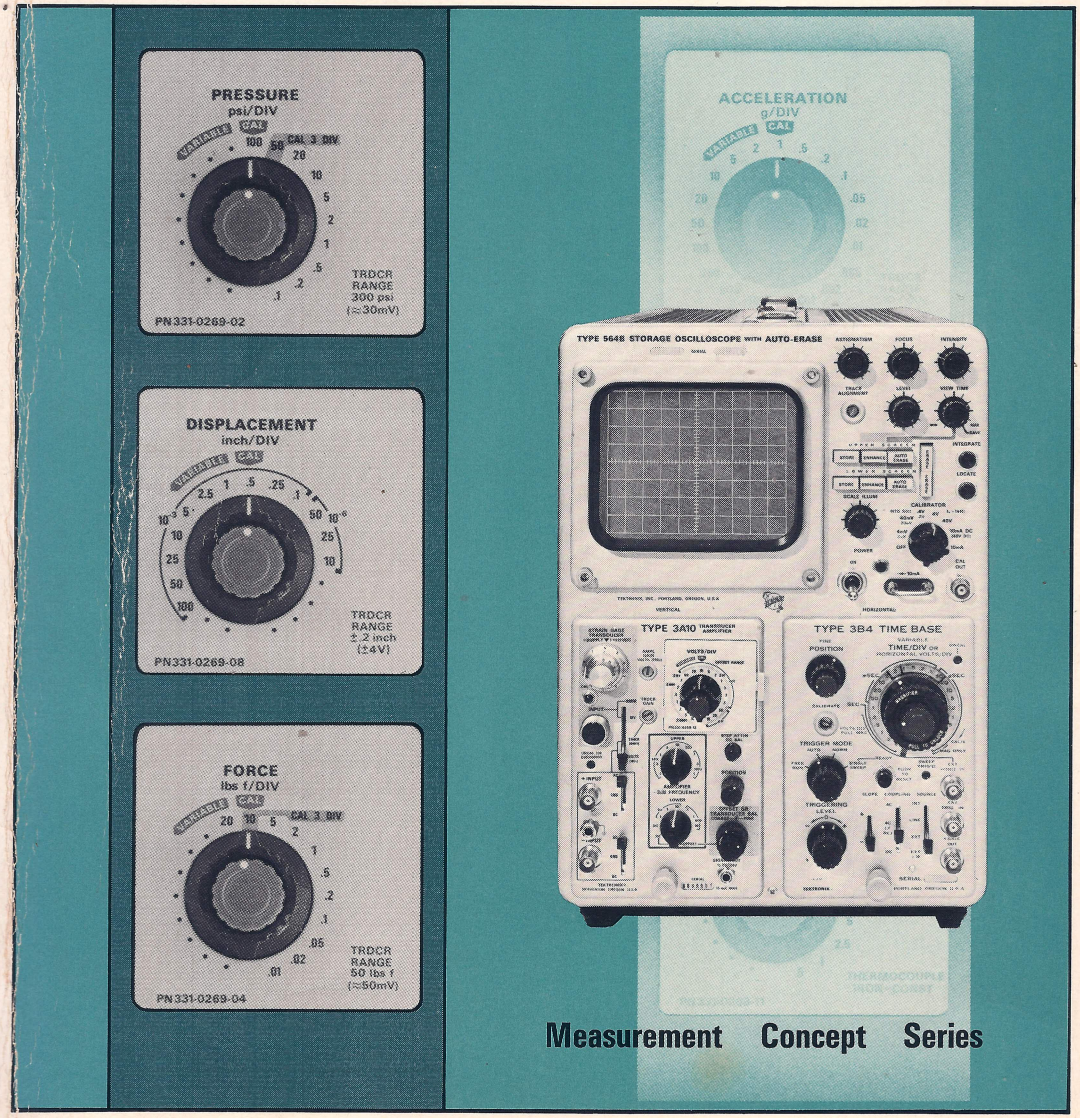
# Transducer Measurements



# TRANSDUCER MEASUREMENTS

BY

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TEKTRONIX®

MEASUREMENT CONCEPTS

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# INTRODUCTION

The cathode-ray-tube oscilloscope has long been recognized as one of the most versatile tools available for the investigation and measurement of time-varying electrical phenomena. With the help of a sensing device called a *transducer* an exciting new field of measurement applications is brought within the reach of the oscilloscope user. This field is broadening rapidly as new devices and techniques are developed. At present, it is hard to exaggerate the wide variety of physical quantities, properties, and conditions that can be measured with instrument transducer systems. One of the objectives of this publication is to reveal the scope of the transducer measurement field in the expectation that greater utilization may be made of the oscilloscope's measurement potential.

Although there is considerable literature available on transducers and associated instrumentation, little attention has been devoted to the needs of those whose background is primarily electronics-oriented. It is hoped that the information supplied in this book will provide useful information to readers in all occupations in which physical measurement plays a significant role.

The first four chapters are devoted primarily to theoretical and operational concepts -- in other words, to the quantities, properties, conditions, etc., which may be measured with the aid of a transducer and to the physical principles involved in the transducer's operation. In addition, a short introduction to transducer measurement systems is presented to round out the general concept.

Chapters Five and Six are devoted primarily to Tektronix transducer instrumentation, including detailed descriptions of transducers, appropriate instrumentation for their employment and typical application techniques. An appendix, containing conversion tables, material characteristics and other information useful in transducer measurement applications is also included.



# 1

## CONCEPTS OF QUANTITATIVE MEASUREMENT

The concepts governing the art of quantitative measurement are basic to scientific discipline. Until man began to test his theories by performing experiments and to *measure* his results, his "science" was largely a matter of conjecture. Even the magnificent contributions of Newton and Einstein would today be classed with those of Aristotle had they not been verified by experiments involving countless painstaking measurements. In fact, proof of the validity of a given theory has often had to be postponed until appropriate measuring instruments or techniqes were developed.

Modern technology also leans heavily on the art of measurement. The production of interchangeable components, essential to mass production, would be impossible without accurate measuring devices. Automatic machines now perform the labor of dozens of skilled workers, with little or no supervision. One of the key mechanisms of such *automation* is the *servo loop*, in which a fed-back *measurement signal* nulls out a *process-command signal* when the proper dimension has been attained.

servo loop

Those charged with the responsibility of taking accurate measurements or calibrating measuring instruments must delve more deeply into the fundamentals of dimensional theory than those less technically oriented. This is especially true in the field of transducer-aided measurements, where an appreciable number of energy translations are sometimes required to convert the quantity under investigation (*measurand*) to a visible analogue or digital registration (*readout*).

In the first place, it is always important to realize that in a large majority of cases, the measurand itself is seldom the quantity which is read. Few, if any, physical phenomena directly evoke a quantitative response in the eye. What the eye does in most measuring situations is to detect *coincidence of position* between a mark, meter needle, liquid level, oscilloscope trace, etc., and a mark on a calibrated scale. Thus a carpenter locates the point on his rule which coincides with the end of a board. Because the rule is divided into equal increments, the board's length can be expressed *in those increments*.

coincidence of position

measurement increments

The *precision* of such a measurement depends on the maximum resolution obtainable: that is, (1) how clearly the incremental marks are defined, and (2) how closely adjacent two marks can exist and still be distinguished separately by the eye of the reader. The first limitation is defined by the quality of the rule. The second is defined by the acuity of the individual's vision.

precision

resolution

The *accuracy* of the same measurement is determined by the *precision* with which the measurement can be made, and the *degree to which the increments* inscribed on the rule *conform to a standard unit* of length under the conditions of the measurement.

accuracy

A standard unit is one which, through wide agreement in a community, is defined in terms of an actual object or a naturally occurring condition, and by means of which all devices for measuring that quantity can be calibrated.

standard unit

If the rule were marked off in purely arbitrary units, the board could still be measured *with the same precision*, in terms of those increments. The important deficiency of such a measurement, however, is quite obvious -- it would mean nothing to someone who did not possess a similarly marked rule. And although a good carpenter could still erect a perfectly sound structure with such a rule, he could never follow an architect's blueprint.



It would appear that with so many measuring units in everyday use, a correspondingly large number of standard units would be required. Fortunately, this is not the case. A closer examination of the situation will reveal that only three *fundamental* quantities exist in nature. These are *length*, *mass* and *time*. All others are *derived* quantities and can be defined in fundamental units. For example, a gallon is a unit of liquid measure. There is no practical way to define a *standard* gallon, however, except in terms of the dimensions of the standard gallon's container. These dimensions must necessarily be given in units of length ($l$), or units of volume -- and volume, of course, is simply $l^3$.

fundamental quantities

derived quantities

The same situation is encountered in defining a standard unit of weight. Since weight is the force exerted on a mass ($m$) by the acceleration of gravity ($g$), weight varies directly with gravitational attraction. Therefore, the definition of a weight standard must specify the unit of mass and the value of gravitational acceleration, or

$$W = mg = \frac{ml}{t^2} = mlt^{-2}$$

As a final example, consider the problem of defining a standard unit of power. Power is the energy expended in a process per unit time. This relationship can be expressed

$$P = \frac{E}{t}$$

Energy itself is expended whenever work is accomplished, and work itself is defined as the product of force and the distance (in the direction of the applied force) over which the force is applied. Thus,

$$E = Fl$$

and

$$P = \frac{Fl}{t}$$

It now remains to define force. It was shown as a special case that weight is the *force* exerted by the *acceleration* of gravity acting on a *mass*. The general expression for force is

$$F = ma$$

and since $a = \dfrac{l}{t^2}$

$$F = m\frac{l}{t^2} = mlt^{-2}.$$

When this value is substituted in the power equation, it is reduced to its basic terms

$$P = \frac{m\left(\dfrac{l}{t^2}\right) l}{t}$$

$$= \frac{ml^2}{t^3}$$

and since distance is measured in units of length, the equation in fundamental unit form becomes

$$P = ml^2t^{-3}$$

The procedures just followed are those of *dimensional analysis* and are very useful in checking the validity of any equation, regardless of the particular units or system of units (see below) used in the equation. For example, assume that from an analysis of the behavior of an unbalanced rotating wheel, an equation for centripetal force emerged in the form

$$F = \frac{Wv^2}{al}$$

To check the dimensional validity of this equation, each term must be reduced to its fundamental unit form. It would then appear

$$(mlt^{-2}) = \frac{(mlt^{-2})(lt^{-1})^2}{(lt^{-2})(l)}$$

After reduction to its lowest terms, this would become

$$(mlt^2) = (mlt^2)$$



and could be considered *dimensionally* correct. This does not guarantee that the equation is valid. However, if the equation is *not* dimensionally correct, it cannot be correct in any sense.

constant of proportionality

Another important point to keep in mind when working with physical equations is that a majority of the equations contain a hidden *constant of proportionality*. Thus, force may be expressed mathematically

$$F \propto ma \text{ or } F = kma$$

where $m$ = mass, $a$ represents acceleration, and k is the constant of proportionality. If force is expressed in dynes, acceleration in cm/s$^2$ and mass in grams, the equation can be written

$$F = ma$$

since the proportionality constant is unity.

coherent systems

This is because the units are taken from a *coherent system*; that is, one in which the product or quotient of any two quantities in the system is the *unit of the resultant quantity*. For example, in a coherent system, the units of area should be the product of unit length. If unit length is the meter, area must be expressed in square meters, and so forth. Other units of area, such as the square foot, acre, square mile, etc., clearly do not fit into such a system.

The advantages of a single, universally accepted system of units are too obvious to merit prolonged discussion. Unfortunately, many factors, including those of national pride, adherence to tradition, and others equally irrelevant, have obstructed progress toward this end. As a result, in the English-speaking countries alone, weight is still measured in grams, grains, carats, ounces, pounds, drams, scruples, pennyweights, short tons, long tons, and so forth. To add to the confusion, a single term, as popularly (if incorrectly) used, may represent a number of different quantities. For instance, the term "pound," depending on the circumstances, may refer to weight, pressure, mass, force, or even a unit of monetary exchange.

In the course of history, a number of unit systems have been developed to clear up this confusion. Although these systems have the advantages of coherence, their number still presents problems to the scientific, engineering and industrial communities. Tables of conversion factors are still necessary to convert units of one system to those of another. Furthermore, there persists within certain segments of society, a tendency to hold to traditional units in spite of their nonconformity with established and accepted unit systems.

Accordingly, the measurement technician must be acquainted not only with several systems of units, both modern and obsolete, but also of any variations in terminology which persist within the group with which he is associated.

SI system

At the present time, a strong international movement is underway which, if successful, will culminate in establishing a single, universally accepted system of units. Abbreviated *SI* in all languages from "Systime Internationale d'Unites" (International System of Units) this system has been developed by the International Organization for Standardization (ISO), a nontreaty organization comprised of the national standards bodies of fifty-six nations. Definitions of units, together with the rules for their use, are set forth in the organization's "Recommendation R-1000." The advantages offered by this system are very impressive, but many years will probably pass before it comes into universal acceptance.

The units most likely to be encountered in transducer measurements will fall into one of the following systems. The first two are based on fundamental (length-mass-time) units and are called *absolute* systems.

British absolute system

The *British absolute* (fps) system is based on the foot, pound (mass) and second. All other units in the system are derived from these units. Thus, velocity is expressed in feet per second, force in pound-feet per second$^2$, or *poundal*, etc. In solving equations within this system, therefore, pounds of force must be converted to poundals, meters to feet, etc., before being inserted in an equation.



metric absolute system

The *metric absolute* (cgs) system was once the most widely used in scientific pursuits. It is based on the fundamental units of centimeter, gram and second. Force is expressed in dynes, mass in grams, acceleration in centimeters per second, etc.

The gravitational systems are quite similar except that force is taken as a fundamental quantity, and mass is considered a derived quantity. The system gets its name from the unit of force which is defined as the attraction of gravity on a certain mass.

British gravitational system

The *British gravitational* system is based on the foot, the pound of *force* (lbf) and the second. This system is the one most commonly employed in engineering work and by the general English-speaking public. The unit of mass, though not often used, is the "slug," defined as the mass which will be accelerated 1 foot/second$^2$ when acted upon by an unbalanced force of one pound.

metric gravitational system

The *metric gravitational* system is based on the centimeter, gram of *force* (gf) and the second. No names have been given to the units of mass and density.

The four systems are outlined in Fig. 1-1 for a comparison of equivalent quantities.

| Absolute units | | | Gravitational units | | |
|---|---|---|---|---|---|
| Quantity | British (fps) | Metric (cgs) | Quantity | British | Metric |
| *Fundamental* | | | *Fundamental* | | |
| Length....... | foot | centimeter | Length....... | foot | centimeter |
| Mass......... | pound | gram | Force........ | pound | gram |
| Time......... | second | second | Time......... | second | second |
| *Derived* | | | *Derived* | | |
| Area......... | $ft^2$ | $cm^2$ | Area......... | $ft^2$ | $cm^2$ |
| Volume....... | $ft^3$ | $cm^3$ | Volume....... | $ft^3$ | $cm^3$ |
| Speed........ | ft/s | cm/s | Speed........ | ft/s | cm/s |
| Acceleration. | $ft/s^2$ | $cm/s^2$ | Acceleration. | $ft/s^2$ | $cm/s^2$ |
| Force........ | poundal | dyne | Mass......... | slug | no names |
| Density...... | $lb/ft^3$ | $g/cm^3$ | Density...... | $slug/ft^3$ | assigned |
| Energy....... | ft-poundal | erg | Energy....... | ft-lb | cm-g |
| Power........ | ft-poundal/s | erg/s | Power........ | ft-lb/s | cm-g/s |

Fig. 1-1. Coherent systems of units.

