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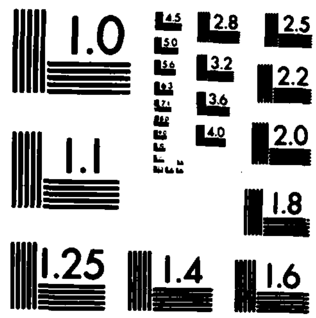

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Describes procedures for measuring dynamic strains that occur during weapon firing and vehicle tests, when the principal direction of the strain is known. Includes the use of foil and wire resistance strain gages.

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US ARMY TEST AND EVALUATION COMMAND
TEST OPERATIONS PROCEDURE

DRSTE-RP-702-102
*Test Operations Procedure 3-1-006 — 20 April 1983
AD No.

STRAIN MEASUREMENT - UNIDIRECTIONAL

1. SCOPE. This TOP covers the use of wire and foil resistance strain gages to measure dynamic strains, e.g., strains that occur during weapon firing and vehicle tests, when the principal direction of the strain is known. This TOP does not include the use of semiconductor gages, nor does it cover measurement and calculation of complex strains and stresses.

2. FACILITIES AND INSTRUMENTATION.

2.1 Facilities. None applicable

2.2 Instrumentation.

ITEM	TYPICAL ERROR OF MEASUREMENT**
Wire or foil strain gage	gage factor ±0.5 to 2.0% resistance ±0.15 to 2.0%
Signal conditioning (excitation, balancing, calibration)	±0.1 to 5.0%
Readout or recording device	analog ±0.5 to 5.0% digital ±0.05 to 0.25%

*This TOP supersedes MTP 3-1-006 dated 3 August 1970.

*Values may be assumed to represent ± 2 standard deviations; thus, the stated tolerances should not be exceeded in more than 1 measurement of 20. Accuracy depends greatly upon installation and measurement techniques. Typical measurement accuracy is ± 2 to 5% of full scale.

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3. REQUIRED TEST CONDITIONS.

3.1 Test Design. Strain gage test design is a process of compromise among the diverse and often conflicting requirements of data accuracy, environmental effects, availability of resources, and economy. In many organizations, some or all of the variables are controlled by standard procedures tailored to typical work requirements and available equipment. Such procedures may be formal documents, field notes, or traditions. It is impossible to write a general procedure that will cover all cases, however, and it is essential that responsible personnel are aware of the limits of applicability of any established procedure, whether formal or traditional. They must also have some awareness of the many parameters that must be taken into account in strain gage test design. Complete coverage of this subject is beyond the scope of this TOP, but some of the more important factors, particularly as they apply to weapons testing, are discussed in the appendices. Whether the result of following a set of rules or application of engineering analysis, the final design must specify the strain gage to apply, the adhesive and coating to use, the lead wire arrangement, and the signal conditioning and recording system.

3.2 Preparation of Test Item. After determining the exact position, either by stress coat analysis[1*] or engineering knowledge, at which the unknown strain is to be measured, carefully prepare the surface for gage mounting. Surface preparation of the area to which the gage is to be mounted is of vital importance in obtaining accurate reproducible measurements. This preparation should develop a chemically clean surface having a roughness appropriate to gage installation requirements (63 to 125 μin) and visible layout lines for locating and orienting the gage.

Materials commonly used in surface preparation are: Chlorothene, freon, or isopropyl alcohol for degreasing; wet/dry silicon carbide paper for sanding (220-320 grit is suitable for most steels and 320-400 for aluminum and other soft materials); cotton swabs and gauze sponges; isopropyl alcohol and distilled water for the final wash of the clean area.

Degreasing should always be the first operation. This is to prevent surface contaminants from being driven into the material by subsequent sanding operations. Porous materials such as titanium, cast iron, and cast aluminum may require heating to drive off absorbed hydrocarbons or other liquids. Surface abrasion is performed to remove any loosely bonded adherents (e.g., scale, rust, paint, galvanized coatings, oxides, etc.) and to develop a surface texture suitable for bonding. For rough or coarse surfaces, it may be necessary to start with a grinder, disc sander, or file. Final abrasion is performed with silicon carbide paper of appropriate grit. For general strain measurements, the grits specified above are suitable and will provide the necessary 63-125 microinches rms of roughness. For unusually high strains, the surface should be cross-hatched, and coarser abrasive than that mentioned above must be used. The surface should then be recleaned to remove all grit and residue. Use of proprietary cleaning agents and metal preparation treatments if desired should be in accordance with the vendor's instructions.

*Footnote numbers correspond to reference numbers in Appendix E.

Gage location layout lines should be made with a tool that burnishes, rather than scores or scribes the surface. A 4H drafting pencil makes a satisfactory burnishing tool for most nonferrous alloys. On hard alloys, alignment marks can be made with a ballpoint pen or a rounded piece of brass rod. If critical alignment is not necessary, gage lines may be located outside the immediate gage location, and any reasonable method of marking is suitable. All marking residue must be removed from the gage emplacement area by rescrubbing the area with cleaning liquid and a final rinse with alcohol or distilled water.

In order to retain a clean surface, it is important to guard against recontamination. The following are practices to avoid: touching the cleaned surface with the fingers; wiping back and forth with gauze sponges or cotton swabs; dragging contaminants into the cleaned area; allowing cleaning liquids to evaporate on the surface; allowing prepared surfaces to sit for more than a few minutes before gage application.

3.3 Strain Gage Bonding. The adhesive bond is critical if the gage element is to accurately sense the strain in the substrate. The most common adhesives for moderate temperature work are nitrocellulose (Duco, SR-4) for paper-backed gages, and epoxy or cyanoacrylate (Eastman 910, M-Bond 200) for plastic-backed gages. Successful installation requires that the gage backing as well as the prepared surface be exceptionally clean. Generally, the gage can be used without additional cleaning if it has been stored properly and care is taken to avoid finger contact with the bonding surface. A common practice is to position the gage on the substrate precisely where it is to go and then apply a piece of cellophane tape so as to form a hinge which will properly relocate the gage after application of the adhesive. The gage is then folded back, adhesive applied to the substrate, and the gage rolled into contact. For slow-drying adhesives, the gage may be readjusted slightly if needed and pressed in several directions to ensure elimination of any bubbles. It is then clamped, often with a rubber pad for even pressure, and cured as appropriate for the adhesive.

Application with cyanoacrylate adhesive (Eastman 910, Micro-Measurements M-Bond 200) requires special care due to the very short setup time. The gage backing should be treated with a catalyst before applying the adhesive. One recommended practice is to pull the tape hinge back about 0.6 cm (1/4 in) and apply a single drop of adhesive at the intersection of the tape and substrate. Rolling the tape and gage onto the surface with a thumb or finger will, if properly done, distribute the adhesive in a thin uniform layer under the gage. Firm pressure must then be maintained on the gage for about one minute. It is of critical importance that no movement of the gage occur during this time. If the installation is unsatisfactory, it will have to be redone, with complete recleaning and a new gage.

CAUTION Most adhesives used with strain gages are harmful if ingested and can cause irritation of skin or eyes. Cyanoacrylate can glue fingers to each other or to other undesired objects in a few seconds. Handle adhesives with caution and see vendor literature for instructions on neutralizing or removing material. A small sheet of teflon is useful for overlaying the gage when finger pressure is used for positioning and clamping.

