on the surface and within the target. The induced current produces a secondary magnetic field that opposes and reduces the intensity of the first field. Changes in the impedance of the exciting coil provide information about the target. The target can be the diaphragm of a pressure transducer, the seismic mass of an accelerometer, the flexure of a load cell, and so on. The coil is one leg of a balanced bridge network. Unbalanced bridge conditions are sensed and converted into a signal directly proportional to the distance between coil and target. Figure 35 schematically illustrates this conversion.

The electrical parameters of resistivity and permeability in the target material influence performance of eddy current transducers. For a specific material, displacement sensitivity is influenced by coil geometry and operating frequency.

Target thickness is generally not a limiting factor. At one "skin depth," the eddy current density is only 36% of the maximum encountered on the target surface; at two "skin depths," it is 13%. Figure 36 defines skin depth as a function of target resistivity and permeability.

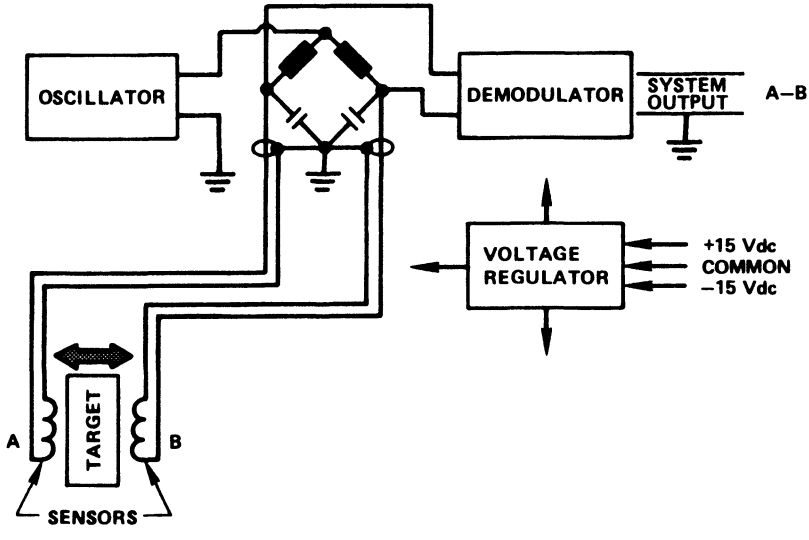


Figure 35 Eddy current inductive displacement measuring system. (Courtesy of Kaman Instrumentation Corporation, Measurement Systems Group, Colorado Springs, CO.)

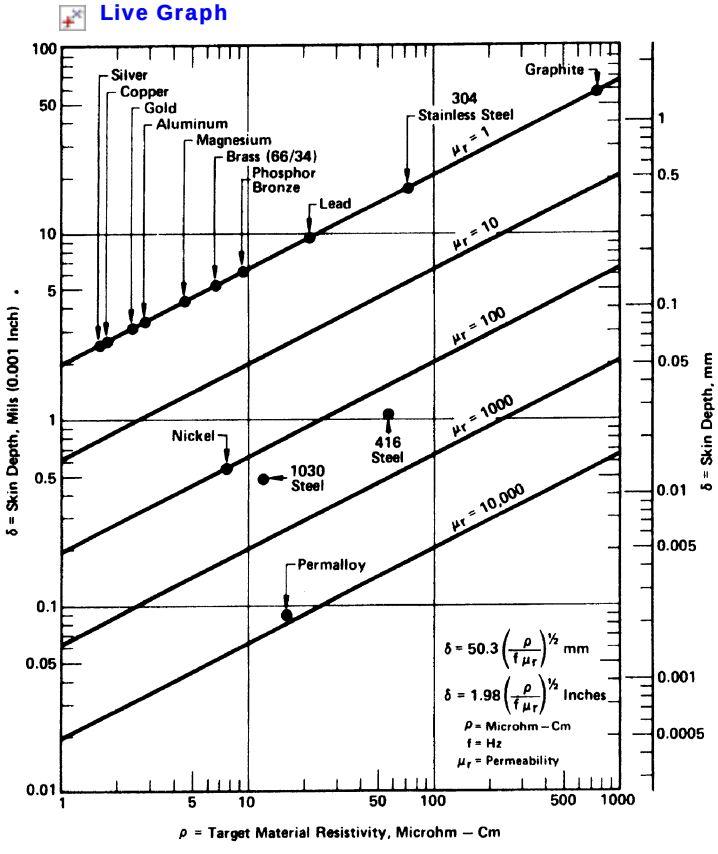


Figure 36 Skin depth versus target resistivity and permeability at 1 MHz. (Courtesy of Kaman Instrumentation Corporation, Measurement Systems Group, Colorado Springs, CO.)

Target shape and alignment also should be considered in application. A flat, circular target equal to the coil diameter appears as an infinite plane. Smaller target diameters produce smaller voltage unbalances in the impedance bridge. Since the transducer senses the average distance to the target, the nonparallelism effect is small up to 15°.

A differential transformer also is briefly mentioned here, although it does not operate in an impedance bridge. A linear variable differential transformer (LVDT) consists of three symmetrically spaced coils wound onto an insulated bobbin. A magnetic core moving through the bobbin provides a path for magnetic flux linkage between coils. The center coil is the primary and has an ac voltage applied. The two secondary coils are wired in a series-opposing circuit. When the core is centered between two secondary coils, the voltages in the two coils cancel. As the core is displaced, the phase-referenced and demodulated output signal provides a linear voltage output with displacement.

8.2 Capacitive Bridges

Capacitance sensors can be integrated into bridge transducers. The capacitance between two metal plates separated by an air gap is $C = kKA/h$, where C is capacitance, K is the dielectric constant for the material between the plates, A is the plate overlapping area, h is the gap

thickness between the two plates, and k is a proportionality constant. The range of a capacitance sensor can be shown to remain linear with changes in area but become nonlinear when the change in gap displacement becomes a significant portion of the original gap.

Again, it should be pointed out that advantages of small size and enhanced dynamic response are to be found with resistance bridge transducers. Increased sensitivity will be displayed by impedance bridge transducers. Both impedance bridges and ac-powered resistance bridges offer noise suppression through separating non-self-generating responses from self-generating responses.

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