**BASE UNITS**

| *Quantity* | *Unit* | *SI Symbol* |
|---|---|---|
| length | meter | m |
| mass | kilogram | kg |
| time | second | s |
| electric current | ampere | A |
| thermodynamic temperature | Kelvin | K |
| luminous intensity | candela | cd |

**SUPPLEMENTARY UNITS**

| | | |
|---|---|---|
| plane angle | radian | rad |
| solid angle | steradian | sr |

**DERIVED UNITS**

| | | |
|---|---|---|
| acceleration | meter per second squared | $m/s^2$ |
| angular acceleration | radian per second squared | $rad/s^2$ |
| angular velocity | radian per second | rad/s |
| area | square meter | $m^2$ |
| capacitance | farad | F |

| *Quantity* | *Unit* | *SI Symbol* | *Formula* |
|---|---|---|---|
| density | kilogram per cubic meter | $kg/m^3$ | |
| electric capacitance | farad | F | A s/V |
| electric charge | coulomb | C | A s |
| electric field stength | volt per meter | V/m | |
| electric resistance | ohm | Ω | V/A |
| electromotive force | volt | V | W/A |
| energy | joule | J | N m |
| force | newton | N | $kg\ m/s^2$ |
| frequency | hertz | Hz | $s^{-1}$ |
| illumination | lux | lx | $lm/m^2$ |
| inductance | henry | H | V s/A |
| kinematic viscosity | square meter per second | $m^2/s$ | |
| luminance | candela per square meter | $cd/m^2$ | |
| luminous flux | lumen | lm | cd sr |
| magnetic field strength | ampere per meter | A/m | |
| magnetic flux | weber | Wb | V s |
| magnetic flux density | tesla | T | $Wb/m^2$ |
| magnetomotive force | ampere | A | |
| potential difference | volt | V | W/A |
| power | watt | W | J/s |
| pressure | newton per square meter | $N/m^2$ | |
| quantity of heat | joule | J | N m |
| stress | newton per square meter | $N/m^2$ | |
| velocity | meter per second | m/s | |
| viscosity | newton-second per square meter | $N\ s/m^2$ | |
| voltage | volt | V | W/A |
| volume | cubic meter | $m^3$ | |
| work | joule | J | N m |

**MULTIPLE AND SUBMULTIPLE UNITS**

| *Multiplication Factors* | *Prefix* | *SI Symbol* |
|---|---|---|
| 1 000 000 000 000 = $10^{12}$ | tera | T |
| 1 000 000 000 = $10^9$ | giga | G |
| 1 000 000 = $10^6$ | mega | M |
| 1 000 = $10^3$ | kilo | k |
| 100 = $10^2$ | hecto | h |
| 10 = $10^1$ | deka | da |
| 0.1 = $10^{-1}$ | deci | d |
| 0.01 = $10^{-2}$ | centi | c |
| 0.001 = $10^{-3}$ | milli | m |

Fig. 1-2. International system of units (SI).



**popular British/USA system**

In addition to these coherent systems, there are two unofficial but popular systems also in use. The first of these might be called the *Popular British/ USA* system. The main departures from the British gravitational system pertain to acceleration, which is measured in g's (32 $ft/s^2$), pressure, measured in pounds/$in^2$ (psi) and temperature, measured in degrees Fahrenheit.

**popular metric system**

The popular metric system resembles the metric gravitational system with the exception of the following units: force, measured in kilograms (kgf); acceleration, measured in g's (9.81 $m/s^2$); and pressure, measured in kilograms force/$cm^2$.

**SI system**

The SI system, mentioned earlier in this chapter, is given a more detailed treatment in Fig. 1-2. Note that all quantities are derived from *six* basic units, and that the unit of force is called the *newton*. The newton is defined as that force which will impart an acceleration to one kilogram of mass of 1 meter per second.

In subsequent chapters, where units of measurement are selected for discussion or example, the choice is dictated by prevailing custom.

# 2

Principe de F^t des transducteurs.

## PRINCIPLES OF TRANSDUCER OPERATION

definitions

In general terms, a transducer is any device which converts energy in one form to energy in another. In this context, an automobile engine, a hydroelectric turbine, or an electric razor are all transducers. In its more common usage, however, the term refers to devices of a rather specialized nature -- those which convert electrical energy to high-frequency mechanical displacement, such as ordinary loudspeakers and ultrasonic generators, and those which convert some physical quantity, property, or condition to an electrical signal. The latter category may be further subdivided into two classes, according to how the output is utilized. In many industrial processes, the electrical output of the transducer is used as a feedback signal in a servo-loop to control the dimensions or properties of the end product. The same transducer, however, when connected to a readout device and used to provide quantitative measurement information to an investigator, becomes what will be called an *instrument transducer*. Since this book is intended primarily for those concerned with electronic measurement systems, the term "transducer," when encountered in the following pages, will refer to instrument transducers, as defined above, unless otherwise noted. The terms "sensor" and "pickup" may be used alternatively in the same sense.

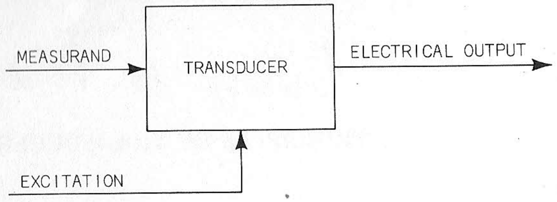



Fig. 2-1.

measurand

The function of an instrument transducer is to sense the presence, magnitude, change in, and/or frequency of some *measurand*, and provide an electrical output which, when appropriately processed and applied to a readout device, will furnish accurate quantitative data about the measurand (Fig. 2-1). The term "measurand" refers to the quantity, property, or condition which the transducer translates to an electrical signal. The measurand, it should be noted, is not always sensed directly by the transducer. In perhaps the majority of actual situations, the stimulus to which the transducer responds, only *represents* the measurand itself. Thus, in measuring acceleration (the measurand), the transducer is activated by a force or displacement which represents the magnitude of the acceleration. (This point will shortly be examined in more detail).

Perhaps the most satisfactory way to classify transducers for the purpose of study is by the electrical principle involved in their operation. In this chapter, therefore, the actual function of a particular transducer will be of secondary interest and primary attention will be devoted to the manner in which electrical outputs are developed. The information thus imparted, together with an understanding of the numerous measurands of interest to science and industry (discussed in the next chapter), should lead to a deeper insight respecting the broad field of transducer-aided measurements.



displacement or stress

Before examining the electrical phenomena involved in transducer design and operation, an important but seldom mentioned aspect of electrical signal generation must be emphasized; that in all but a few instances, the generation of an electrical signal involves either *displacement* or *stress*. A little thought should make this clear. In any event, the point will be reinforced by many examples as this discussion proceeds. The significance of the point is that many transducers require, in addition to some kind of electrical element, a *force-summing* device.

force summing

In principle, such a device converts the measurand into a stress or displacement that is proportional by some constant to the magnitude of the measurand. The stress or displacement thus produced is then applied to the electrical transduction element to generate the required signal.

Considerable ingenuity has been devoted to the development of devices for this purpose. These are too numerous to be catalogued in the space available, but the principles involved in their design bear examination.

Hooke's law

Generally speaking, the measurand is caused to exert a *force* on an elastic member of the mechanical element. According to Hooke's law, the dimensional deformation (strain) of an elastic body is proportional to the force (stress) applied to it. When this strain (a form of displacement) is applied to an electrical transducer, the output signal will bear a definite proportion to the magnitude of the measurand. It follows that most transducers actually consist of *two* transduction elements, one *electrical* and one *mechanical* (hence the term "electromechanical transducer." See Fig. 2-2.).

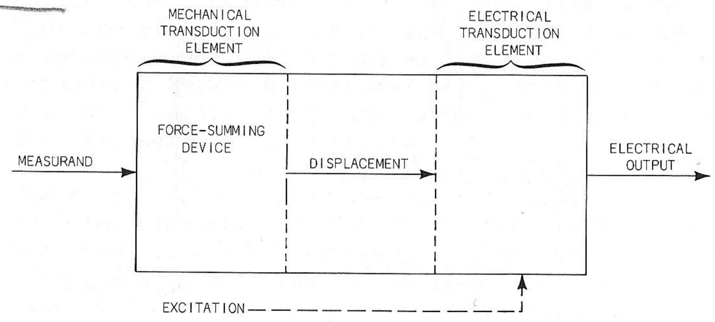



Fig. 2-2. Electro-mechanical transducer principle.

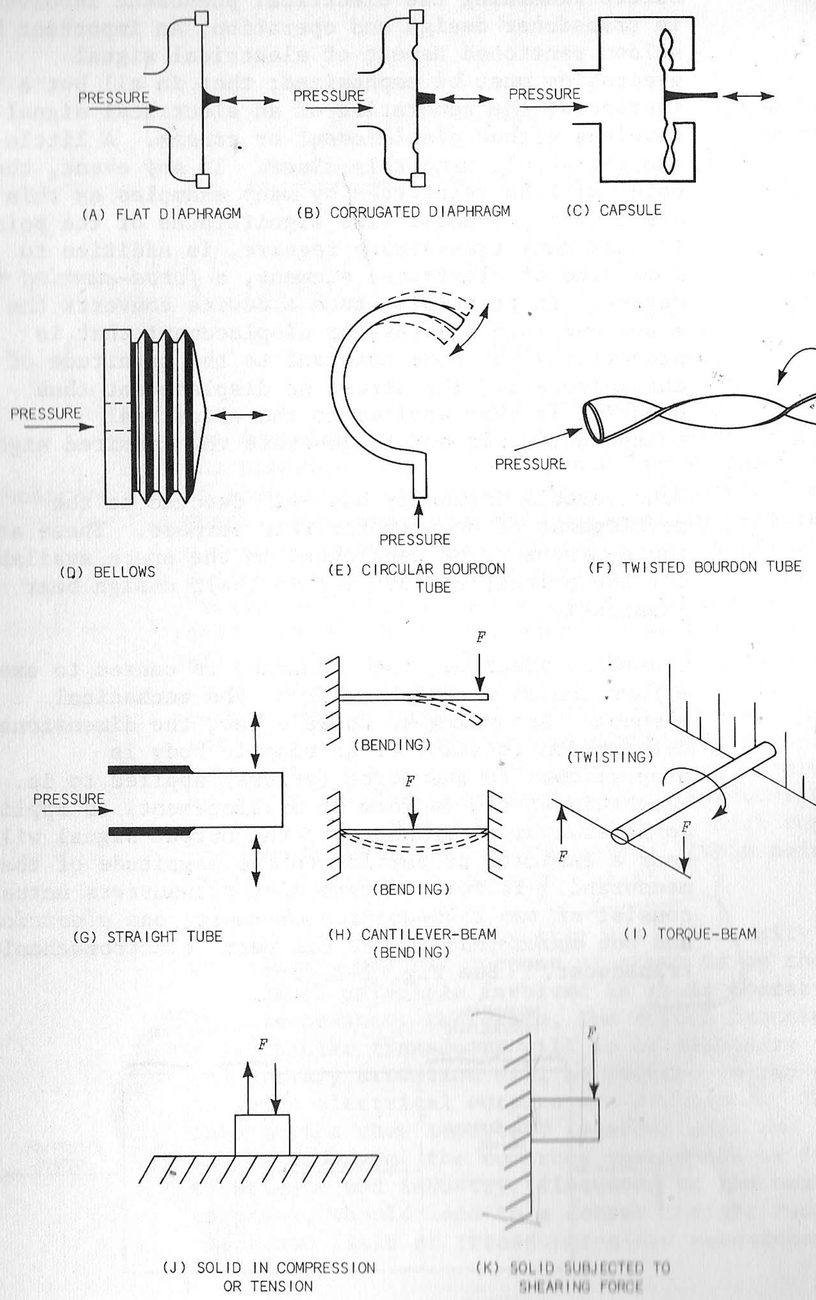



Fig. 2-3. Force-summing devices.



**force-summing devices**

The mechanical devices most frequently used to convert applied forces to displacement are the diaphragm -- flat (A), corrugated (B) or capsule (C), bellows (D); Bourdon tube -- circular (E) or twisted (F), straight tube (G); cantilever -- beam (H), torque beam (I), solid in compression or tension (J), and solid subjected to shear (K). Examples of these devices are portrayed by the diagrams in Fig. 2-3.

**natural frequency**

The type of force-summing device chosen for a given transducer depends primarily on the force to be applied and the action necessary to activate the electrical transducer. However, in dynamic applications, the frequency response of the device must also be considered. The natural or resonant frequency of a seismic system having one axis of freedom is given by:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

where k = spring constant
$m$ = mass

Comparing the diaphragms of Figs. 2-3A and 2-3B and assuming the same dimensions and mass for both, it is evident that the maximum stiffness (k) is exhibited by Fig. 2-3A. Therefore, this type of transducer will have the highest natural frequency and be the least sensitive to vibratory acceleration. (The latter characteristic is desirable, since sensitivity to vibration would introduce "noise" into the pressure readout.) When larger applied displacements or forces must be transmitted to the electrical transduction element, or when a higher degree of linear displacement is desired from the device, the corrugated (B) or capsule diaphragms (C) are more efficient. The values of $m$ and k in the seismic devices will depend on the type of transducer in which they are used. Seismic devices will be discussed in greater detail in Chapter 3 in the discussion of Acceleration.

**electrical transduction element**

The electrical transduction element utilizes familiar electrical principles in translating the measurand to electrical energy. Those which generate an electrical output directly from the measurand or the output of the mechanical transduction element are called *self-generating* transducers. Those which require a source of external "excitation" power are called *passive* transducers.

resistive transducers

*Resistive* transducers are those in which the measurand either directly or indirectly (through a force-summing device) causes a change in the ohmic resistance of an electrical element. Transducers of this type fall into two main categories: Those whose resistance is altered by a physical or chemical change in the resistive element and those whose resistance is varied by the movement of contacts.

bonded strain gages

Chief among transducers of the first type is the wire, foil, or semiconductor *strain gage*. This group may be further subdivided into bonded and unbonded types. Fig. 2-4 shows the construction details of bonded foil and wire gages. Bonded foil strain gages are by far the most universally used, although bonded semiconductor gages (Fig. 2-5) are finding increased applications. In practice, the gage is cemented to the member to which stress is applied. The resulting strain in the member is communicated by the bonding material directly to the filaments of wire or foil or the semiconductor material of which the gage is constructed. In the case of the wire or foil gage, the strain increases the length and reduces the cross-sectional area of the conductor. Both effects increase the conductor's resistance. The semiconductor material experiences an alteration of crystalline structure, producing what is called the *piezo resistive* effect or change in resistance with applied stress. This effect is usually of much greater magnitude than that produced in wire or foil gages under equal stress.

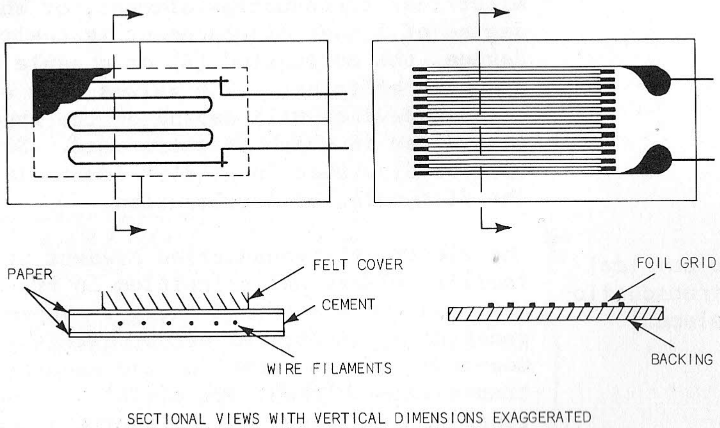



Fig. 2-4. Wire and foil strain gage construction.



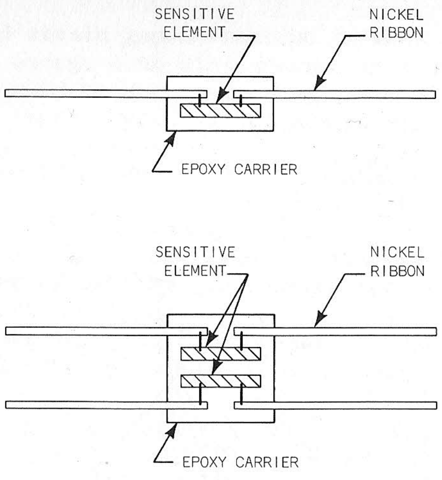



Fig. 2-5. Semiconductor strain gage construction.