3.4 Gage Wiring and Protection. Electrical conductors used to transmit signals from the strain gage to the measuring instrumentation are important to the accuracy of the measurement. Care must be taken to ensure that the lead wires do not introduce significant resistance, cause resistance changes, or generate electrical signals that are not related to the strain gage output. The wiring configuration will depend upon the number and arrangement of active gages and the characteristics of the signal conditioning (bridge balance and calibration system) used. For single active gages without dummies, a two-wire connection is suitable for moderate accuracy and environmental conditions if series calibration is used (see Appendix C). In two-gage installations where each gage senses the principal strain (e.g., gages on opposite sides of a gun tube or pull rod to provide cancellation of bending), the gages can be connected in series and treated as a single arm. In any two-wire system, temperature changes will affect the balance due to the relatively large temperature coefficient of the copper lead wires. This can be avoided if the signal conditioning permits, by use of a three-wire connection. When dummy gages are installed on the test item or two or more gages sense opposing strains, half- or full-bridge configurations result, requiring three- or four-wire connections as a minimum. Additional wires may be desirable to reduce lead resistance effects on calibration accuracy. A six-wire system is often used in which the extra pair may be used either for connection of a shunt calibration resistor, or to provide remote sensing for the excitation power supply depending on the nature of the signal conditioning. For more detailed discussion of lead arrangements and examples of other multi-wire options, see Appendix C.

Connections to the gage are usually made with fine-stranded copper wire. In many cases, it is advantageous to use separate "printed circuit" terminals close to the gage or incorporated on the same backing. This allows use of very fine (No. 30 to 36) wire between the gage and terminals to provide optimum gage performance while still providing a connection point for heavier leads from the signal conditioning to reduce errors due to lead resistance. Such terminals also provide a convenient place close to the gage for branching to multi-wire or multiple gage connections.

The connection at the gage and at flat terminals is usually made with a good 60/40 or 63/37 tin/lead solder. On extremely small gages, there is some advantage to solders with lower melting points and at high temperatures silver soldering or welding may be required. It is important that the materials be clean and properly fluxed and the joint made with the minimum of heat and solder. Use of a temperature-controlled soldering iron is strongly recommended to avoid distorting or destroying the backing or bond layers.

In some applications where long cable runs are required between the test item and associated instrumentation, it has been found useful to attach a second terminal strip of the screw and barrier type to the test item to provide a disconnect point as well as a transition from light to heavier wire or cable. If this is done, the wire ends should be doubled and coated with solder, or terminated in spade lugs so that the terminal screws can be securely tightened without cutting the leads. The screw tightness must also be checked regularly.

For any but the briefest tests under laboratory conditions, every gage installation should be provided with a protective covering. This can vary with the requirements from a light coating of soft wax for moisture protection to an elaborate multilayer cover of rubber, plastic, and metal foil. One of the more widely used coatings suitable for a fairly wide range of environmental conditions, is RTV silicone rubber.

3.5 Instrumentation. The quality of a strain gage measurement depends heavily on the proper selection and use of associated signal conditioning equipment. The most common mode of operation for strain gages is in the form of an unbalanced Wheatstone bridge. The bridge circuit is composed of one or more active strain gages with the rest of the four arms consisting of dummy gages or fixed resistors. The bridge corners may be closed at the test item or transducer ("full bridge"), or two or three arms may be contained in the signal conditioner. The "unbalanced" description refers to the fact that, although the bridge is usually close to balance initially, it is not rebalanced when the strain level changes, but the unbalance voltage is used as the measure of the input strain. This means that not only the resistor values in the bridge, but also the excitation voltage and amplifier gain effect the output. Moreover, the bridge output is nonlinear with resistance change.

To avoid the need for precise measurement of many variables and to minimize the amount of calculation involved in data reduction, it is often desirable and essential for precision work with analog recording systems, to provide for an electrical simulation of known strain level for recording system calibration. The gage configuration and the capabilities of signal conditioning used will determine choice of lead system and calibration mode (see Appendix C). Electrical simulation (calibration) signals can be generated by three types of circuits described generally as shunt resistance, series resistance, or voltage insertion calibration. Any of these can be related to strain by auxiliary measurements and appropriate computation (Appendix D). Series resistance change is the most direct since only the gage resistance and calibration step value are required and lead effects are eliminated. However, most commercial signal conditioning does not make provision for series calibration, and it can only be used with quarter- or, with some restrictions, half-bridge configurations. In shunt calibration, a selected resistance is shunted across either an active gage or dummy arm. A simple shunt calibration will introduce errors due to lead resistance if the gage leads are long. These errors may be accounted for by calculation or use of additional wires.

Voltage insertion systems may simply inject a known voltage level into the amplifier in place of the bridge output, or may rearrange the bridge circuitry to provide a signal in millivolts output per volt of excitation. The latter is particularly useful for use with commercially available full-bridge transducers which are usually calibrated in millivolts per volt at full-scale input.

In most applications, amplification of the bridge output signal is required to provide sufficient input to the recording device. The amplifiers must have sufficient bandwidth to pass the frequencies of interest and must not add excessive noise to the signal. The gain must be reasonably constant during the period of a test, but whether it needs to be known accurately will depend on whether an in-line system calibration is used at frequent intervals. The amplifiers may also provide adjustable filtering to reduce noise at frequencies outside the range of valid data. Use of amplifiers with differential inputs is often very effective in reducing noise pickup and interaction between channels or with other signals.

4. DATA REQUIRED. Record the following during strain gage measurements:

a. Strain versus time data
b. Gage location (sketch may be required)
c. Type of gage

d. Gage factor
e. Gage resistance
f. Calibration resistance
g. Time standard
h. Magnetic tape recording speed (if applicable)
i. Digitizing rate (if applicable)
j. Data bandwidth
k. Test round or run identification
l. Any changes in gages or calibration values as the test progresses

In addition, some or all of the following may be required:

m. Environmental conditions (primarily temperature)
n. Lead wire configuration and resistance
o. Excitation voltage or current
p. Amplifier gain
q. Signal polarity
r. Bridge configuration

The data may be recorded on any available system which will provide accuracy, time resolution, and frequency response adequate for the purposes of the test. Typical systems include analog recording on pen, galvanometer, or fiber-optic oscillograph, or FM magnetic tape. Digital techniques currently coming into wider use range from self-contained systems based on digital oscilloscopes to elaborate multi-channel computer-based systems. The technology in this area is so new that nothing "standard" has evolved. Digital systems offer many advantages and allow use of techniques impractical in analog systems, but often require rethinking of old habits and assumptions and have their own pitfalls. Bridge configurations and calibration schemes well suited to analog recording may not give optimum results or exercise the full capabilities of a computer-based system.

5. DATA PRESENTATION. Reduction and analysis procedures for dynamic strain gage data depend on the gage configuration, recording method, and system calibration technique. They may range from hand-scaling of oscillograph records to computerized plotting of engineering data by the recording system itself. However, there are two basic processes which must be accomplished. The first is determination of the overall system sensitivity from gage to final output in output units (volts, millimeters deflection, "counts") per input unit (ohms change, millivolt/volt, standard shunt) which can be related to strain. The second process is converting the raw data to equivalent strain in the form of data tabulations or plots using the determined sensitivity. This may include incorporation of correction factors for lead resistance, etc, based on knowledge of the bridge and signal conditioner characteristics. Some of these correction formulas are given in Appendix D.

For work of any precision on analog recording systems, use of an accurate, multi-step, in-line strain simulation is strongly recommended. This should be included in every record and taken as close in time to the events of interest as practical. Then the calibration steps can be reproduced on the same system as the data records and many of the recording system parameters drop out of the calculations. This provides a quite reliable system when used in conjunction with analog FM tape recording and playback into an analog to digital conversion system for direct input to a digital computer.

The minimum data requirement for a particular test will vary with its purpose from a single peak strain value to time versus strain plots for several different time scales and bandwidths. For most dynamic events, a time history is of great value and the plot should be considered the primary output, supplemented as needed by tabulated values. If the test design includes specification limits for the values, they should be included on the plots. Plots of multiple channels should have correlated time scales and if practical, a minimum number of amplitude ranges for ease of comparison. Plots should include enough baseline before the event to allow estimation of the noise and stability. If the strain is to be correlated to specific events, the events should also be indicated on the time scale. It is conventional and recommended that tensile strain is shown as positive.