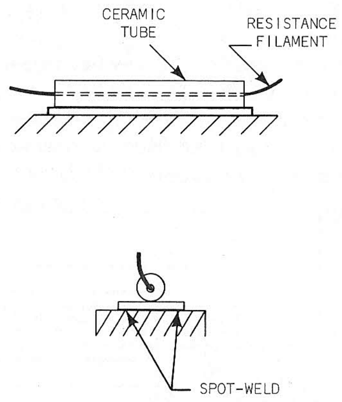



Fig. 2-6. Welded strain gage.

Quite similar in principle, but designed for high-temperature applications, is the welded strain gage (Fig. 2-6). The resistance filament is centered in a special alloy tube and insulated from the walls of the tube by a solid ceramic material. The tube is welded to a mounting flange of the same material. The flange, when spot welded to the mounting surface, allows the gage to become virtually an integral part of the test member.

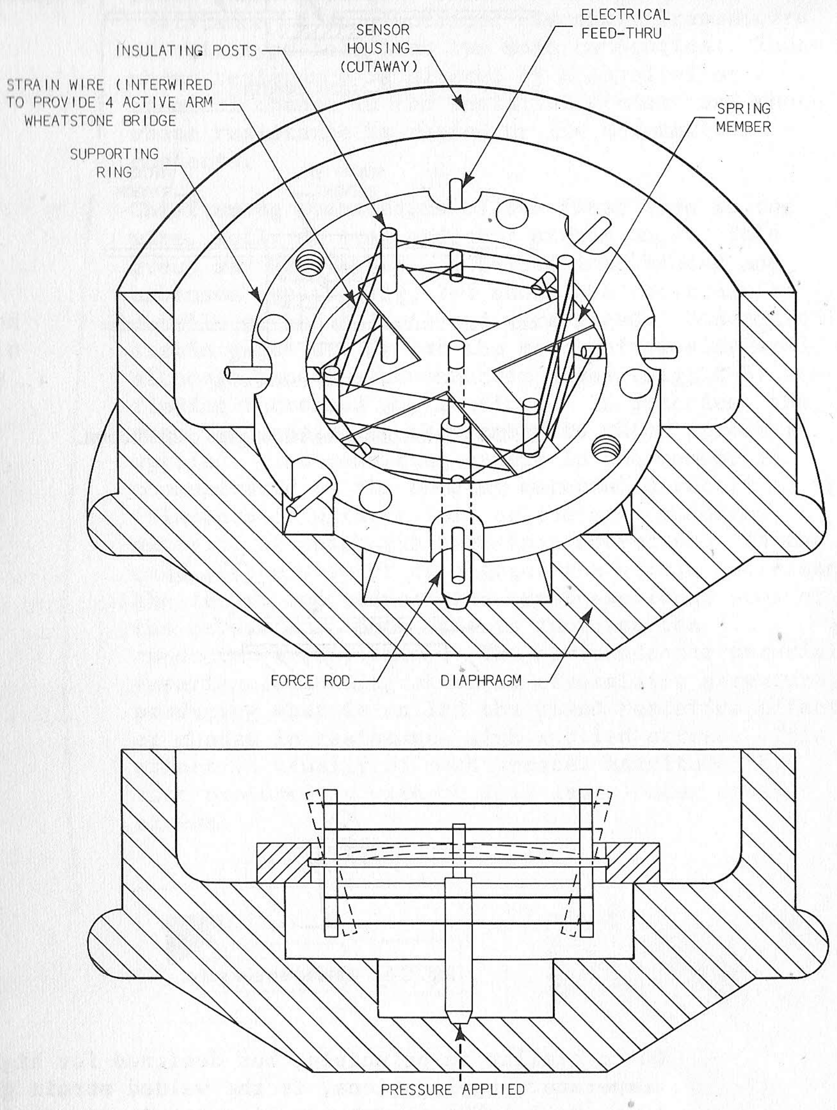



Fig. 2-7. Sensor module of an unbonded strain-gage pressure transducer.



unbonded strain gages

Unbonded strain gages function in much the same manner, except that displacement is communicated mechanically to the conducting material. An example of this type of gage is the movable-post or biradial strain gage shown in Fig. 2-7. The strain-sensitive filaments are wound around insulated posts mounted on a spring structure and connected so that they constitute a Wheatstone bridge. When a force is applied normal to the plane of the spring structure, the posts are tilted, increasing the stress on one set of filaments and decreasing it on the other set. The resulting resistance changes in the filaments, due to strain, are added in the bridge (Fig. 2-8).

Strain gages are used not only in making strain measurements, but also as the electrical transduction element in many other kinds of transducers.

Strain, of course, is not the only measurand which can cause changes in the resistance of a material. A cotton fiber, for instance, when impregnated with a saline solution will vary in resistance inversely with humidity. Electrolytes, in general, vary in resistance inversely with their concentration, within certain limits. In fact, any material that changes its resistance when subjected to some physical phenomenon can be used to produce an electrical signal for observation and measurement of that phenomenon.

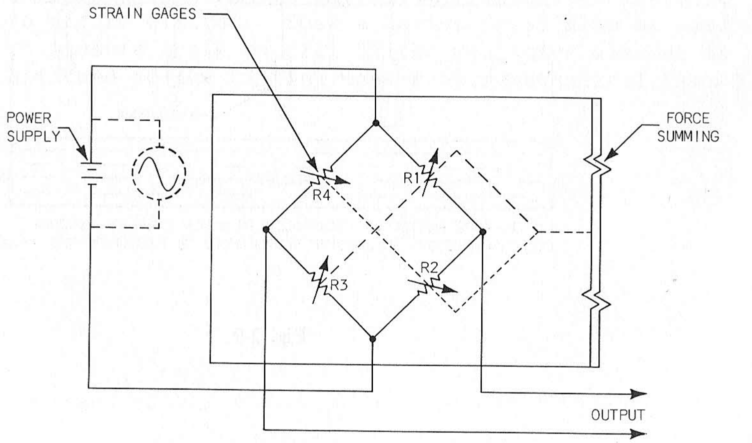
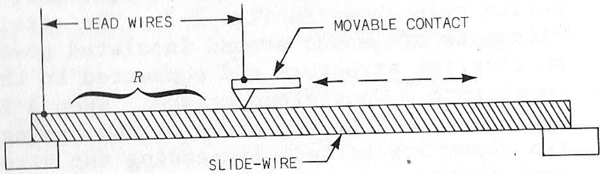
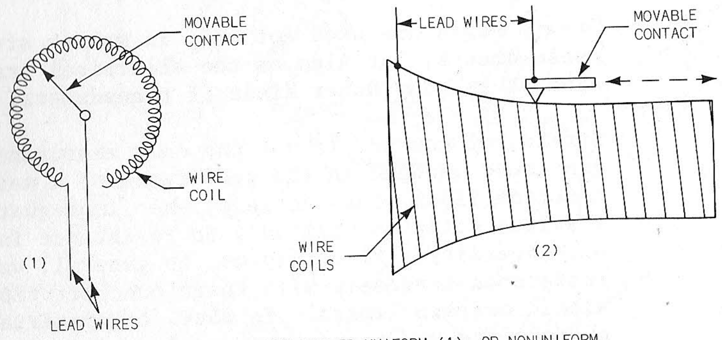



Fig. 2-8. Strain-gage transducers in bridge configuration.



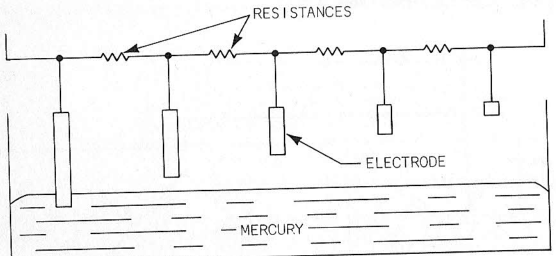

SLIDE-WIRE RESISTIVE TRANSDUCER. RESISTANCE CHANGES WHEN A CONTACT IS MOVED ALONG THE LENGTH OF THE RESISTIVE ELEMENT.

(A)




RESISTIVE TRANSDUCERS FOR EITHER UNIFORM (1), OR NONUNIFORM (2), RESISTANCE CHANGES.

(B)




LIQUID-TYPE RESISTIVE TRANSDUCER IN WHICH A RISING MERCURY LEVEL SHORTS OUT SUCCESSIVE RESISTANCES OF PREDETERMINED VALUES.

(C)

Fig. 2-9.



movable-contact transducers

Movable-contact transducers, as the term implies, consist of a resistive element and a movable contact. Displacement of the contact causes a change in resistance between the terminals of the device. See Fig. 2-9. The slide-wire rheostat or potentiometer is typical of this type of device and also the simplest in construction. Other types are constructed from coiled wire. The form around which the wire is coiled may be cylindrical, for sensing reciprocal motion, or doughnut-shaped, for sensing angular displacement. In cases where a nonlinear output is desired, the cross-section of the form may be nonuniform. A digital output is obtained by the tapped-resistance coil and mercury-pool combination. As the mercury rises in its containing vessel, one after another of the coil's resistive segments is shorted out, reducing overall resistance of the coil in discrete steps. Such a device could also be used to measure angle of tilt if the resistive element is attached to the tilting member of a mechanical device.

**capacitive transducers**

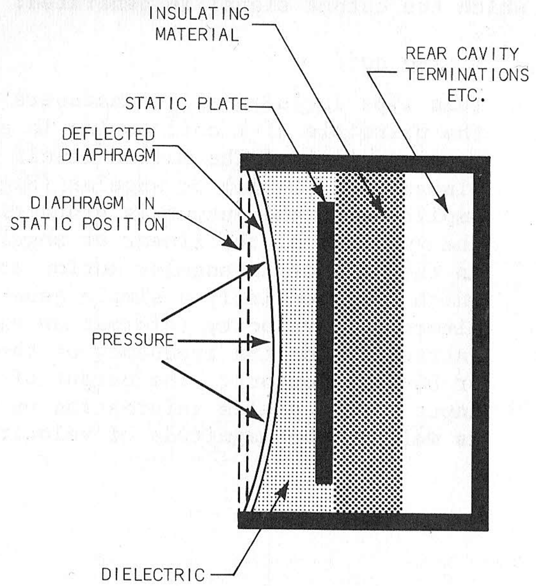
Capacitive transducers (Fig. 2-10) are those in which the measurand directly or indirectly (through a force-summing device) causes a change in capacitance of a variable capacitor. This is accomplished by changing (1) the distance between the plates (thickness of dielectric), (2) the composition of the dielectric, or (3) the area of the plates. In operation, the measurand (force, stress, displacement, etc.) moves the plates of the capacitor closer together or farther apart. The capacitor may be connected in a biased DC circuit (most common), an AC-bridge circuit, a feedback amplifier circuit, or act as part of the tank circuit of an oscillator. In other applications, the distance between the plates is fixed, while the measurand (density, flow, etc.) causes changes in the dielectric constant of the capacitor. Metallic objects may be counted by an arrangement which causes the object to act as one plate of a capacitor as it travels past a fixed plate.

The capacitance of the leads to the transducer must be kept at a minimum when using capacitance transducers.

**inductive transducers**

Inductive transducers, unlike those which operate on the resistance principle, may be either the *self-generating* or *passive* type. The self-generating type utilizes the basic electrical principle that when there is relative motion between a conductor and a magnetic field, a voltage is induced in the conductor. In the case of transducers, the relative motion is supplied by changes in the measurand; thus, only dynamic measurements are possible with the self-generating type.





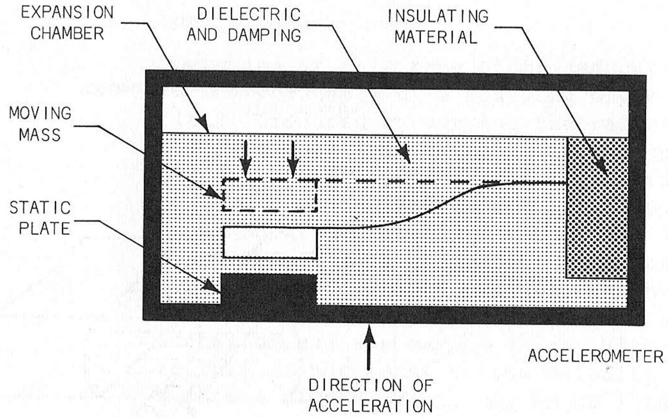




Fig. 2-10. Capacitive transducers.

self generating

*Self-generating inductive* transducers fall into one of four principal categories, according to the manner in which the output signal is generated:

1. *Moving coil*

   This type includes all transducers employing the principle of a coil moving in a fixed magnetic field. The motion itself may be linear (Fig. 2-11A) or angular (Fig. 2-11B). Amplitude of the output is proportional to the velocity of the linear or angular motion. In the case of an angular motion transducer, which is essentially a simple generator or alternator, velocity information can also be extracted from the frequency of the sinewave or DC-pulse output. The output of the linear input device yields information on direction as well as the magnitude of velocity.

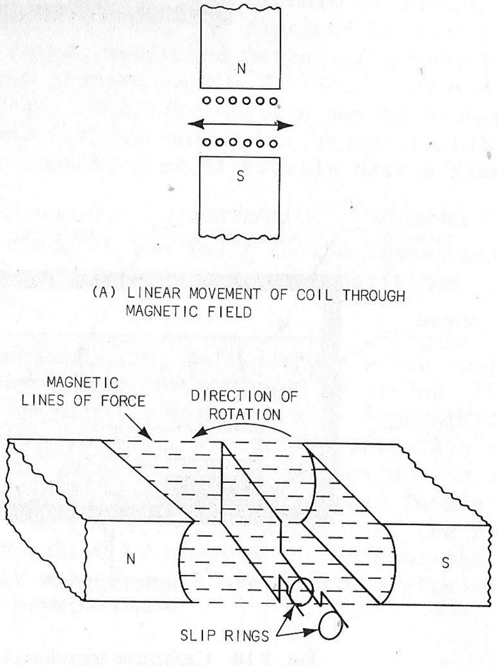



Fig. 2-11. Electrodynamic magnetic transducer.



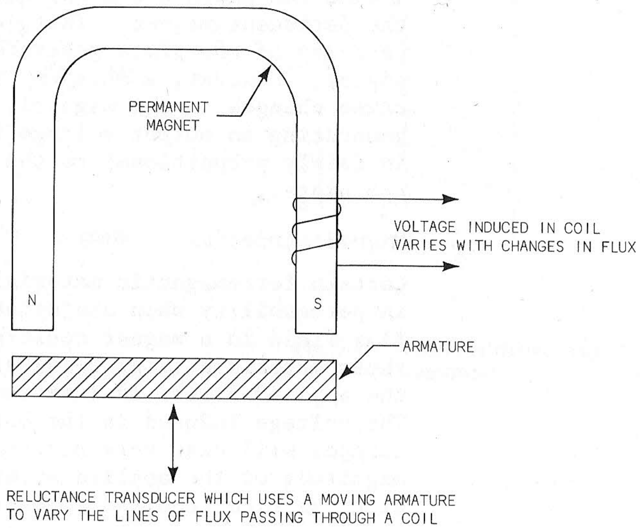



Fig. 2-12. Variable reluctance (electromagnetic) magnetic transducer.

2. *Variable reluctance*

   Operation of this type of transducer rests on the principle of a changing magnetic flux field, produced by varying the reluctance in the flux path (Fig. 2-12). An armature is moved, through changes in the measurand, closer to or farther away from the poles of a permanent magnet. The larger the air gap, the weaker the concentration of magnetic lines of force in the permanent magnet. These changes in magnetic flux induce a voltage in a coil around the magnet which, although only roughly proportional to the velocity of the armature displacement, may be calibrated in terms of the measurand.

3. *Eddy current*

When the plate in Fig. 2-13 is moved in the indicated directions, eddy currents are set up in the plate in proportion to the velocity of motion. These currents create a field around the plate which opposes the field of the permanent magnet. Thus, a constant velocity of the plate generates no output signal. However, a *changing* velocity will cause changes in the magnetic flux, generating an output voltage in the coil which is fairly proportional to the *acceleration* of the plate.

4. *Magnetostrictive*

Certain ferromagnetic materials exhibit changes in permeability when subjected to stress. The flux field in a magnet constructed of one of these materials (Fig. 2-14) will thus vary as the applied stress is increased or decreased. The voltage induced in the coil by these changes will also vary directly with the magnitude of the applied stress and inversely with the time required to make the change.

passive

*Passive inductive* transducers are those which require an external source of power. The action of the transducer is principally one of modulating the excitation signal. Thus, static or slowly-changing measurands can still be converted to quantitative electrical outputs, the unmodulated excitation signal acting as the zero reference of measurement. This type has four main categories:

1. *Mutual inductance*

The principle involved in this type of transducer is that of varying the inductive reactance in an AC circuit. The transducer itself is thus a variable inductor. Inductance values are usually established by positioning a ferromagnetic core within a coil. The sensitivity of response to changes can be increased by connecting a center tap to the coil (Fig. 2-15A). In effect, this arrangement provides two coils wrapped around a common core. As the core is displaced, the inductance of one coil increases while that of the other decreases, yielding twice the change in signal current provided by a single coil.



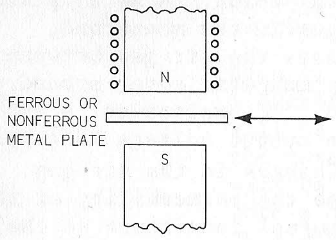



Fig. 2-13. Eddy current magnetic transducer.

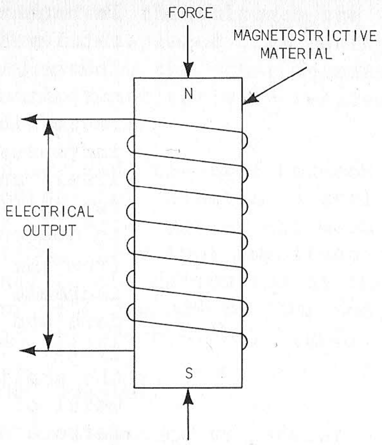



Fig. 2-14. Magnetostrictive magnet transducer.

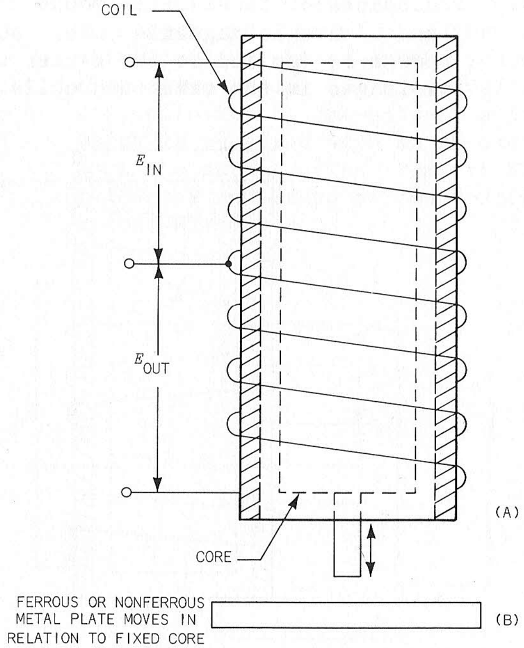



Fig. 2-15. Mutual inductance magnetic transducer.

In both types, directional information can be retrieved from the polarity of the signal change. A similar effect is achieved by the circuit shown in Fig. 2-15B. A metal plate, responding to changes in the measurand, increases or decreases the air gap between itself and the ferromagnetic core, around which two coils are wound. AC excitation is applied to one coil and the output voltage is taken from the second. Changes in the air gap increase or decrease the permeability of the core and thus the mutual inductance of the coils. These changes are seen as changes in the amplitude of the output voltage. The metal of the movable plate may be either ferrous or nonferrous, since in the latter case, eddy currents set up in the plate will also affect the mutual inductance of the coils and thus the output voltage.

2. *Differential transformer*

Fig. 2-16 is a diagram of a linear variable differential transformer (LVDT). This device consists of three coils wound on a common form, and a movable magnetic core. AC excitation power is applied to the center winding, inducing voltages in the other two coils.

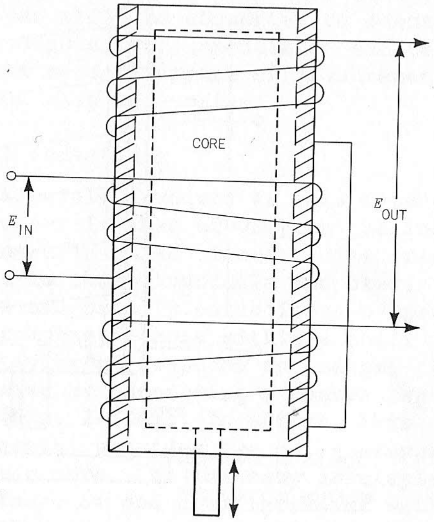



Fig. 2-16. Differential transformer magnetic transducer.



When the core is centered, the voltages are equal; when the core is displaced from center, one voltage increases while the other decreases. This difference can be quantitatively related to the position of the core.

When DC excitation is used, the LVDT becomes a dynamic measurand device. Since no signal will be present at either output except when the core is in motion, the output amplitude will be proportional to the *derivative* of the core's *displacement with respect to time* and thus acts as a velocity-proportional signal.

3. *Variable reluctance (passive)*

The passive variable reluctance transducer consists of two coils with one common connection wound on an E-shaped core and a movable armature (Fig. 2-17). When the armature is parallel to the back of the "E," the inductance of the coil is balanced. When tilted around its pivot point, however, the air gap increases on one end and decreases on the other. This changes the reluctance in the upper and lower flux paths, causing a corresponding change in the inductance of the respective coils. In a typical application, the coils act as one-half of a bridge circuit, which is supplied with an AC-excitation voltage. Thus the output taken from the bridge has twice the amplitude of the voltage change across either coil.

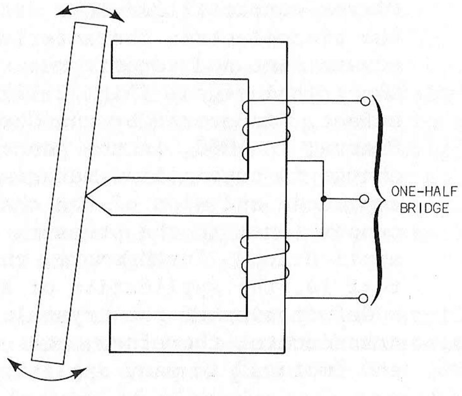
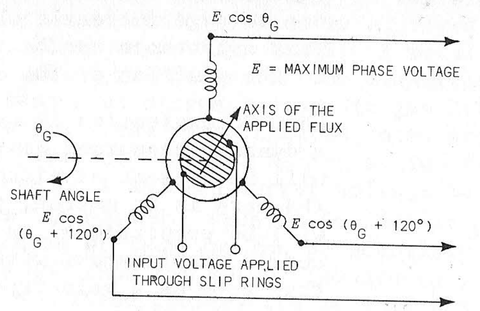



Fig. 2-17. Variable reluctance magnetic transducer.




SIMPLIFIED DIAGRAM SHOWING HOW THE INPUT VOLTAGE APPLIED TO THE ROTOR WINDING OF A SYNCHRO GENERATOR INDUCES SECONDARY VOLTAGES IN THE THREE-PHASE OUTPUT WINDING WHICH VARY SINUSOIDALLY WITH SHAFT POSITION.

Fig. 2-18. Synchro transformer magnetic transducer.

4. *Synchro transformers*

A number of devices, which can be grouped under the general heading of *synchro transformers* (Fig. 2-18), make excellent angular displacement transducers. The input voltage applied to the rotor winding induces a secondary voltage in the three-phase output winding which varies sinusoidally with the angle of displacement of the rotor shaft. The advantage of this device is that an output signal is always present, whether the rotor is in motion or not. Static or slowly-changing angular displacement can thus be measured.

piezo-electric transducers

Piezoelectric transducers are those which utilize the piezoelectric characteristics of certain crystalline and ceramic materials to generate an electrical signal (Fig. 2-19). The piezoelectric effect, discovered by the Curie brothers, Jacques and Pierre, in 1880, is the generation of an electric charge in crystalline materials by pressure. The amplitude and sign of the charge are directly proportional to the pressure and direction of application. Furthermore, the process is reversible -- that is, the application of an electric field causes a deformation of the crystal. Piezoelectric transducers, therefore, are used both as "generators" and "motors" in many applications.



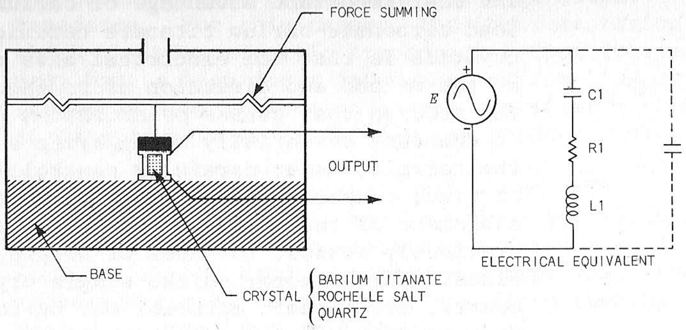
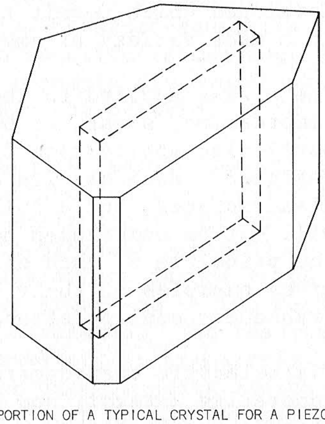



Fig. 2-19. Piezoelectric transducers.



USABLE PORTION OF A TYPICAL CRYSTAL FOR A PIEZOELECTRIC TRANSDUCER. CRYSTALS ARE PREPARED BY SLOW CRYSTALLIZATION FROM A SATURATED SOLUTION OF THE BASIC SALT.

Fig. 2-20. Piezoelectric transducer.

crystal

Until recently, all piezoelectric crystals had to be cut from naturally occurring crystals of quartz or tourmaline or from crystals grown in concentrated solutions of various salts. The polarization of such crystals is inherent in their structure, so that wafers must be cut from the crystal in such a way as to take maximum advantage of the crystal's characteristics (Fig. 2-20).

ceramics

The discovery that polarized polycrystalline barium titanate ceramics also exhibited piezoelectric response led to a rapid growth in the development and manufacture of piezoelectric transducers of many types.

**poling**

The most important advantage of barium titanate and lead zirconate-barium titanate ceramics over natural crystals is that the electrical axes can be varied by the method and direction of *poling*. Poling is the *process* that causes *polarization* of the ceramic. It consists essentially of applying a potential to the ceramic, under carefully controlled conditions of time, temperature and voltage, so as to cause alignment of the molecular *domain* axes. As previously stated, the axes of single crystals are fixed. Furthermore, unlike single crystals such as quartz, the ceramic material may be formed into a wide variety of useful and sometimes complex shapes. Finally, piezoelectric response of these ceramics is not only considerably greater than that of other materials, but techniques of construction have been developed which permit the use of ceramic transducers in a wide variety of ambient conditions.

**stress**

The stress applied to the crystal may be that of compression, shear, or bending, depending on the particular application for which the transducer is designed. Each has its own advantages and disadvantages, but a full discussion of these factors will not be undertaken here. Fig. 2-21 illustrates the principle of each of these types of stress and gives examples of their utilization in basic transducer configurations.

Piezoelectric transducers belong to the self-generating category and are thus useful only in dynamic applications.

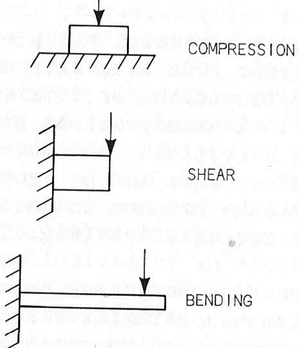



Fig. 2-21.



**impedance**

All piezoelectric crystals have a high output impedance. For this reason, the instrumentation to which the piezoelectric transducer output is applied must have a high input impedance, or for low-frequency applications, a charge amplifier must be interposed between transducer and readout device.

Within the limitations set forth above, the piezoelectric principle may be used effectively in pressure, force and acceleration transducers; in fact, it can be used in almost any type where the measurand can be converted by the force-summing device to some type of stress.

**pressure-sensitive semi-conductor transducers**

Although the organization of this chapter is based on operating principles rather than on specific types of transducers, an exception must be made in the case of the pressure-sensitive transducer. This is because no specific terminology has emerged to describe the recently discovered phenomenon responsible for the behavior of these devices.

The effect is quite easily described. It has been clearly established that certain semiconductors, when appropriately doped, exhibit an extreme sensitivity to pressure directly applied to their surfaces. This effect is not to be confused with piezoresistive phenomena -- the mechanisms involved are entirely unrelated. The resultant behavior of the device, however, is comparable. Current through the transistor changes quite radically with small changes of pressure on the device. No force-summing device is required, so the transistor can be directly exposed to the medium whose pressure is under investigation. Output signals vary quite directly with applied pressure over a fairly wide range. Although only recently appearing in the commercial transducer field, these devices have excited considerable interest for their simplicity and ease of application.

**photo-electric transducers**

There are three kinds of photoelectric effects that can be utilized in transducers. These are:

1. The photovoltaic effect, or the generation of a potential between two electrodes when one of them is illuminated.

2. The photoconductive effect, or a change in the electrical resistance of a material in response to variations in illumination of that material.

3. Photoemissive effect, or the emission of charged particles from a material when subjected to illumination.

photocell
phototube

The term "photocell" is applied to both photovoltaic and photoresistive devices, while the term "phototube" refers only to photoemissive, vacuum-tube devices.

Photoelectric devices require no force-summing device when used to measure some property of light such as color, intensity, etc. However, there are applications in which the measurand is converted to displacement, which in turn is caused to vary the intensity of light falling on a photoelectric cell. See Fig. 2-22. Thus, measurands other than light can be converted to electrical signals.

photo-
voltaic

Photovoltaic cells exist in either wet or dry form. A wet cell consists of a liquid electrolyte in which two electrodes are immersed. Illumination of one of the electrodes results in the generation of an electromotive force across the electrodes. Such units are hard to handle, due to the liquid electrolyte, and have been largely superseded by dry cells or barrier-layer types.

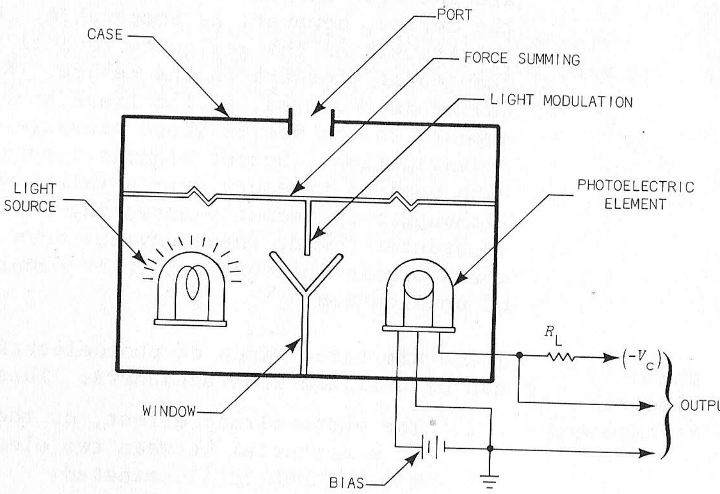



Fig. 2-22. Photoelectric transducer.