Error analysis of strain measurement is not an exact science due to both the large number of error sources and the difficulty of estimating the quality of the adhesive bond, gage orientation, etc. However, it is usually possible to estimate the accuracy of the electronic components and signal conditioning. If these values are joined to the specifications for gage factor accuracy and resistance tolerance, a "best case" error estimate is possible. This may be calculated for each test, or, if the data acquisition system is fairly well standardized, documented in a general way for a typical application and referenced along with any special conditions relating to the specific test in the data documentation.

The documentation should also include a brief description of the test setup, the equipment used, and the data reduction and analysis procedures. There should be sufficient detail that a knowledgeable reader can form his/her own estimates of the reliability of the data and accuracy statement.

Information concerning the complex interrelationship between measured strains and derived magnitude and direction of the principal stress may be found in any standard reference on strength of materials.

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APPENDIX A

PRINCIPLES GOVERNING STRAIN MEASUREMENT

Strain is a fundamental engineering phenomenon, existing in all matter at all times, attributable either to external loads or to the weight of the matter itself. The terms "strain", "total strain", and "linear deformation", are commonly used in referring to the total change in any linear dimension of a body due to its own weight or the application of external force. Average unit strain (also commonly termed "strain") is defined as $\Delta L/L$, the change in length divided by the original length.

The ability of a material to support loads or external forces is usually expressed in terms of the applied stress rather than the resultant strain. Below the elastic limit of a material, the ratio between stress and strain is constant, in accordance with Hooke's Law. The constant of proportionality is called the "modulus of elasticity", and may be expressed as:

$$E = \frac{\sigma}{\epsilon}$$

in which: E = modulus of elasticity
σ = stress (kPa)
ϵ = strain (meters/meter)

Note that since strain is dimensionless, E takes on the units of stress, force per unit area, usually in pounds per square inch or newtons per square meter (kPa). This relationship may be used directly to derive stress from strain measurements if the stress is unidirectional and parallel to the measurement axis, and E is known. Moreover, several strain gages can be employed to measure corresponding components of complex strains when the basic stress-strain directional pattern is unknown.

In extreme or complex stress-strain situations, theoretical prediction is always subject to experimental verification. For this reason, methods for measuring strain are important in testing weapon systems, when parts are stressed to the highest permissible values, and in measuring linear and torsional strains engendered by the operation of vehicles. In addition, many tranducers convert input of pressure, force, acceleration, displacement, etc. into strain in an elastic element which is then converted into an electrical signal by strain sensors.

The most widely used strain-measuring device is the resistance strain gage. This is in basic form a grid of fine wire or etched foil bonded to a flexible carrier. This carrier is in turn bonded to the test item with the longer (more sensitive) axis of the grid aligned with the direction of measurement. The strain (tension or compression) on the outer surface of the material under test is transmitted by the cement and gage backing to the gage wire or foil. By virtue of this strain, the grid will increase or decrease in length. This produces a change in the electrical resistance of the grid. In suitable materials, this change is proportional to the change in length. The ratio between these two variables is called the "gage factor" of the gage and is expressed as:

$$G = \frac{\Delta R/R}{\Delta L/L}$$

in which:
R = initial gage resistance
ΔR = change in resistance due to strain
L = initial length
ΔL = change in length due to strain
G = gage factor

If the gage is subjected to axial tensile strain, the loops at the ends of the grid undergo compression in accordance with Poisson's ratio, reducing the net resistance change. The gage factor supplied by the manufacturer is determined by measurement under axial tension so that the effect of this transverse sensitivity is absorbed in the overall gage factor.

Resistance strain gages are manufactured commercially in grid sizes from 0.2 mm (0.01 in) square to 152 mm (6 in) long and as wide as 13 mm (1/2 in). Composite gages with several grids on a common backing are made for measurement of complex strains and other special applications. Gage resistance can vary from 50 ohms to several thousand ohms depending on size, material, and processing. The grid material is a metal alloy chosen for sensitivity, stability, and minimum response to environmental effects, particularly temperature. The backing material may be paper or one of several plastics, with or without fibreglass reinforcement. Materials are available for both grid and backing to accommodate special requirements such as extreme temperature, strain level, or other environmental condition.

In addition to wire and foil resistance gages, semiconductor gages are available (although not covered by this TOP). The semiconductor strain gage is characterized by a very high gage factor (as much as 175 as compared to 2 or 3 for the wire or foil gage). By virtue of this high gage factor, the gage output is large, and less amplification is required. On the other hand, this gage has a high temperature sensitivity and exhibits nonlinear behavior at high strains. The semiconductor gage is extremely useful for measuring very small strains, in the order of one microstrain or less.

A major complicating factor in use of resistance strain gages is their response to temperature as well as strain. Some useful strain-sensitive alloys have large temperature coefficients of resistance. Moreover, their coefficient of thermal expansion is often different from that of the substrate material. Both of these effects cause drift in the output unrelated to force-induced strain if there is any change in temperature. There are two main approaches to minimizing temperature error. One is to cancel the effect by use of a "dummy" gage. If similar gages are used in adjacent arms of a wheatstone bridge circuit, their outputs oppose one another. If only one senses strain, but both are exposed to the same temperature environment, the temperature-induced outputs cancel. This can be accomplished by locating one of the gages in an unstrained area, or by positioning them so that they detect strains of an opposite sense as on opposite sides of a bending member. If the stress is known to be unidirectional and uniform in the vicinity, the dummy gage can be installed adjacent to the active gage but at right angles to it. In this orientation, the dummy senses Poisson strain which is opposite in sense to the principal strain but of lower magnitude, typically about 1/3 as great. With the active and dummy gages in adjacent bridge legs the signals will add. Data reduction must be modified to take the unequal contributions of the two arms into account.

The second approach is based on the fact that the temperature coefficient of resistance of some alloys can be modified during manufacture. Normally, this is used to obtain a coefficient near zero, but for strain gage use, it can be adjusted so that the resistance change with temperature is equal and opposed to that due to differential thermal expansion of the grid and any specific substrate material. Such "self-compensated" gages have greatly reduced response to temperature effects and are available in various "ST" ratings to match many common materials. The ratings are usually given in terms of the approximate thermal coefficient of expansion of the designated substrate material in parts per million per degree F. Typical values are 6 for steel and 13 for aluminum.

The Gage Factor is also a function of temperature, with the change depending on alloy and deviation from nominal temperature. This source of error cannot be eliminated by circuit design, but can be minimized by choice of gage material and adjustment of the factor used in data reduction.

APPENDIX B

STRAIN GAGE SELECTION AND INSTALLATION

Resistance strain gages are available in a variety of combinations of diverse parameters. These include type of strain-sensitive alloy, backing (carrier) material, gage length, gage pattern (number, arrangement, and orientation of grids), grid width, self-temperature-compensation rating, and grid resistance.

The gage-selection process consists of determining the particular combination of gage parameters most compatible with the test conditions and environment. Among the factors to consider are the material and geometry of the test item, the duration and rate of loading, the maximum expected strain, the required accuracy, the duration of the test, the test environment, particularly temperature, and the availability of materials, application time, and associated instrumentation. It should be realized that the selection of a gage involves compromises. This is because parameters chosen to satisfy one requirement may work against satisfying others. Therefore, it is imperative that the most important requirements be determined, and that the gage that will most closely produce the desired results be selected.

B1 Gage material. Both wire and foil grids are made from a variety of metal alloys chosen for good strain sensitivity, low thermal coefficient of resistance, high elongation, and good stability. These include Constantan, Karma, Isoelastic, and Nichrome and analogous alloys.* Constantan is the most widely used due to suitability for a wide variety of tests in moderate environments. Karma has a slightly wider temperature range and less variation with temperature but is more expensive and more difficult to work with. Both of these alloys can have their temperature coefficient of resistance adjusted to provide a self-temperature-compensated gage for use on common structural materials.

Nichrome and platinum alloys can be used at much higher temperatures but cannot be temperature-compensated and are not generally used at temperatures where other alloys are satisfactory. Isoelastic has the advantage of a gage factor about 50% greater than the others, but very large change of resistance and gage factor with temperature.

The common backings are paper and plastic film. The paper backing is often used with "Duco" type cements for non-critical application. The plastic films include polyimide, phenolic, and epoxy, with or without fibreglass reinforcement. The polyimide film is the most versatile of these and is suitable for use from cryogenic temperatures from 204 to 316° C (400 to 600° F) at very high strain levels. Epoxy and phenolics, especially when glass-reinforced, are somewhat more stable and tolerate higher temperature but will not follow large strain levels. Gages are also available on metal foil for attachment by spot welding. For use at temperatures over 316° C, the strain grid is supplied on a removable backing for attachment by embedment in ceramic cement.

*These and various other names used herein are trademarks of various vendors, but the names are used for convenience only without endorsement.

For many dynamic measurements on mechanical systems such as vehicles and weapons a limited number of gage types will meet most requirements. One common selection is a constantan foil gage of 0.6 to 1.3 cm (0.25 to 0.5 in) grid length, temperature-compensated for the substrate material. A resistance of 350 ohms is a convenient compromise between source resistance and voltage sensitivity. A larger gage is easier to handle but will have less high frequency response. For installation in limited space, or where high frequency signals are expected, a gage length down to 1/8 inch is practical but bonding is more critical. If very low strain levels are encountered and stability with time and temperature is not required, use of "Isoelastic" alloy will provide about 50% greater output.

B2 Mounting and Connection. Adhesives used to attach strain gages to test specimens must possess sufficient shear strength after curing to accurately transmit the strain to the gage carrier and subsequently to the gage sensing element. Adhesives capable of maintaining a shear strength of 10342-13790 kPa (1500-2000 psi) over the temperature range encountered during testing are generally acceptable for strain gage applications. Some typical adhesives include:

Gage Backing Material	Maximum Temp. °C	°F	Adhesive Type	Adhesive Cure Time
Paper	71	160	Duco	48 hr RT[a], or 12 hr 49° (120° F)
All			Cyanoacrylate	1-5 min. RT
All			Epoxy RT[b]	2-16 hr RT
Hi-temp glass-reinforced	177	350	Bakelite	5-6 hr., 121° C (250° F)
Cast film hi-temp glass	316	600	Hi-temp epoxy	1-2 hrs 121° C
Removable	982	1800	Ceramic	1 hr., 316° C (600° F)

[a]RT = room temperature
[b]Caution: Many household or lab utility epoxies are unsuitable for gage application because they are too viscous to form a suitably thin adhesive layer for good performance.

Selection of conductor and insulation materials is of great importance and must be compatible with the environment of the test specimen and test area to which it will be exposed. For most dynamic tests at moderate strain and environmental conditions, copper wire is suitable. Although copper is low in resistance, its large temperature coefficient and poor resistance to fatigue and corrosion make it less than ideal in severe or extended tests. The following are a few examples of alternate strain gage lead materials:

Conductor	Operation Temperature Stable	Operation Temperature Maximum
Nickel-clad copper	371° C	538° C
Stainless steel-clad copper	427° C	704° C
Nickel-clad silver	538° C	816° C
Nichrome	371° C	927° C

In conjunction with the conductor material, a lead insulation material should be chosen that is compatible with the environment to which the leads will be exposed. The following are some typical examples:

Polyvinylchloride	-50° to 66° C
Polyethylene	-50° to 93° C
Irradiated polyethylene	-50° to 204° C
Teflon	-250° to 260° C
Polyimide film	-250° to 427° C

Above 427° C, glass or quartz fiber sleeving, glass or ceramic beads are used to insulate the conductor materials.

In attaching leads to strain gages, solder is the most widely used material. A list of typical strain gage solder materials is:

Alloy	Melting Temp	Recommended Operating Temp
60% tin, 40% lead	182° C	-73° to 149° C
96.5% tin, 3.5% silver	218° C	-73° to 191° C
2.5% silver, 97.5% lead	304° C	-73° to 260° C
tin-free silver alloys	316° C	-196° to 316° C

When soldering gage leads, particularly with thin foil gages, it is a good practice to heat-sink the gage lead between the gage and the soldered connection by pressing the lead with a good heat-sink material (brass or copper rod, screwdriver, etc.). A temperature-controlled soldering iron is also valuable in avoiding damage to the gage.

APPENDIX C

SIGNAL CONDITIONING

Signal conditioning for resistance strain gages may take many forms depending on the test requirements, desired flexibility, cost, and final destination of the data. Since a voltage output is the form most often desired, signal conditioning will usually include at least provision of excitation current to the gage, and elimination of the voltage developed across the initial resistance. Additional functions frequently included are provisions for multiple active gages, introduction of calibration signals, limitation of bandwidth, and amplification of the small strain-generated output to a level suitable for recording or display. These functions may all be included in one unit, or distributed in various ways into several units, e.g., power supply, bridge balance and calibration unit, and amplifier.

One of the oldest and simplest forms, suitable for dynamic strains down to a fraction of a hertz at the low frequency end, consists only of a power supply, series resistor, gage, and a coupling capacitor. The series resistor typically was made several times larger than the gage resistance, so that the current through the gage was nearly constant. The voltage across the gage was then proportional to its resistance. The voltage due to the initial resistance was blocked by a coupling capacitor, and changes in gage resistance under dynamic deformation caused voltage changes that were coupled through the capacitor to a readout device.

A variation on this circuit is practical with modern equipment. The power supply and series resistor are replaced by a constant-current supply and the capacitor is replaced by a floating voltage source which is adjusted to cancel the voltage drop across the gage resistance (fig. C-1). This arrangement provides the maximum output signal possible for a single gage, has DC response, is insensitive to line resistance, allows for convenient calibration in terms of resistance change, and provides an output voltage linear with resistance over a wide range of variation.

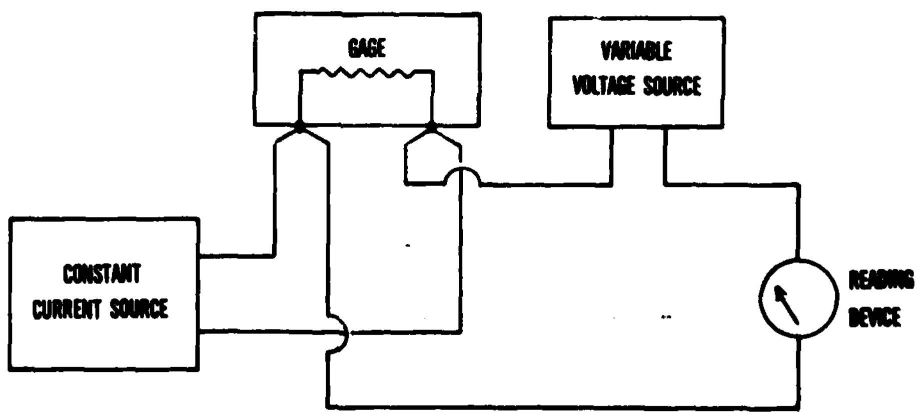


Figure C-1. Constant Current Circuit for Single Gage

Its main disadvantage is that it is not easily modified to accept multiple gages in other than series configuration. More elaborate systems have been designed using active elements, power supplies and amplifiers, to circumvent this limitation, but the complexity increases rapidly. These systems will not be discussed further here.

C1 Bridge Circuits. The vast majority of strain gage installations use one form or another of the Wheatstone bridge circuit. In classic form, this consists of four resistive "arms" in a ring with excitation voltage or current applied at one set of diametrically opposed junctions, and the output voltage taken at the other set (fig. C-2).