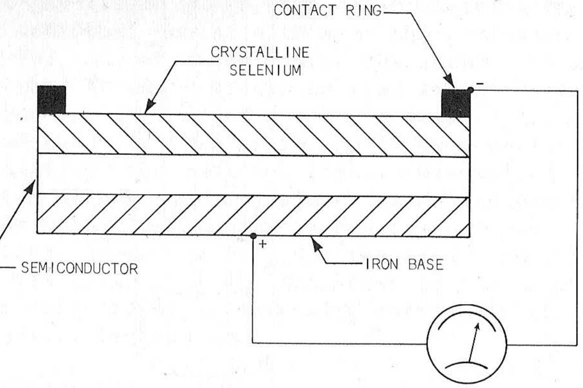



Fig. 2-23. Selenium photoelectric transducer.

Typical of the latter type is the selenium photoelectric cell. See Fig. 2-23. A thin layer of semiconductor material is sandwiched between an iron base plate and a crystalline selenium layer. Light falling on the selenium layers sets up a potential difference between the iron and selenium which varies directly with intensity.

photo-
conductive

A photoconductive cell requires external excitation current. This current is passed through a resistive element made of selenium, germanium, thallium oxysulfide, silicon, or cadmium sulfide. When exposed to variations in light intensity, this element alters its resistance to the excitation current, thus providing an electrical signal for measurement. The ordinary light meter used in photography functions on this principle. Units of this type respond not only to visible light but also to the infrared and ultraviolet wavelengths.

Photoconductive cells are usually inserted as one arm of a Wheatstone bridge to increase the sensitivity of the measuring system.

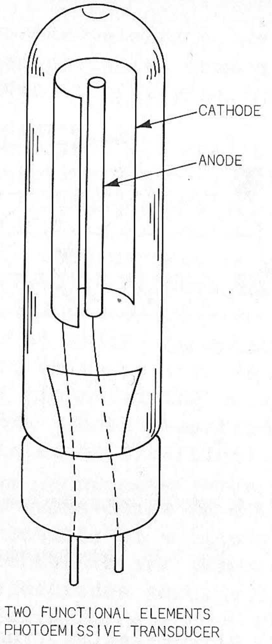



Fig. 2-24. Phototube.

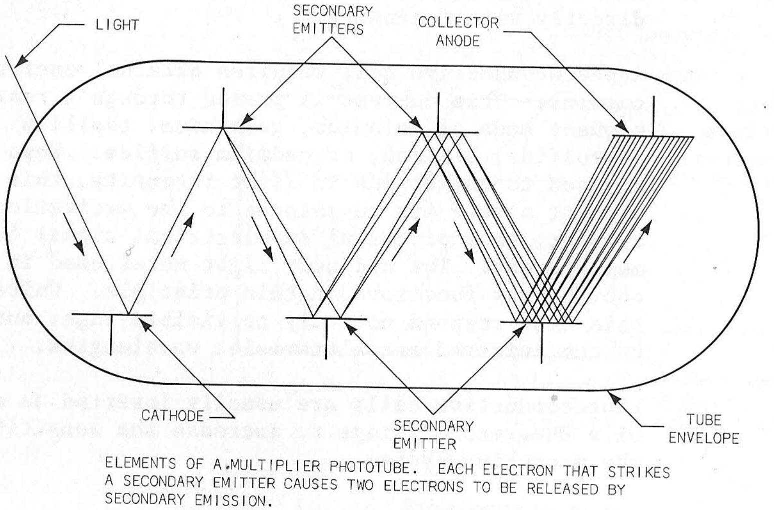



Fig. 2-25. Photomultiplier.



photo-emissive

There are several types of photoemissive tubes. The basic structure, Fig. 2-24, is an evacuated or inert-gas-filled glass envelope containing one or more cathodes, coated with some photoemissive material, and an anode. When the cathode is exposed to light, it emits electrons that are attracted to the positively charged anode. A small current flows in the circuit, varying in amplitude directly as the intensity of the incident light. Gas-filled tubes develop higher current, since the moving electrons strike molecules of the gas and create ions. Both the ions themselves and the free electrons resulting from the collisions are attracted to the cathode and anode respectively, increasing current in the tubes and associated system.

photo-multiplier tubes

Phototubes may be constructed with several cathodes called dynodes (Fig. 2-25) in order to increase their sensitivity to light. These tubes utilize the principle of secondary electron emission. Light falling on the cathode results in the emission of electrons, each of which is attracted to an adjacent dynode riding at a higher potential. The increased velocity of the electron is sufficient to cause the emission of two electrons at the dynode, each of which is attracted to the second dynode. The process is repeated until, in a six-electrode tube, for instance, sixteen electrons are collected at the anode for every electron emitted at the cathode. Of course, the geometry of the tube and configuration and potential of the electrodes must be precisely controlled to yield the result. Tubes of this kind are called *photomultiplier* tubes for obvious reasons. The gain of such tubes is usually great enough to eliminate the need for amplifiers in the measurement system. Their susceptibility to temperature variations, however, is greater than that of simple phototubes.

thermal-effect transducers

The effect of temperature on the transfer characteristics of transducers is usually mentioned as an undesirable side effect. However, in designing temperature transducers, these same effects often become the operating principle itself. Generally, all such effects can be divided into two broad categories: (1) thermomechanical effects and (2) thermoelectric effects.

In the first category, changes in temperature cause a dimensional change in the sensitive element. This change may then be translated to an electrical signal by some type of displacement or force transducer. The second type requires no intermediary device, directly translating changes in temperature to an electrical signal.

thermo-mechanical

The two most common thermomechanical devices are the bimetallic strip or spring (as found in most common thermostats) and the fluid-filled vessel. The ordinary household thermometer is a good example of the latter type.

bimetallic strip

When strips of two different metals are bonded together to form a leaf or spring, changes in temperature will tend to deform the original shape. This effect is caused by the difference in *temperature coefficient of expansion* of the two metals and is increased by choosing metals of widely divergent expansion characteristics. Fig. 2-26 is a schematic diagram illustrating one method of incorporating this device into a transducer.

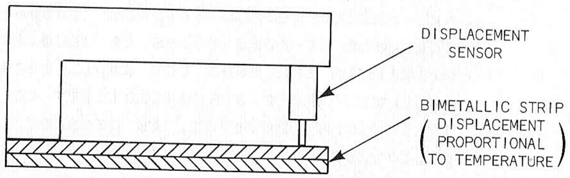



Fig. 2-26. Bimetallic strip used in a transducer.



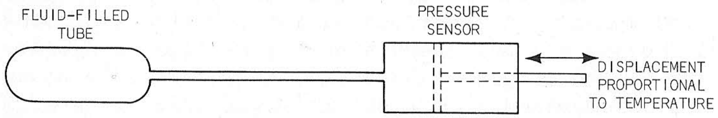



Fig. 2-27. Gas or liquid-filled sensor used in a transducer.

fluid filled

Perhaps the simplest method of using the mechanical output of a fluid-filled device is shown in Fig. 2-27. The gas or liquid in the sensor expands or contracts with changes in temperature, increasing or decreasing the pressure applied to a pressure transducer. The electrical output of the pressure transducer can thus be measured in terms of temperature.

thermo-electric

*Thermoelectric* transducers also fall into two categories:

1. Those whose electrical resistance changes in response to temperature variations (passive type).

2. Those which generate an electrical signal in response to temperature variations (self-generating type).

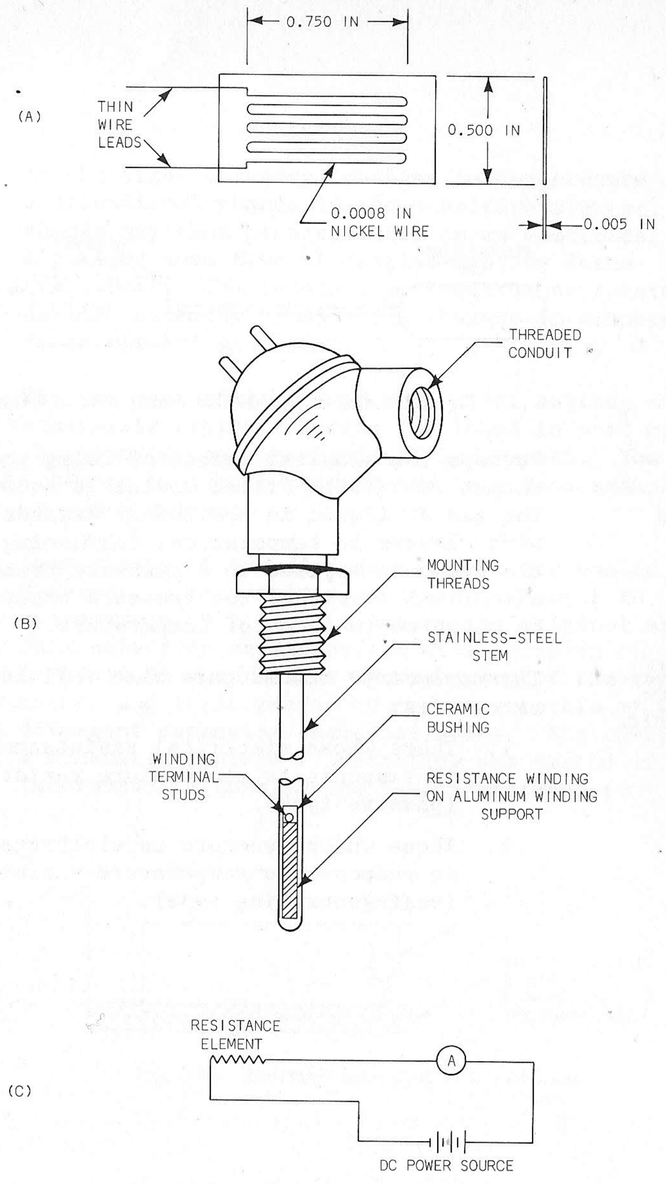



Fig. 2-28. Resistance thermometers.



In the first category are the *resistance thermometer* and the *thermistor*. The resistance thermometer makes use of the principle that the resistance of most electrically conducting materials increases directly with temperature. The resistance element is made of very fine wire, arranged in a flat grid (Fig. 2-28A) or round coil (Fig. 2-28B) and is sometimes shielded for protection. A constant DC voltage is applied to the element and the current is measured in terms of temperature (Fig. 2-28C). For greater sensitivity, the resistance thermometer can be connected in a Wheatstone bridge. Because of their fine-wire construction, these thermometers respond rapidly to temperature changes. Their range is usually between -110° to 300° F.

resistance thermometer

Thermistors are made of semiconductor materials which exhibit a negative temperature coefficient of resistance. In other words, the resistance of the material decreases with increases in temperature, and vice versa. A number of metal oxides, either alone or in combination, are used in this type of transducer. Among these are oxides of cobalt, copper, iron, magnesium, manganese, nickel, tin, titanium, uranium and zinc. The element itself is constructed by embedding fine wire leads in the material before it is crystallized. The shape of the element depends on its application and may be a disc, washer, rod, fluke, or any convenient configuration. The wire leads can be constructed of ordinary copper, since the device has a very high electrical resistance and can therefore be operated at high potentials with a low current. Like the resistance thermometer, the thermistor's sensitivity can be augmented by connecting it in a Wheatstone bridge. The voltage-current characteristic of a thermistor is linear only when power dissipation is kept low. When this condition is met and the thermistor (or bridge) connected to a voltage source, the output voltage can be calibrated and measured in terms of temperature.

thermistor

**thermocouple**

The second category of thermoelectric transducers operates on the principle of the thermocouple. When strips of two dissimilar metals are bonded together at one end and the junction exposed to heat, a voltage is developed across the unjoined ends that is proportional to the temperature difference between the junction and the free ends (Fig. 2-29). Combinations which yield the highest potentials include copper-constantan, iron-constantan, chromel-alumel, and platinum-platinum rhodium.

**thermopile**

For greater sensitivity, a number of thermocouples may be connected in series to form a *thermopile* (Fig. 2-30).

**radiation pyrometer**

A thermopile is the sensing element in a device called a radiation pyrometer, an instrument for measuring high temperatures without actual contact with the hot material under investigation. The thermopile is located at the focal point of a lens, which is sighted on the hot object. Radiation of a particular wavelength (selected by the optical system) is focused on the thermopile, thereby generating an electromotive force proportional to the temperature of the target.

Thermocouples and thermopiles exhibit the fastest response to temperature changes of all existing types of temperature transducers.

**crystal-controlled oscillator**

A novel and highly accurate temperature transducer utilizes the effect of temperature on a quartz crystal. The crystal constitutes the resonant circuit of a conventional oscillator. Changes in temperature cause changes in the physical dimensions of the crystal, thereby changing the resonant frequency of the oscillator's "tank" circuit. When designed for relatively high frequencies, such an oscillator will exhibit large frequency shifts for very small changes in ambient temperature. Oscillator frequency thus becomes a measure of temperature.

**semiconductor**

Finally, although not usually considered as such, an ordinary silicon diode or transistor can be employed as a passive temperature transducer. The voltage drop across the diode or base-emitter junction varies inversely with the temperature of the semiconductor and exhibits a remarkable linearity over a wide range of temperatures.



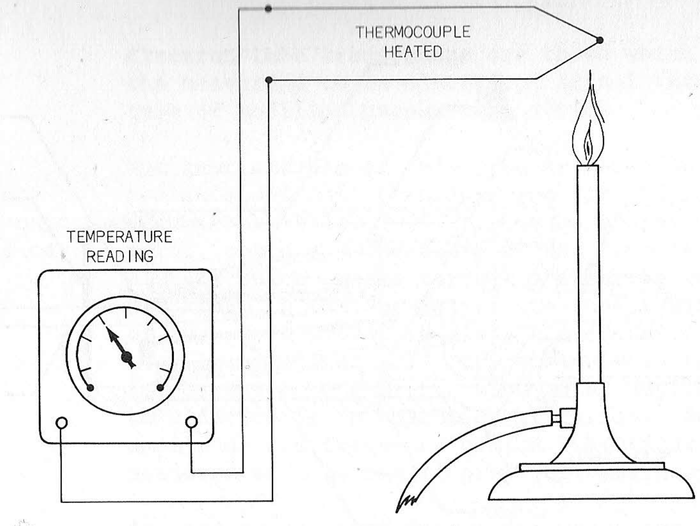



Fig. 2-29. Thermocouple.

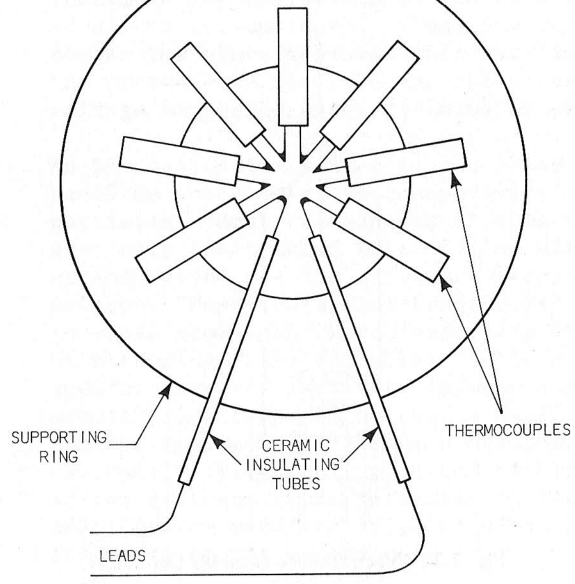



Fig. 2-30. Thermopile.