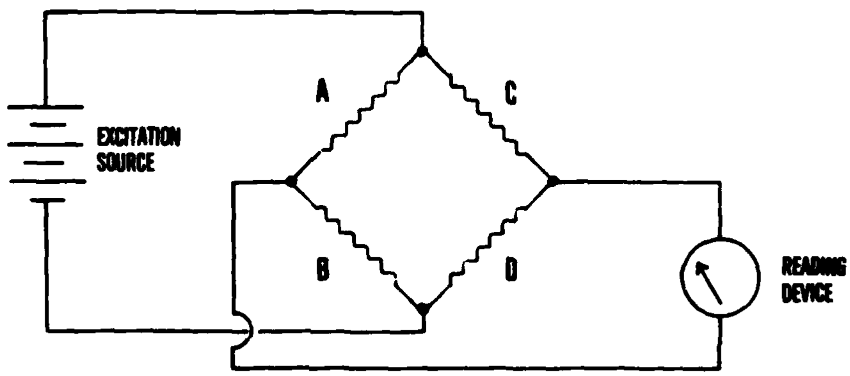


Figure C-2. Wheatstone Bridge

Regardless of the value of the resistors or excitation, if the ratios of the resistances in each path between the excitation points are equal, i.e., A/B=C/D, the output voltage from the bridge will be zero. In the original use of the bridge circuit for resistance measurement, one arm contains the unknown resistance. One or more of the remaining arms is varied to produce zero output. The value of the unknown arm can then be calculated from the known values of the remaining arms.

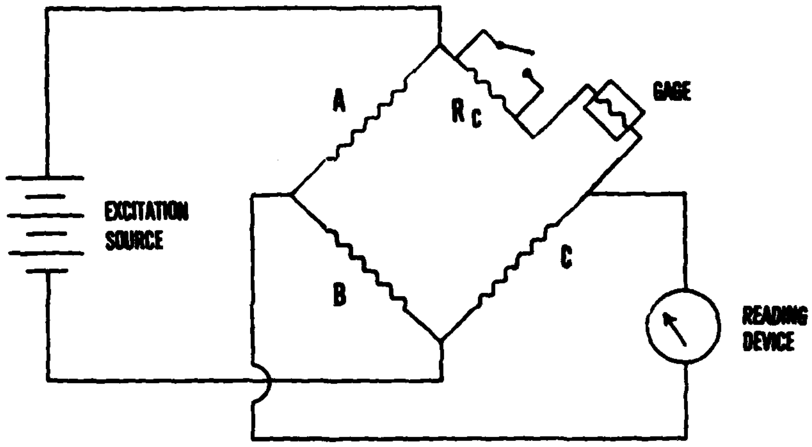
For strain gage applications, however, rebalancing during measurement is practical only in limited cases when strain varies very slowly. Most dynamic strain measurements are made with the bridge in an unbalanced mode. Bridge elements can be adjusted to establish an initial balance condition of close to zero output, but are not subsequently changed. Instead, as strain changes the resistance of the gages in one or more bridge arms, the output voltage is allowed to change. This varying voltage is recorded as a measure of the strain. This means that not only the resistance values in the bridge but the excitation voltage and the sensitivity of the output device effect the apparent strain. These values can be measured and included in calculation or it is frequently convenient to include all the variables implicitly by provision of a means for simulating a known resistance change at the bridge. The resulting signal is then recorded and processed in the same way as the test data and so the data can be properly scaled in terms of the amplitude ratios. Many of the details of signal conditioner design relate to the various ways in which this can be done. Some provision for adjustment of bridge output (balance) under static initial conditions is also usual.

The choice of calibration and balance methods is related to another classification of strain bridges, into quarter-, half-, and full-bridge configurations. These designations refer to the fraction of the bridge circuit that is external to the signal conditioning unit. For a single active strain gage, the quarter bridge arrangement provides the simplest installation and wiring. Only two wires are needed for many applications and the other three-bridge arms are contained in the signal conditioner. This does not allow for a temperature-correcting dummy gage, or for more than one active gage unless they can be connected in series and treated as a single arm. In a half-bridge configuration, two adjacent arms are external to the conditioner, usually between the excitation lines, and the two remaining arms are internal. The external arms may be two active gages sensing opposite strains, one active and one dummy gage, or one gage and a fixed resistor. At least three wires are required. In a full-bridge configuration, all four arms are external to the signal conditioning. This provides maximum flexibility for use of multiple active gages but makes single active gage installations considerably more complex. It requires at least four wires, but more are often used to reduce errors. Transducers based on strain gage sensing are usually supplied as full bridges. Most commercial signal conditioning equipment can be used with any of these bridge configurations by installation of internal resistors or jumpers, and some provide switch selection of some variations.

<u>C2 Calibration and Balance</u>. Calibration circuits can be classified as series or shunt resistance change, or voltage insertion. The first two of these directly affect the resistive balance of the bridge circuit. Insofar as they simulate the resistive effect of a known amount of strain, they exercise the entire measurement system in place. The effects of excitation voltage, bridge configuration, amplifier gain, recorder characteristics, etc., are all included in the resulting output. Only two basic conditions need to be satisfied to ensure that such calibration accurately reflects the response to a known amount of strain. One is that conditions remain the same from the time the calibration signal is recorded until the events of interest. The second and more subtle requirement is that the selected circuit change truly produces the predicted equivalent strain signal. It will be seen that there are many reasons why this may not be so.

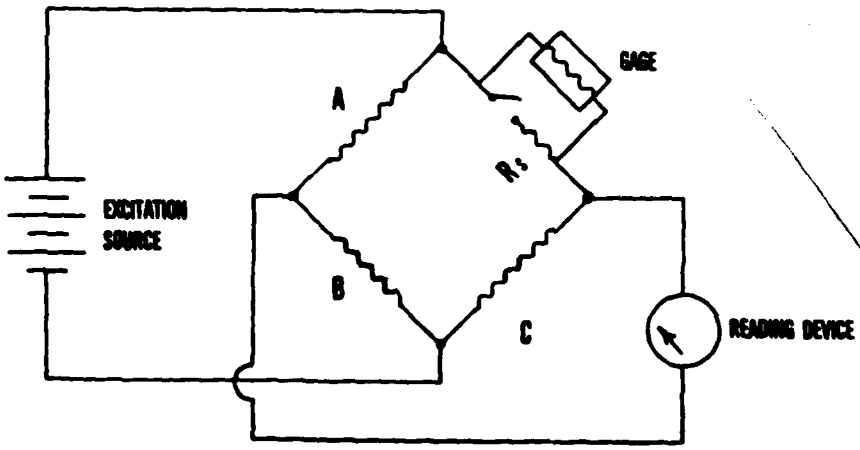
Series calibration attempts an exact substitution of resistance change within the active leg for that expected of the strain gage. A simplified example is shown in Figure C-3(a).

Regardless of the values in the rest of the circuit, switching the calibration resistor RC in and out of the circuit will generate exactly the same output as a corresponding change in the active gage, X1. However, there are some practical difficulties in using this system, and it rapidly loses its advantages as more active arms are used. Few commercial signal conditioners make provision for series calibration.



a. Series Calibration
Figure C-3. Simplified Calibration Circuits

Some of the practical problems with the series circuit are avoided by the shunt calibration circuit shown in Figure C-3(b). If the resistance of both the bridge arm and the shunt RS are known, the equivalent resistance change can be calculated. The shunt can be placed across any arm and places no restriction on the number of active or external arms. It is subject to a number of potential errors and its very flexibility complicates the analysis.



b. Shunt Calibration
Figure C-3. Simplified Calibration Circuits

The dominant variables outside the bridge itself in strain measurement are the excitation voltage and system gain, often the product of several individual adjustments. Voltage insertion systems attempt to account for one or both of these with less circuit complexity than resistive simulation. The simplest form consists of substituting a known voltage for the bridge output. This calibrates overall gain only. The more satisfactory methods rearrange the bridge circuit in one of several ways so that the resulting calibration signal is specified in millivolts of output per volt of excitation. Some of these effectively include variations in bridge resistance and wiring resistance in the result. (Such circuits have at times been called "series calibration" in the technical literature but here, that designation is reserved for series resistance changes.)

Balance circuits may also be described as series or shunt resistance, and voltage insertion and the circuitry are analogous. Simplified circuits are shown in Figure C-4. Variable resistances R_B are used in series (fig. C-4a) or shunt (fig. C-4b) modes to rebalance the bridge resistively. In the voltage insertion mode (fig. C-4c), the initial unbalanced voltage is cancelled by a floating voltage source.

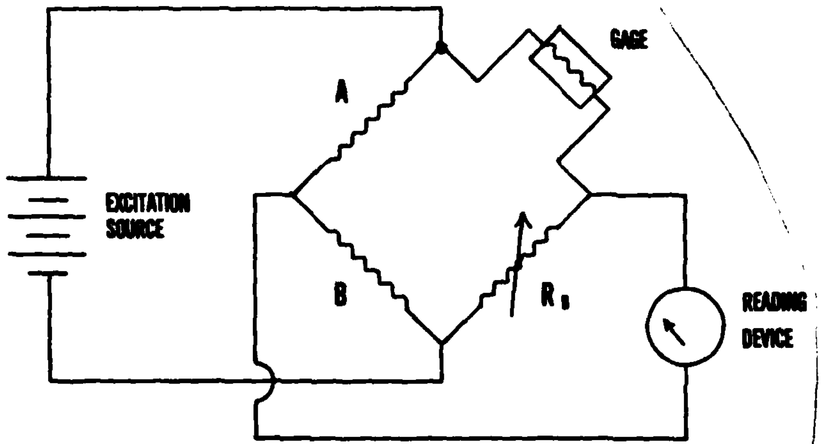


Figure C-4. Simplified Balance Circuits a. Series

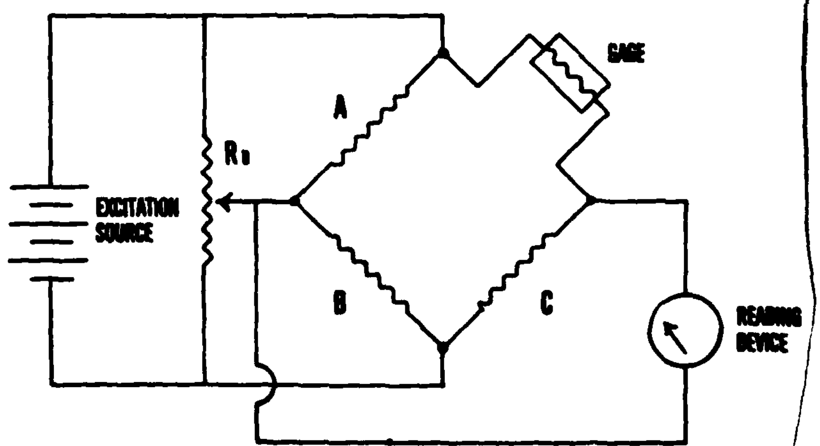


Figure C-4. Simplified Balance Circuits b. Shunt

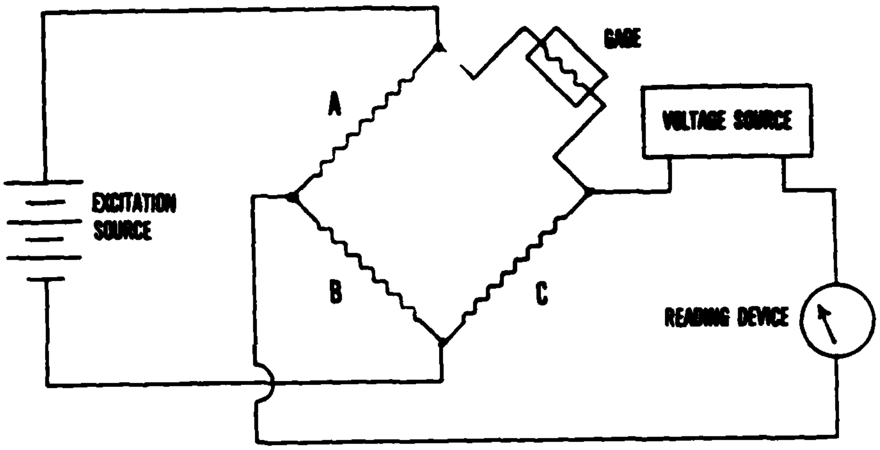


Figure C-4. Simplified Balance Circuits c. Voltage Insertion

The shunt balance in one of several variations is used almost exclusively in commercial equipment, but it has one fundamental liability: in greater or lesser degree, it changes the ratios and resistive sensitivities of the shunted arms, usually in an undocumented way. Particularly it can interact with the calibration circuit to cause unsuspected errors. Both the series balance, used in some custom equipment, and the voltage injection system have some desirable characteristics but are limited in application and in the case of voltage injection, add considerable complexity.

AC excitation of strain gages has been used in some systems with narrow band amplifiers and phase-sensitive detectors ("carrier systems") for stable low-noise performance at high gains. They have limited applicability to dynamic strain measurements due to their limited band width. Excitation with triggered or periodic unidirectional voltage pulses is sometimes used to obtain extreme sensitivity when short-event duration or effectively time-sampled data are acceptable. Use of low duty-cycle pulses permits very high instantaneous excitation voltage with moderate power dissipation.

In theory, these balance and calibration categories and their variations could be combined in a very large number of ways, any many variants have in fact been used for special purposes. However, the vast majority of strain work is done with a very limited subset. Two combinations widely used at TECOM installations are discussed below.

<u>C3 Shunt Balance-Shunt Calibration</u>. This is nearly a standard configuration. It is simple and economical and offers maximum flexibility. There is generally a provision in the conditioner for mounting resistors to form any or all of the bridge arms. Mounting for from two to ten calibration resistors with switching and/or jumpers to allow shunting of selected arms provides for choice of calibration polarity. In some cases, there is provision for double-shunt operation in which the calibration resistance is split and applied simultaneously across opposite arms. The balance network is usually elaborated from the simplified figure above only by addition of resistors on both ends of the potentiometer, or from the wiper to bridge corner, or both. This reduces balance range but also

improves resolution and minimizes loading errors. Sometimes these buildout resistors are field-replacable, but such modifications should be made cautiously since a poor choice can introduce significant error.

Vendor literature varies somewhat in suggesting particular configurations, but generally, the arms shunted by the balance network are fixed resistors in quarter- and half-bridge applications. This reduces desensitizing of the active arms, but presents a dilemma in which arm to shunt for calibration. If the calibration shunt is placed across the active gage, its equivalent value will vary with the gage resistance. If the shunt is placed across the fixed arm, its effect is changed slightly by the position of the balance control. This error may be negligible if the unbalance is small and the balance network well designed, but should be considered.

If long lines are used between the conditioner and test structure, line resistance can cause errors in several ways. As long as calibration shunts internal arms, resistance in the external circuit adds to unbalance and desensitizes the active arms in proportion to the voltage drop, or equivalently, by the fraction lead resistance is of the total of gage plus line resistance. If the calibration resistance shunts an external arm, additional error is caused by the fact that gage current causes a voltage drop along the line between the calibration resistor and the arm. This error can be avoided by use of a 6-wire gage connection (fig. C-5).