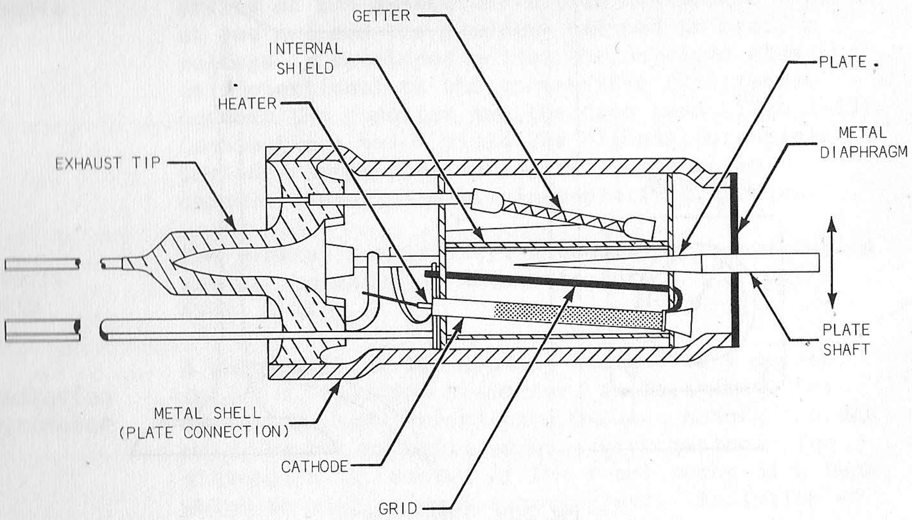



Fig. 2-31. Mechanoelectronic transducer.

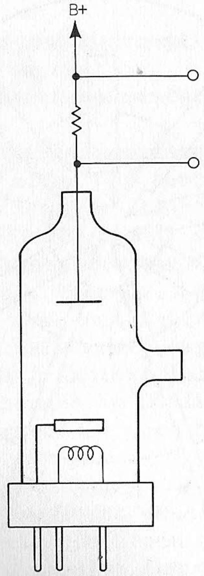



Fig. 2-32. Vacuum-tube pressure transducer.



Electron-tube transducers are those which convert the measurand to an electrical signal through some type of modified vacuum-tube device.

mechano-electronic transducer

The best example of this type is known as a *mechanoelectronic* transducer, a specially constructed vacuum tube (Fig. 2-31). A wedge-shaped piece of metal, acting as the plate of the tube is attached to a shaft which passes through a flexible metal diaphragm to the outside of the tube. Displacement of the shaft moves the plate closer to or farther away from a fixed grid, respectively increasing or decreasing tube current. The chief application of this device is in measuring vibration. Both the amplitude and frequency of the vibrations can be measured with an oscillograph or oscilloscope.

vacuum-tube pressure transducer

Another vacuum-tube device for measuring very low pressure (high vacuum) is shown in Fig. 2-32. Note that in most respects the vacuum tube is a simple diode. The glass envelope, however, includes a fitting for connecting the tube to the chamber or device whose pressure is to be measured. As with all conventional vacuum tubes, the presence of gas increases the resistance of the tube to the passage of electrons (current). Thus, the voltage drop across the plate resistor will vary inversely with the pressure in the tube and under test. This voltage can be measured in terms of pressure.

ionization transducers

An ionization transducer is one whose operation is based on the electrical conductivity of ionized particles. Most transducers of this type are specially constructed tubes filled with inert or organic gases. A few, however, are solid-state devices. Most ionization transducers are designed to sense some form of radioactivity but are capable of measuring other variables if the measurand modifies the radioactivity in some way. For instance, a material interposed between a radioactive source and the ionization transducer absorbs some of the radioactivity, depending on its thickness and density. If one of these characteristics is held constant, the other can be measured in terms of radioactive intensity at the transducer.

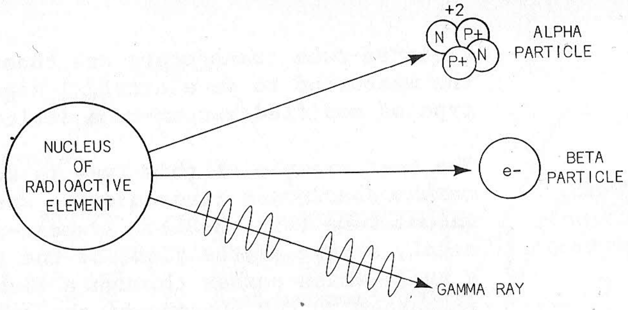



Fig. 2-33. Natural radioactivity.

radio-activity

The term "natural radioactivity" is applied to the phenomenon exhibited by certain unstable elements in which their atomic nuclei spontaneously "decay" into more stable forms. In the process, energy is radiated in the form of charged particles or rays. Three distinct particles are involved in natural radioactive decay. These are: (1) the alpha particle, identical in all respects with the helium nucleus (2 protons, 2 neutrons) and thus carrying a double-positive charge; (2) the beta particle, actually a high-speed electron and (3) the gamma ray, similar in most respects to a photon of light but having a higher frequency. The alpha particle, because of its large size and low velocity can be stopped (absorbed) by a thin sheet of paper. The beta particle has a mass only 1/1850 that of a single proton, and this, together with its high velocity, gives it considerable penetrating power. Gamma rays have the greatest penetrating power of all and are able to pass through several millimeters of lead, one of the most effective shielding materials. Ionization transducers "count" these radioactive particles, producing an electrical output that is proportional to their absolute numbers or to their rate of occurrence.

ionization tubes

Gas-filled ionization tubes usually consist of a metallic envelope filled with an inert gas. An electrode is centrally located in the tube and insulated from the shell. The shell is held at ground potential while a higher positive potential is applied to the central electrode (anode). A schematic diagram of this arrangement is shown in Fig. 2-34. The resistor is usually on the order of several megohms.



In principle, radioactive particles are admitted into the tube through a "window" of beryllium, mica, nylon, or similar material that is relatively transparent to nuclear energy. These particles eventually collide with a gas molecule, producing a free "primary" electron and a positive ion (in the case of inert or "noble" gases).

If the primary electron is given added velocity by the potential across the anode and shell, it may in turn collide with another gas molecule with sufficient energy to produce a secondary ion and electron. This process may be repeated until a shower of electrons is produced in what is known as the "avalanche" effect.

ionization chamber

Several modes of operation are possible, determined by the potential applied to the anode. When operated in the first mode, the tube is called an *ionization chamber*. The anode potential is high enough to collect all primary electrons but too low to give them sufficient energy to produce secondary electrons. Each ionization event gives rise to a current pulse in the tube. These pulses may be measured by discrete counting, integration, or by pulse amplitudes.

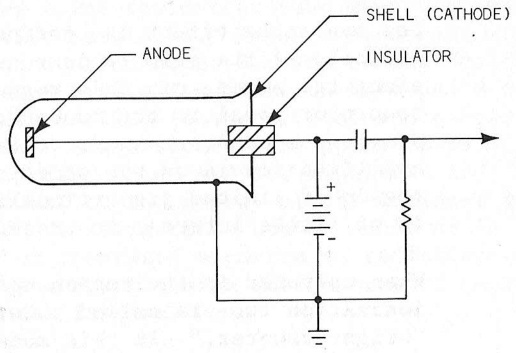



Fig. 2-34.

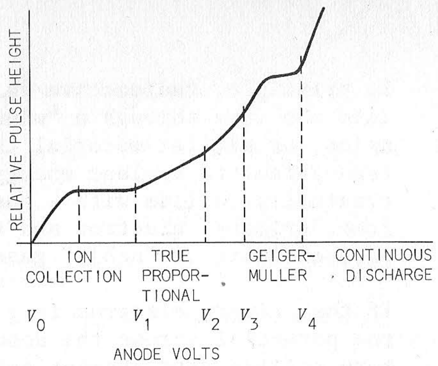



Fig. 2-35.

Fig. 2-35 is a plot of pulse amplitude versus anode voltage applied to a gas ionization tube. In the flat region between $V_0$ and $V_1$, further increases in anode voltage effect no increase in pulse height. This "saturated" mode is the defining region for an ionization chamber.

proportional counter

The proportional counter is operated in the region between $V_1$ and $V_2$. Here the anode voltage may supply the primary ions with sufficient energy to produce secondary ions, upon inelastic collision with the neutral gas molecules. In this way, a whole chain of ionization events may be set in motion, effectively amplifying the primary ion pulse.

The avalanche effect is confined to the immediate vicinity of the primary ions and does not spread along the anode. In this region, the pulse amplitude is proportional to the number of primary ions, provided a constant anode voltage is maintained. Amplification is on the order of $10^2$ to $10^3$. The region of limited proportionality between $V_2$ and $V_3$ is of little interest in transducer applications.

Geiger counter

When operated in the region between $V_3$ and $V_4$, the ionization tube is called a Geiger-Muller tube, or "Geiger-counter." In this mode of operation, all primary ions produce pulses of uniform size. The anode voltage is so high that avalanche occurs along the entire length of the anode, rather than being confined to the region around the primary ions.



Every primary ion sets the avalanche in motion, regardless of its energy level. Furthermore, the positive ions travel to the cathode where they absorb an electron. In thus returning to the neutral or "ground" state, these ions emit photons of ultraviolet light which have sufficient energy to knock "photoelectrons" from other gas molecules. These can, in turn, start another avalanche in motion, so that a single event becomes self-perpetuating. This effect, of course, would destroy the usefulness of the tube as a radiation detector, so some means must be provided to stop the action after each discharge. This may be done either internally by the addition of certain organic gases or by an external "quenching" circuit which briefly reduces the anode potential after each discharge. Best results are obtained when the Geiger tube is operated in the short "plateau" region between $V_3$ and $V_4$. Although this plateau always has an upward slope, proper design can restrict it to about 1% per 100 volts. This allows greater tolerance in anode voltage variations when the tube is in operation.

crystal radiation detectors

Certain crystals of nonconducting material such as silver bromide, sulfur, and sodium chloride behave much like a gas ionization tube when exposed to radioactive particles. Valence electrons are raised to the conduction band, leaving behind "holes" in the valence band. The electron-hole pairs drift to electrodes affixed to the crystal and current flows in the external circuit. The pulse rises and falls at a very fast rate, and its amplitude is proportional to the energy of the incident particle. Very high counting rates can be achieved in this manner but continued exposure to radiation eventually builds up a space charge due to trapped charges in the crystal lattice.

**semiconductor radiation detectors**

One of the most active areas of transducer development in the field of radiation measurement is that of the semiconductor radiation detector. One form of this type of diode is shown in Fig. 2-36. When the p-n junction is reverse biased, a wide depletion region develops. Incident radioactive particles interact with the depletion region, liberating electrons and creating holes. These are absorbed by the electric field of the depletion region and a current pulse whose amplitude is proportional to the energy of the incident particle occurs in the external circuit. A single alpha particle can produce millions of electron-hole pairs, with a resultant output pulse of several volts.

**scintillation counter**

A number of substances absorb energy from incident radiation and re-emit it as photons of light. These flashes, or scintillations, can be counted by photomultiplier tubes (Fig. 2-37) as a measure of radioactivity. Such an arrangement is called a *scintillation counter*. Fig. 2-38 is a table listing the most common scintillating materials and their significant characteristics. The scintillating element may be coupled directly to the photomultiplier tube or through "light-pipes" of fiber optical bundles.

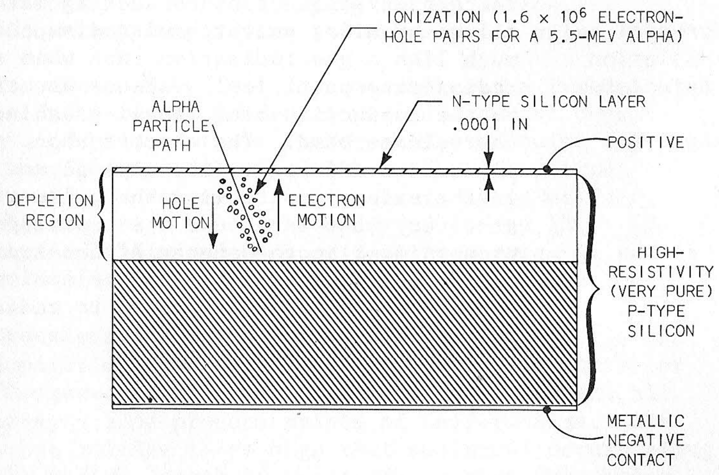



Fig. 2-36. Semiconductor detector.



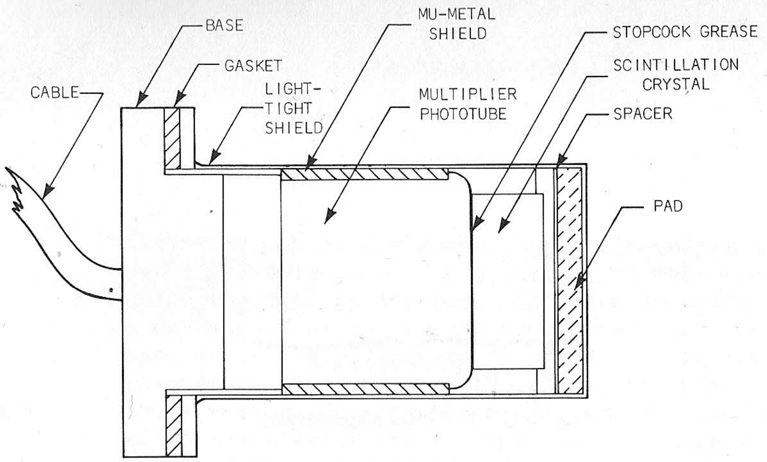



Fig. 2-37. Multiplier phototube and housing.

| SCINTILLATORS | | | |
|---|---|---|---|
| SCINTILLATOR | EMISSION WAVELENGTH, Å | RELATIVE EFFICIENCY PULSE HEIGHT | DECAY TIME, NANOSECONDS |
| ANTHRACENE | 4470 | 100 | 30 |
| NAPHTHALENE | 3450 | 11 | 81 |
| FLUORANTHENE | 4770 | 35 | 45 |
| DIPHENYLHEXATRIENE | 5900 | 2 | ? |
| TERPHENYL IN POLYSTYRENE (PLASTIC) | 3900-4300 | 48 | ·5 |
| TERPHENYL IN XYLENE (LIQUID) | 3900-4300 | 48 | 10 |
| XENON (GAS) WITH QUATERPHENYL | 2400-4380 | ??? | 5 |
| NaI (Tl) | 4100 | 210 | 250 |
| ZnS (Ag) | 4500 | 200 | $10^4$ |
| LiI (Eu) | 4400 | 75 | 250 |

Fig. 2-38. Scintillating materials.

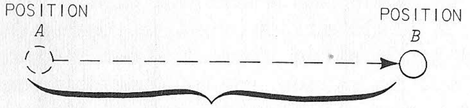



Fig. 3-1. Linear displacement.

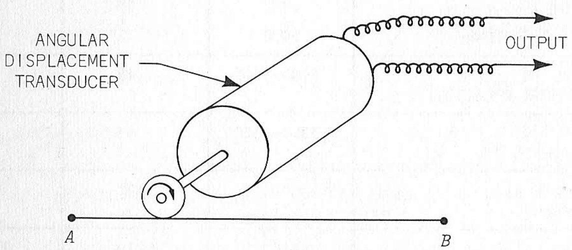



Fig. 3-2. Linear displacement measurement with angular displacement transducer.



# 3

## THE MEASURAND

Effective use of any measuring tool requires a working knowledge of the quantity, or measurand, to which the tool is applied. Accurate definition of a quantity does not always communicate the concept upon which the definition is based. It is the purpose of this chapter, therefore, to enumerate those measurands commonly subjected to transducer-aided measurement and to explore the concepts involved in that measurement. Special emphasis has been placed on those measurands which, in conventional applications, can be expected to vary at relatively high frequencies and which are therefore of particular interest in oscilloscope measurement applications.

In the following pages, measurands are grouped by the variable they describe. This system was adopted from the *ISA Compendium* published by the International Society of Engineers. It thus reflects the area of greatest interest to those in the field of transducer-aided measurement.

### MEASURANDS OF MOTION

All motion can be expressed in terms of displacement, which may be defined simply as the effect produced when an object or particle changes its position. All other measurands of motion are derivatives of displacement with respect to time.

linear displacement

Linear displacement ($s$) is measured in units of length (Fig. 3-1). Very small displacements are usually measured with strain gages, capacitive, inductive or photoelectric transducers. Ionization and electronic transducers are also used for this purpose. Larger measurements are made with slide-wire or potentiometric types. Measurements beyond the range of linear displacement transducers are made by converting linear to angular motion, which is then measured with an angular displacement transducer (Fig. 3-2).