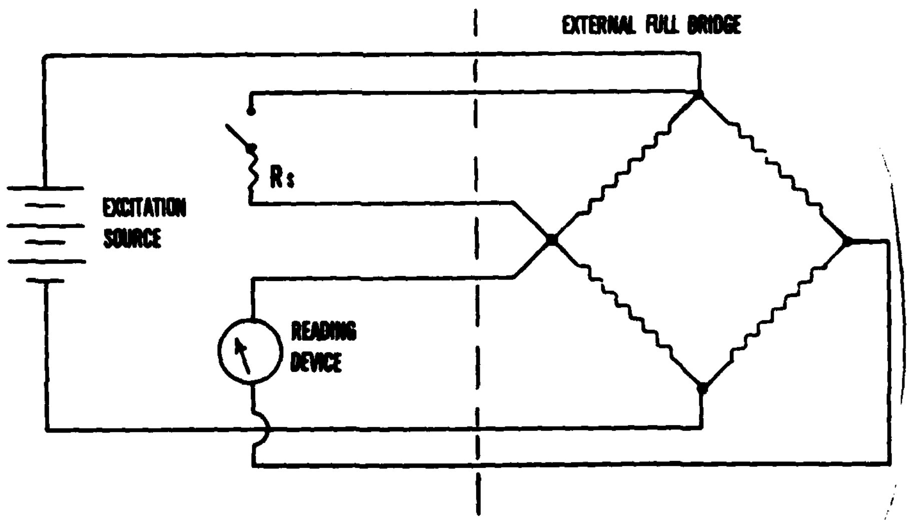


Figure C-5. Use of Separate Shunt Calibration Leads

<u>C4 Series Balance and Calibration.</u> For use with single active arms and, with some care half-bridges, the series-balance/series-calibration scheme has many advantages. A typical circuit is shown in Figure C-6.a.

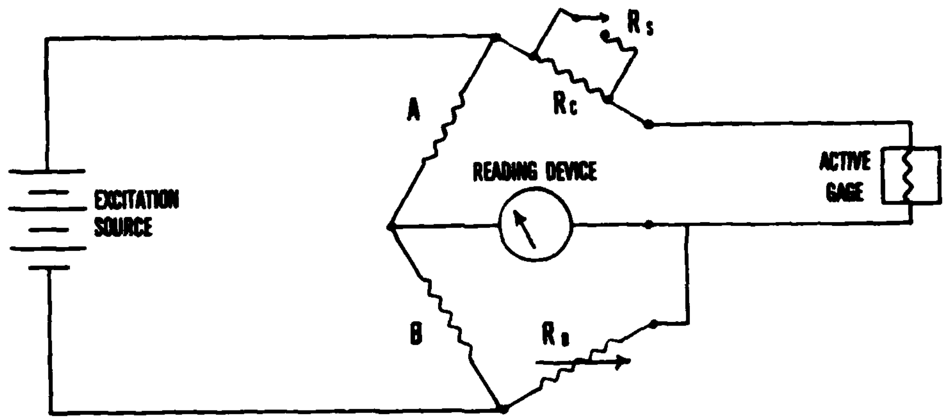
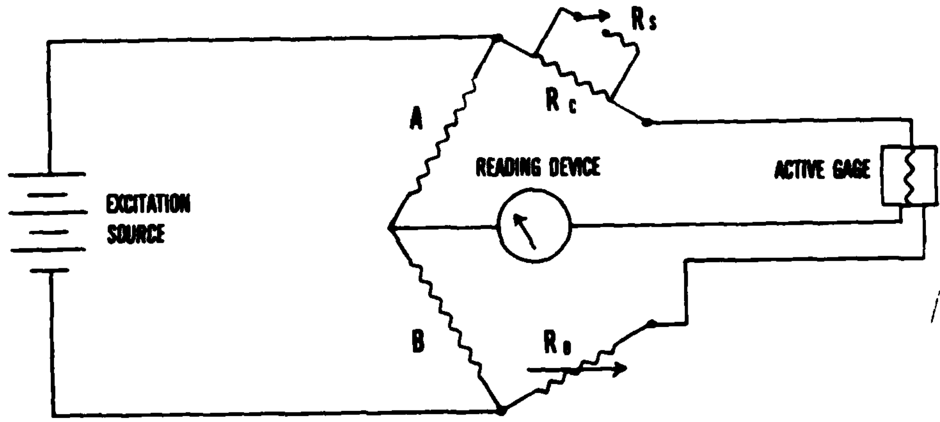
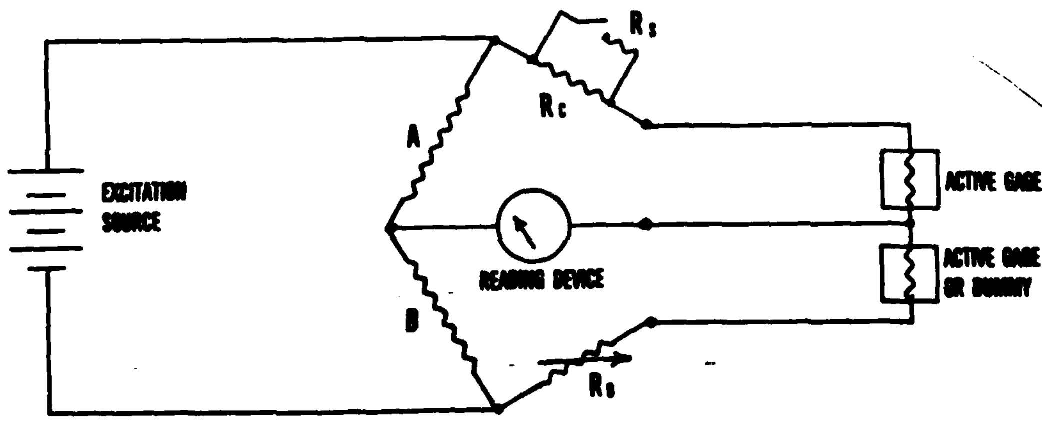


Figure C-6. Series -Shunt/Series Calibration Circuits a. 2-wire connection



b. 3-wire connection



C. Half-Bridge Connection

Resistors A and B form a precise 1:1 ratio. Resistance R_B is the balancing element. It may consist of several decades of stable resistors adjustable over a range from 0 to 1100 ohms. In the case of a single active arm, R_B forms the entire dummy arm. Resistor RC is typically 25 to 50 ohms and is always in series with the active gage. The calibration step is generated by shunting R_C with one or more resistors R_S. This configuration is used in preference to simply switching the series resistor in and out to avoid errors due to switch contact resistance and the need to use precise low-value resistors which are difficult to make and measure. The values of the shunting resistors are calculated to provide convenient and precise resistance changes in the combination. This arrangement gives an exact simulation of a known change in the resistance of the active strain gage, including any effects of excitation change or lead resistance. For a single arm, not even the ratio A:B needs to be known. Although a two-wire connection will not lead to a calibration error, the large temperature coefficient of copper wire may cause undesired baseline drift with varying ambient temperature. The circuit configuration shown above permits use of a three-wire connection as shown at (b) which will largely cancel this effect.

The same circuit can be used with half bridges with either two active or one active and one dummy gage if the ratio A:B is known to be precisely 1. The absence of a shunt balance network across the ratio arms permits this determination with ease and assurance. In this mode (fig. C-6.c) the balance resistance R_B will be adjusted close to the value of R_C.

<u>C5 Excitation</u>. Excitation power for strain gage bridges is typically provided by an electronically regulated supply. This may be either constant voltage or constant current, and may power a single bridge, or several of them in parallel. The choices are both technical and economic. Constant voltage supplies have been more common and therefore more highly developed and lower in cost. Constant current excitation has the advantage that bridge output voltage is not affected as much by long lines, and in some circumstances, bridge linearity is improved, but it has not been widely adopted except for semiconductor gages. A common supply for several bridges is generally less costly than individual supplies, but requires the use of differential amplifiers which may be more expensive than would otherwise be required. A common supply also increases the risk that trouble in one bridge will affect others. Individual supplies can be used with remote voltage sensing whereby, at the cost of an extra pair of wires, the voltage is regulated at the bridge rather than the supply terminals. This eliminates the effect of lead resistance on sensitivity. Caution is needed in evaluating excitation supplies for high-frequency applications as some regulators with good low-frequency performance will not follow rapid load changes well. For maximum benefit from individual supplies, very good isolation from power lines and ground is required.

APPENDIX D

DATA REDUCTION AND ERROR ANALYSIS

D1 Operational Modes. The reduction of strain gage data and identification and analysis of error sources depend on the choices made in test design about bridge configuration, signal conditioning equipment, calibration signals, and recording method. Although there is no specific division of techniques between them, it is possible to identify two general classes of approach to operation and analysis. One mode of operation might be called absolute because it depends on calibration and documentation of many intermediate factors such as bridge configuration, excitation voltage, amplifier gain, recorder sensitivity, playback gain, etc. Once these factors have been determined, a measurement of final output voltage can be converted to input strain by computation. The other mode depends heavily on provision in the system of a calibration signal which accurately simulates a specific quantity of the input variable such as strain. If this signal is recorded and reproduced in the same way as the test data, the data reduction consists primarily of establishing an amplitude relation between the calibration signal and the test data. This eliminates a lot of uncertainty and bookkeeping. This relative mode has been widely used in multi-channel analog work. Both methods have advantages and disadvantages, and either can be made to work with care and insight. They are subject to some common and some different error sources. Necessary computation and sources of error in Wheatstone bridge will be applicable to both modes of operation will be discussed.

D2 Bridge Output Voltage. The analytical problem in both absolute mode and voltage insertion calibration is determination of the relation between strain and bridge output. For equal-arm bridges and small deviations from balance, a frequently used equation holds:

$$\epsilon_i = \frac{e_o/e_i}{\frac{N}{4} \times G}$$

in which: ϵ_i = indicated strain
e_o = output voltage
e_i = input (excitation) voltage
N = number of active arms
G = gage factor

Note that both the voltage ratio and the strain are given in consistent units, i.e., volts/volt and meters/meter. If e_o/e_i is expressed in millivolts per volt and ϵ_i in microstrain, the right side of the equation must be multiplied by 1000. If Poisson dummy gages are used, their contribution to the output is accounted for by using the value of Poisson's ratio in place of unity in adding the number of active arms, N. For example, if one active and one Poisson dummy gage are mounted on steel, for which Poisson's ratio is about 0.3, N would be set equal to 1.3.

For any case in which adjacent bridge arms are not varied in a complementary manner, which includes single active arms and half and full bridges with inactive or Poisson dummies, the bridge output voltage is measurably nonlinear with respect to strain at some practical strain levels. The error can be ignored for many engineering measurements or corrected with the following expression:

$$\epsilon = \epsilon_i \left(1 + \frac{G \times \epsilon_i}{2 - (G \times \epsilon_i)}\right)$$

in which: ϵ = corrected strain
ϵ_i = indicated strain

If the calibration system injects fixed voltages, or in absolute mode, the excitation voltage must be known or measured. Line resistance may be taken into account by measurement at the bridge if it is external, or if the line resistance is known, a correction calculated.

If a calibration system is used that ostensibly provides values in millivolts per volt, the equations are convenient as they are, but care is needed to determine whether the voltage drop in long lines is accounted for. If not, it can be measured and the deviation from nominal used to calculate a correction. Calculation of output is much more difficult if the bridge is asymmetrical or a single active arm is used in a two-wire arrangement. In a computer-based system, it may be feasible to program an exact solution to the generalized bridge equations and input individual arm and lead resistance values. The effects of the balance network could also be taken into account.

D3 Series Resistive Calibration. The only values needed to calculate the strain value of a calibration step are the delta-R value of the step, the gage resistance, and series gage factor. For many applications, it is sufficient to take the manufacturer's package values for the latter two. The relevant equation is obtained by rearrangement of the basic strain gage equation. It is:

$$\epsilon_{eq} = \frac{\Delta R/R_g}{G}$$

in which: ϵ_{eq} = strain equivalent of the calibration step
ΔR = resistance change of the calibration step
R_g = initial gage resistance
G = manufacturer's supplied gage factor

Potential error sources include change in the initial resistance due to mounting, detectable and correctable by in-place resistance measurement, and the inevitable output nonlinearity. If the calibration step approximates the expected strain signal in level and polarity, this will be minimized, or if maximum precision is desired, several steps over the range of interest can be recorded and a curve fit to the values.

D4 Shunt Resistive Calibration. The most widely available resistive simulation in commercial signal conditioning equipment is the resistive shunt. It is simple in concept and easy to implement, but because of the large number of possible circuit configurations, it can be difficult to analyze. In general, a selected resistance is shunted across an active gage or dummy arm. In the simplest case, the equivalent ΔR is given by:

$$R = R_g - \frac{R_g \times R_C}{R_g + R_C}$$

in which: R_C = calibration resistance
R_g = resistance of shunted arm
ΔR = resistance change caused by shunting R_C across R_g

This shunt method of calibration will introduce errors caused by lead resistance if the gage leads are long. These errors in resistance change, ΔR, can be accounted for by using the following equation:

$$\Delta R_C = \Delta R_i \left[\frac{(R_g + 2R_L)^2}{R_g} \times \frac{R_C + 0.5R_g}{R_C + 1.5R_L + 0.5R_g} \right]$$

in which: R_g = gage resistance; ΔR_C = corrected resistance change
R_L = lead wire resistance; ΔR_i = indicated resistance change
R_C = calibration resistance

An alternate to the above expresses the step value in strain when a single active gage is shunted:

$$\epsilon_{eq} = \frac{R_g}{G(R_C + R_g)}$$

in which: ϵ_{eq} = strain equivalent of the step
R_g = gage resistance
R_C = calibration resistance
G = gage factor

D5 Additional Factors Affecting Accuracy. When strain gages are installed on sharply curved surfaces, the apparent strain differs from the apparent strain on a flat surface. As a general rule, this incremental apparent strain can be neglected when the radius of curvature is 1.3 cm or greater. On installations of smaller radius, corrections may be desirable, depending upon the accuracy required.

Transverse gage sensitivity is the response to strains that are perpendicular to the primary sensing axis of the gage. Introduction of error from strain perpendicular to the main axis of plain wire gages can easily be calculated from gage geometry. In foil strain gages, the transverse sensitivity results from almost every aspect of grid design and gage construction. Gage manufacturers attempt to reduce the transverse sensitivity in their design of foil gages, and unless extreme accuracy is required, this error can be neglected.

Gage Length. Strain measurements are usually made at the most critical points on the structure being tested. The most highly stressed points are associated with stress concentrations where the strain gradient is quite steep and the area of maximum strain is restricted to a very small region. The strain gage tends to integrate or average the strain over the area of the grid and the average of non-uniform strain distribution will be less than the maximum strain. Therefore, grid area exceeding the area of maximum strain can introduce considerable error in the measurement.

Frequency Response. In dynamic strain measurements, the low frequency response is not generally a limiting factor, except for zero-balance drift. High frequency response must often be considered. The fundamental limit is set by the gage length. A high frequency signal represents a stress wave in the structure which, in the elastic region, will have a definite wave length related to the velocity of sound in the material. As this wave length becomes a small multiple of the gage length, averaging the wave form begins to be significant. However, the frequency at which this occurs in metals for reasonable gage lengths is quite high, e.g., more than 100 kHz for a 1/4-in. gage on steel. Usually, electrical factors in the signal conditioning and wiring will impose lower limits. The dominant constraints for DC systems are amplifier and recorder band width and cable capacitance. Even assuming perfect excitation regulation, the bridge resistance comprises the source resistance which must drive the cable and amplifier input capacitance. If long lines are required, this load can be important. For example, a 500-ft cable might present a load of 10 nanofarads to a 500-ohm bridge. The time constant is then 5 microseconds for a -3db frequency of 55 kHz. Different or longer cable, higher bridge resistance, or imperfect regulation of the excitation could all reduce this frequency still more. If response beyond about 10 kHz is required, consideration must be given to careful analysis or electrical testing to verify system performance.

APPENDIX E

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