In some applications, it is more feasible to measure velocity than displacement. In this case, the output of the velocity transducer can be electrically integrated to yield a measurement of displacement. With sufficient output, a simple *RC* circuit can be used for this purpose.

**angular displacement**

Angular displacement is a change in angular position, measured in degrees or radians. Angular displacement is usually measured by potentiometers or inductive transducers such as synchros, resolvers, inductive potentiometers, and similar devices. The symbol usually employed for angle of displacement is the Greek letter theta (θ) (Fig. 3-3).

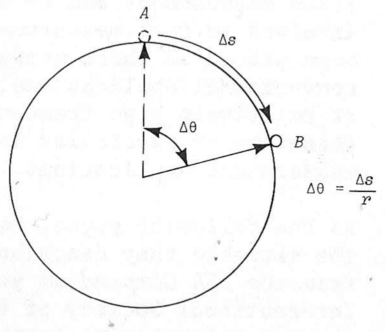



Fig. 3-3. Angular displacement.

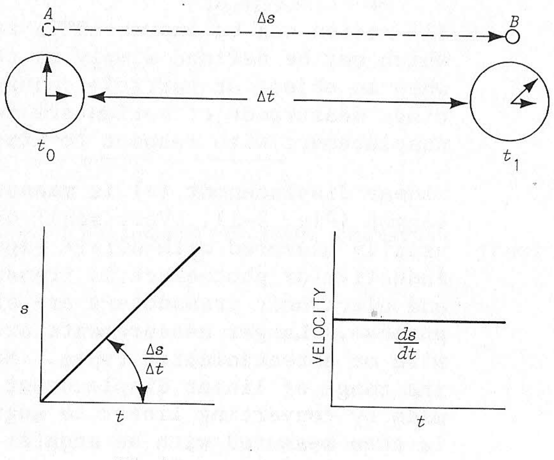



Fig. 3-4. Uniform linear velocity.



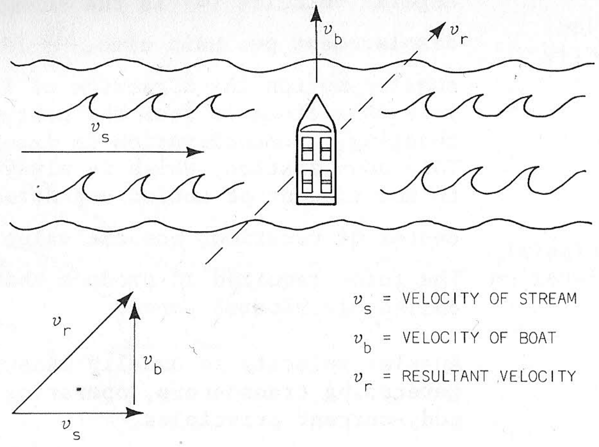



Fig. 3-5. Adding velocities.

**linear velocity**

Linear velocity ($v$) is the *rate of change of displacement*, $\frac{ds}{dt}$, and is measured in units of length per time unit (Fig. 3-4). It should be noted that the term "speed" is not synonymous with velocity since velocity must be defined in terms of speed *and direction*. Thus, as vector quantities, velocities are not additive arithmetically, but must be summed by vectorial methods (Fig. 3-5). However, speed can obviously be measured with velocity transducers.

Velocity is most easily measured by transducers whose output is proportional to the first derivative of displacement, such as the self-generating type of inductive transducer. Since stops are necessary to confine displacement to the linear region of signal generation, such transducers are limited to small or moderate displacement applications.

Velocity can also be calculated by measuring the time consumed by a moving object in traversing a measured distance. This method is particularly suited to measurement of high velocities, such as those encountered in the study of ballistics, nuclear radiation, etc. Because acceleration is the first derivative of velocity, it is also possible to measure velocity by electrically integrating the output of an acceleration transducer (see Acceleration).

angular velocity

Angular velocity ($\omega$) is the change in angular displacement per unit time, $\frac{d\theta}{dt}$ (Fig. 3-6). Since in angular motion the *direction* of linear motion of a mass at a distance from the center is constantly changing, an acceleration is imposed upon this mass. This acceleration, which is always at right angles to the tangent of motion and directed toward the center of rotation, has the value $\frac{v^2}{r}$ (Fig. 3-7).

centripetal acceleration

The force required to produce this acceleration is called *centripetal force*.

Angular velocity is usually measured with self-generating transducers, operating on induction or eddy-current principles.

linear acceleration

Acceleration ($a$) is the *rate of change* (first derivative) of velocity, $\frac{dv}{dt}$, or the second derivative of displacement, $\frac{d^2s}{dt^2}$. Units are those of length, divided by the square of unit time $\left[\frac{\text{length/time}}{\text{time}} = \frac{\text{length}}{\text{time}^2}\right]$. Common units are $cm/s^2$, $ft/s^2$ and "g." One g equals 32 $ft/s^2$ (9.8 $m/s^2$), the acceleration imposed on a free body at sea level by the earth's gravity. This same term is often mistakenly applied to the *force* exerted by the attraction of gravity, giving rise to confusion. However, since one g of acceleration of a mass requires a force equal to the *weight* of that mass, the term "g force" is commonly used.

Linear acceleration is measured with *accelerometers*. These transducers are described under the heading "Vibration and Shock" later in this chaper.

angular acceleration

Angular acceleration ($\alpha$) is the first derivative of angular velocity $\frac{d\omega}{dt}$ or the second derivative of angular displacement $\frac{d^2\theta}{dt^2}$ and is measured in units of angular rotation per unit time squared. Typical units are $radians/s^2$, $degrees/s^2$, or $revolution/min^2$. Measurements are usually made by electrically differentiating the output of an angular velocity transducer.



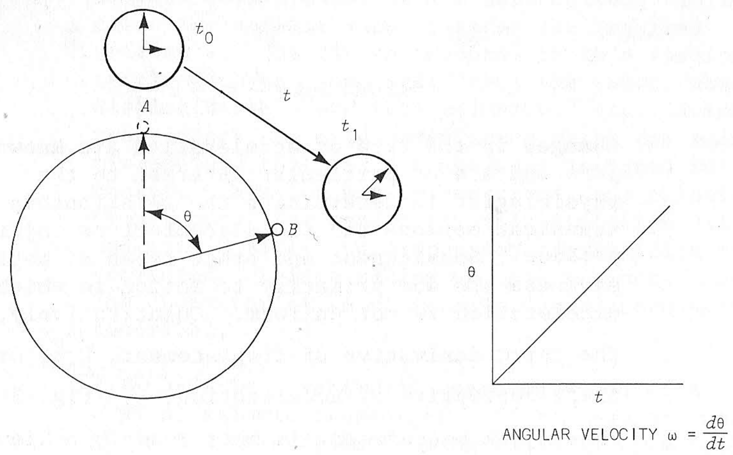



Fig. 3-6. Uniform angular velocity.

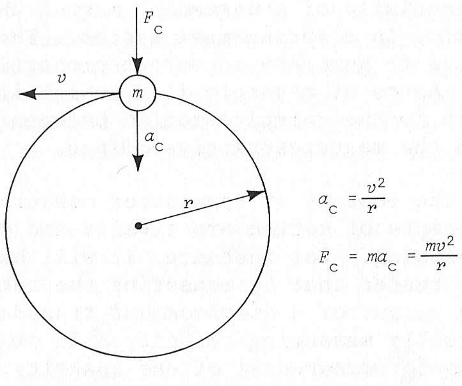



Fig. 3-7. Centripetal acceleration.

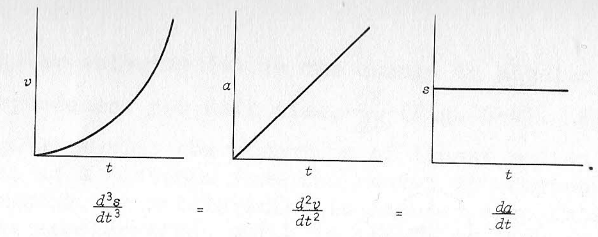



Fig. 3-8. Jerk $= \frac{da}{dt} = \frac{d^2v}{dt^2} = \frac{d^3s}{dt^3}$.

**jerk**

Changes in the rate of acceleration are known as *jerk* and are of particular interest to the physiologist in determining the relationship between transient motions and the discomfort or injury they produce. Seasickness and other types of motion sickness are due primarily to motion in which acceleration is not uniform. Quantitatively, jerk is the third derivative of displacement, $\frac{d^3s}{dt^3}$, or the first derivative of acceleration, $\frac{da}{dt}$ (Fig. 3-8). Thus, jerk measurement is most readily achieved through electrical differentiation of an accelerometer output. Since the piezoelectric accelerometer represents a capacitive source, only a low resistance load is required to perform the required integration with this type of transducer.

Another simple jerk-measuring system consists essentially of a permanent magnet which acts as the spring in a spring-mass system. The coil is located so as to generate an output proportional to the *rate of change* of magnetic flux, which in turn is due both to the relative motion between mass and coil and the magnetostrictive effect.

**dynamic measurements**

In the context of transducer measurements, the concepts of motion are elusive and sometimes confusing. For instance, it will have occurred to the reader that by measuring the rate of change in the output of a *displacement* transducer, he is actually measuring velocity. In other words, *dynamic measurement* of one quantity of motion yields readings in another. In contrast with the preceding example, a self-generating *velocity* transducer, although activated by displacement, yields an output in *velocity*. It should be clear then that correct interpretation of the results of many motion measurements requires an understanding of a transducer's operating principles, as well as the measurand itself.



**seismic transducers**

One of the most important tools of measurement in studies of motion is the "seismic mass" type of transducer. In many measurement applications, no fixed point of reference is available from which to measure displacement or its derivatives. In these cases the seismic mass provides the required reference. Quantities measured in this fashion are referred to as "absolute;" thus the terms "absolute displacement," "absolute velocity," etc. Seismic transducers are sold under names which are sometimes misleading; that is, a transducer designed to measure vibration may be described as a velocity transducer. The reason for this confusion will be understood after the discussion of vibration is completed. Before taking up this subject, however, the characteristics of seismic transducers must be described.

**accelerometer**

Fig. 3-9A is a schematic representation of a typical seismic transducer. If the support upon which the transducer housing rests is accelerated in an upward direction (Fig. 3-9B), the inertia of the mass causes it to resist this motion until the force exerted by the spring is equal to the product of the mass and the acceleration (see "Force"). The displacement of the mass is thus proportional to the acceleration and can be measured by the displacement sensor. The electrical output is thus also proportional to the acceleration. The device, used under conditions of constant or slowly changing acceleration, can thus be used as an acceleration transducer or *accelerometer*. If the output were electrically integrated with respect to time, the device could be used to measure velocity.

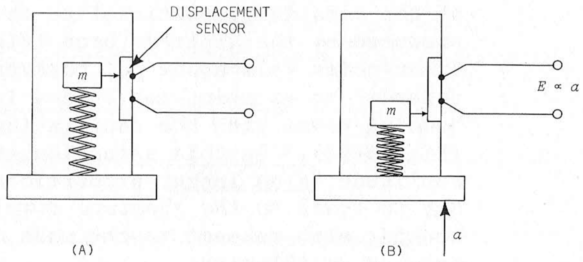



Fig. 3-9. Seismic transducer.

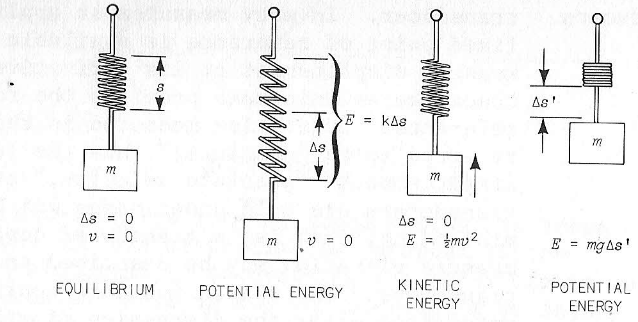


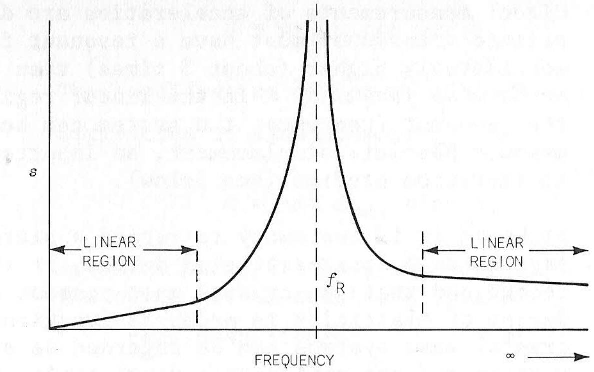

Fig. 3-10. Energy transfer at natural frequency.

If the acceleration is too rapid, or changes abruptly, the device may be entirely useless, however. This depends on the *mechanical* (frequency) *response* of the transducer. For all spring-mass systems, confined to a single degree of freedom (Fig. 3-10), there exists a frequency at which energy is transferred back and forth between the spring and the mass. This frequency is known as the *natural* or *resonant frequency* of the system and is found from the equation $f_R = \frac{1}{2\pi}\sqrt{\frac{m}{k}}$, where k is called the *spring constant* and is a measure of the "stiffness" of the spring.

resonant frequency

When an external oscillating force is applied to such a system and the relative displacement between housing and mass is plotted against frequency, a curve such as that shown in Fig. 3-11 will result. An examination of this curve reveals that at frequencies well below $f_R$ the displacement amplitude of the mass is proportional to the acceleration produced by the applied force (Fig. 3-12). At frequencies well above $f_R$, however, the mass can be regarded as existing motionless in space, while the housing moves with the oscillating support (Fig. 3-13). In this situation, the displacement amplitude is no longer proportional to acceleration but *is equal to the absolute displacement* of the housing with respect to the mass and to that of the imposed oscillation.





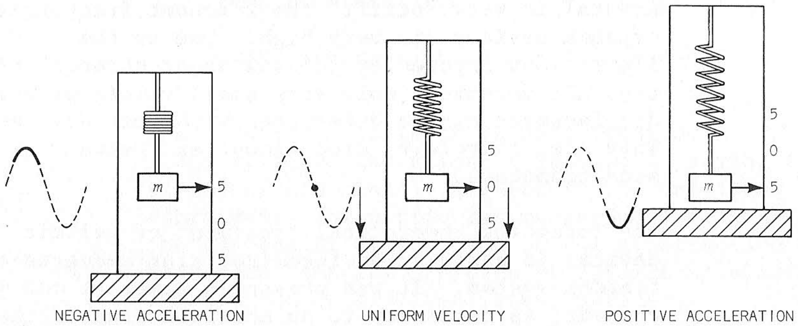




Fig. 3-12. Behavior of accelerometer below $f_R$.

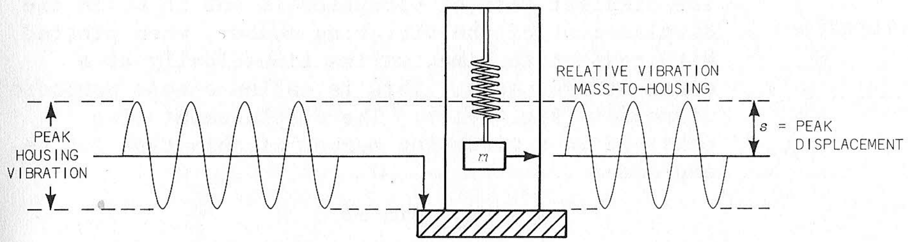



Fig. 3-13. Behavior of accelerometer above $f_R$.

Although the motion applied to seismic devices is not always oscillatory in nature, every change of motion has a frequency characteristic. Thus, where direct measurements of acceleration are desired, the seismic transducer must have a resonant frequency considerably higher (about 3 times) than the imposed or *forcing frequency*. In the linear region above the resonant frequency, the system can be used to measure absolute displacement, an important dimension in vibration studies (see below).

Although it is customary to regard a piezoelectric crystal as a force-activated device, it should be recognized that the crystal must possess a certain degree of elasticity in order to function. Thus, crystal-mass systems can be regarded as semiseismic devices and are employed in many accelerometers and vibration transducers. Because the piezoelectric crystal is very "stiff," the resonant frequencies of such devices are very high. Due to the limitations imposed by the low shear strength of the crystal, moreover, only very small values of peak displacement can be determined with such devices. They are, therefore, used almost exclusively as accelerometers.

The foregoing theoretical treatment of seismic devices is based on an idealized single-degree-of-freedom system. It was presented somewhat out of context, as necessary to an understanding of the related measurands of motion. The behavior of commercial seismic transducers in practical applications is discussed in Chapter 6.

vibration

The simplest form of vibration is one in which the displacement of the vibrating member, when plotted with respect to time, varies sinusoidally at a constant frequency. This is called *simple periodic vibration* (Fig. 3-14). The displacement of a particle in a vibrating member of this type can be expressed

$$s = s_{max} \sin \omega t$$

where $s_{max}$ is the maximum amplitude of displacement

$$\omega = 2\pi f$$

$$t = \text{time}$$



The velocity of the particle is the first derivative of displacement $\frac{ds}{dt}$ or

$$v = \omega s_{max} \cos \omega t$$

The acceleration of the particle is the second derivative of displacement $\frac{d^2s}{dt^2}$ or

$$a = -\omega^2 s_{max} \sin \omega t$$

An examination of the graph will reveal the following useful relationships:

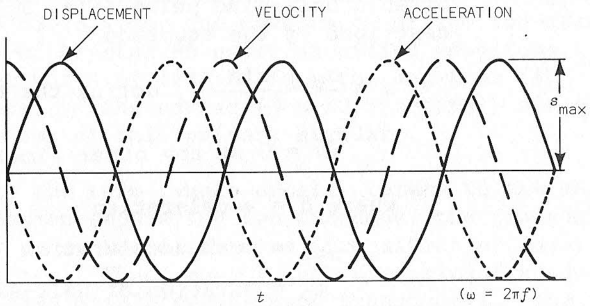
Peak displacement $= s_{max}$

Peak velocity $= \omega s_{max}$

Peak acceleration $= \omega^2 s_{max}$

Peak acceleration in g's $= \frac{\omega^2 s_{max}}{g}$

The quantity $s_{max}$ is of primary interest in vibration studies, since the stresses induced in a vibrating structure are closely related to the amplitude of the vibration. The particular measurand obtained from the transducer will depend on the construction of the transducer and the presence or absence of electrical integration or differentiating devices.




DISPLACEMENT $= s_{max} \sin \omega t$ PEAK DISPLACEMENT $= \Delta_{max}$

VELOCITY $= \frac{d(s_{max} \sin \omega t)}{dt} = \omega s_{max} \cos \omega t$ PEAK VELOCITY $= \omega s_{max}$

ACCELERATION $= \frac{d(\omega s_{max} \cos \omega t)}{dt} = -\omega^2 s_{max} \sin \omega t$ PEAK ACCELERATION $= -\omega^2 s_{max}$

Fig. 3-14. Relationship of measurands of oscillatory motion.

It should be clear now why some vibration transducers can be called velocity transducers as noted earlier in this discussion. That is, an accelerometer may sense vibration acceleration, but through electrical integration, provide an output proportional to vibration velocity.

Vibration rarely occurs as simple periodic motion. In most cases harmonic distortion will be present, and in some cases the vibration will be entirely random in amplitude and frequency. Simple periodic and harmonic vibrations are classed as *steady-state* vibration, since both are cyclic in nature. Random vibration, although entirely noncyclic, has a steady-state component.

shock

Shock is a special type of nonperiodic acceleration. It can be defined as an abrupt acceleration of a system, resulting from the application of a transient force of short duration. The absence of any steady state component distinguishes shock from random vibration, which is also aperiodic in nature.

The most significant characteristics of shock are the duration of acceleration, and the amplitude of acceleration. Both quantities are related to the ability of a structure to withstand dropping, collision, explosions, and similar catastrophes.

In shock testing, the acceleration waveform is most often a half-sine pulse (Fig. 3-15). This pulse is described by the equation

$$a = \frac{a_{max} \sin \pi t}{t_p} \quad \text{during the time } 0<t<t_p$$

($a$ = 0 at any other time)

where $a$ = acceleration

$a_{max}$ = peak acceleration

$t_p$ = duration of half-sine pulse

Shock, like vibration, is usually measured in inches/s$^2$ or g's.

Analysis of the output of vibration transducers requires a knowledge of vibration theory, a subject beyond the scope of this book.



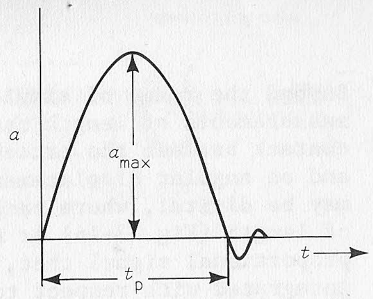



Fig. 3-15. Half-sine shock pulse.

## MEASURANDS OF DIMENSION

length

The primary standard of length was defined from 1899 to 1960 as the distance between two finely etched lines on a platinum-iridium bar known as the *International Prototype Meter* which is kept in a vault at 0°C at the International Bureau of Weights and Measures at Sevres, France. In the present state of technological and scientific development, even this standard lacks sufficient precision, so the International Meter is now defined as being 1650763.73 times the wavelength of the red-orange line of krypton 86 under specified conditons. All other units of length, from the angstrom ($10^{-12}$ meters) to the parsec ($3 \times 10^{16}$ meters), are defined in terms of this primary standard.

Since the term length usually refers to the shortest dimension separating two extremes, the transducer must sense the difference in position of these extremes. Thus, most length-measuring transducers are also displacement-input transducers. The particular operating principle of such devices depends largely on the magnitude of the measurement, as described under "Displacement."

Beyond the range of simple displacement transducers, measurements of length can be made by rolling contact between the article undergoing measurement and an angular displacement transducer. The output may be digital, where each pulse represents a unit of length (Fig. 3-16) or may be a velocity-proportional signal that, when electrically integrated with respect to time, yields a reading in terms of length.

thickness

Thickness is a linear dimension and can thus be measured with displacement transducers of all types, when appropriate mechanical linkage is provided.

Inductance-type transducers may be employed to measure the thickness of metallic sheets on a continuous basis (Fig. 3-17). Two electromagnets, one on each side of the material under measurement, are placed close to, but not in contact with, the material. Variations in thickness change the mutual inductance of the system, causing variations in the excitation current which can be calibrated and read out in terms of thickness. The same materials may be measured by a magnetic reluctance system in a similar manner. In this application a single electromagnet suffices. Only very thin sheets or foil can be measured by this method. The same is true of capacitive systems, where the moving sheet acts as the capacitor dielectric.

Other methods employ photoelectric or nuclear radiation transducers. An example of the second application is shown in Fig. 3-18. Radiation transducers sense the amount of radiation from a source on the opposite side of the sheet. Variations in thickness cause variations in the amount of radiation absorbed by the sheet, resulting in current changes in the radiation detector.



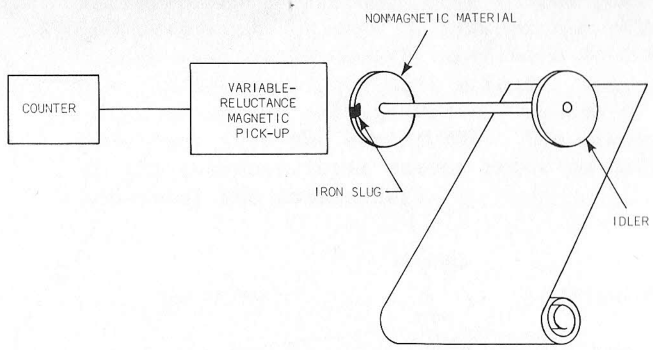



Fig. 3-16. Measurement of material length.

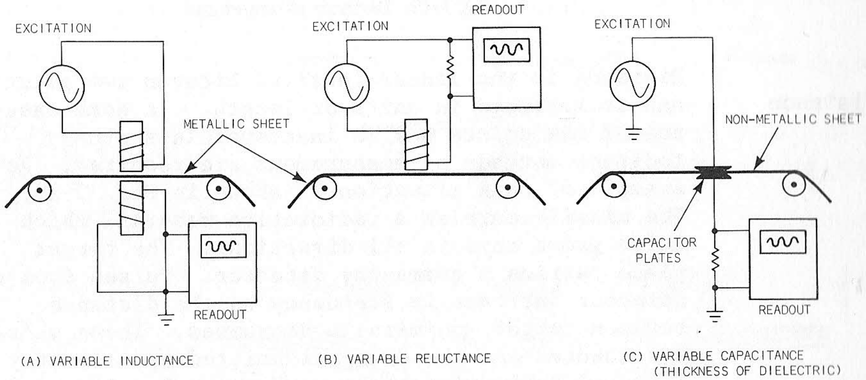



Fig. 3-17. Thickness measurement.

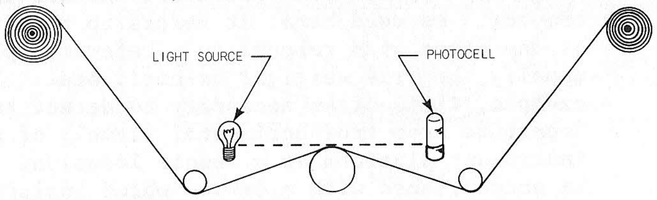



Fig. 3-18. Photoelectric transducer measurement of thickness.

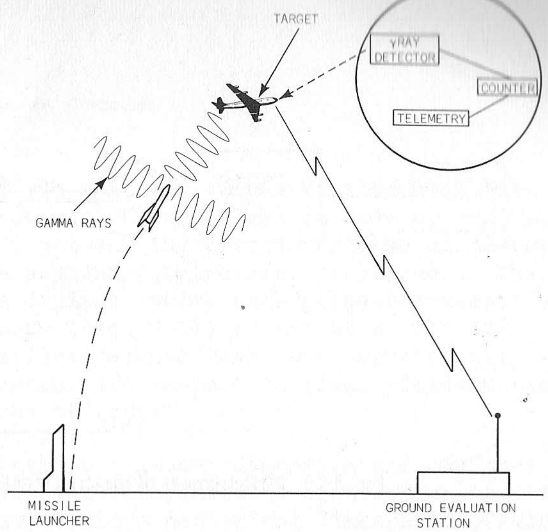



Fig. 3-19. Distance measurement.

**distance**

Distance is the linear interval between two points and is measured in units of length. In some cases, one of the points may be inaccessible so that indirect methods of measurement are required. An example of this situation is shown in Fig. 3-19. The missile carries a radioactive material which emits gamma rays in all directions. The target plane carries a gamma-ray detector. Pulses from the detector increase in frequency as the distance between target and missile decreases. These pulses are counted and the data transmitted by telemetry to a ground evaluation station, where pulse frequency is translated in terms of distance.

**angle**

The quantity called "angle" is not the same as "angular displacement" discussed earlier in this chapter. As used here, it refers to the inclination of one plane with respect to a reference plane, usually the true vertical or horizontal. For example, it is often necessary to detect any departure from true horizontal (level) of an instrument platform at a remote location. This can be accomplished with a device which includes a transducer of the type shown in Fig. 3-20A. When the device rests on a true horizontal reference plane, the electrolyte in the transducer is distributed so that the resistance between electrodes A and C and between B and C are equal.



Any departure of the transducer from the horizontal increases the resistance between one pair of electrodes and reduces it between the other. A bridge circuit is usually used with this device to take advantage of the dual effect. Fig. 3-20B is a graph of output voltage versus minutes of "tilt," or departure from the horizontal. The numbers assigned to the characteristic curves refer to different models of the transducer.

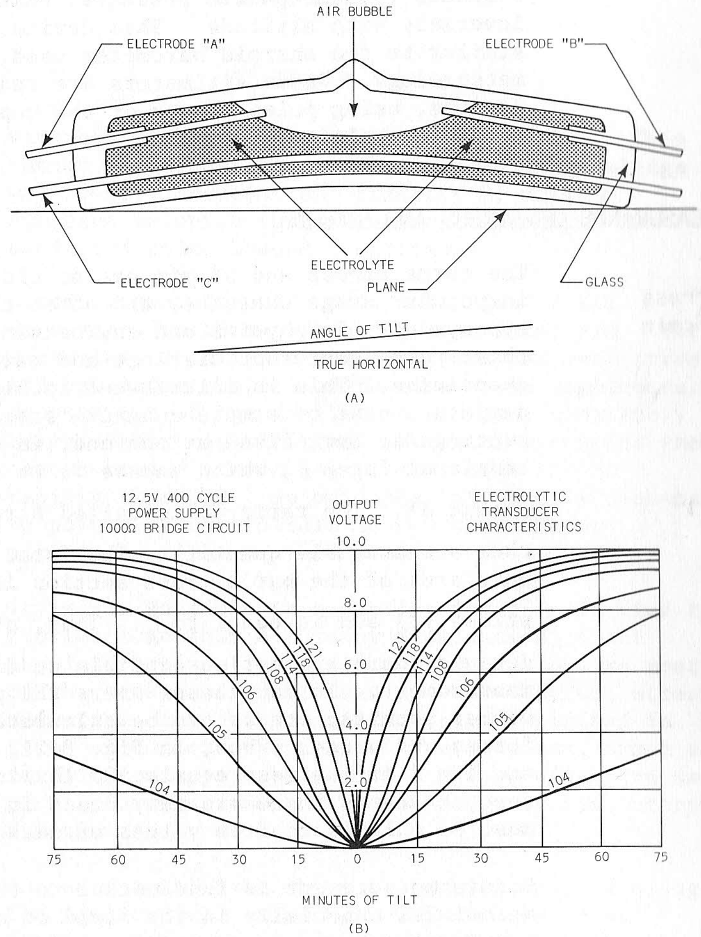



Fig. 3-20. Angle measurement transducer.

altitude

Altitude is a measure of the vertical distance between a point above sea level and sea level itself. When referring to points on the earth's surface, the term "elevation" is used. Units customarily employed are feet or meters, depending on the country involved.

Transducers designed to measure altitude are called altimeters and may operate on one of several physical principles. By far the most common type responds to atmospheric pressure, which varies inversely with altitude. This device is very similar to the aneroid barometer used in meteorology. Radio altimeters are radar-type devices, using pulse echoes or the Doppler effect to measure altitude.

## MEASURANDS OF STRESS AND STRAIN

stress
strain

The terms *stress* and *strain* are so closely associated in popular usage that they are often thought to be synonymous. In physics and engineering, however, these terms represent distinct and carefully defined quantities. This is illustrated in Fig. 3-21, which depicts a case of simple uniaxial stress. A rectangular bar, fixed at one end, is subjected to tensional force $F$, which causes it to stretch by the amount $\Delta l$. The ratio $\frac{\Delta l}{l}$ is called strain ($\varepsilon$) and is thus a measurable quantity. The force exerted per unit area of the bar's cross section is called stress ($\sigma$) and is equal to $\frac{F}{A}$. Thus, stress is a derived quantity, not susceptible to direct measurement. In many cases where the geometry of the member permits, stress can be calculated from known forces and areas. Thus, in Fig. 3-21, if $F$ = 1000 lbs and $A = 2$ in$^2$, stress equals 500 lbs/in$^2$. As will be seen, however, there are many cases in which stress must be calculated from values of measured strain.

Strain measurement is fundamental to the study of materials, especially in the field of engineering. For fairly obvious reasons of economy, weight reduction and overall efficiency, it is desirable that a structure or machine be designed with maximum



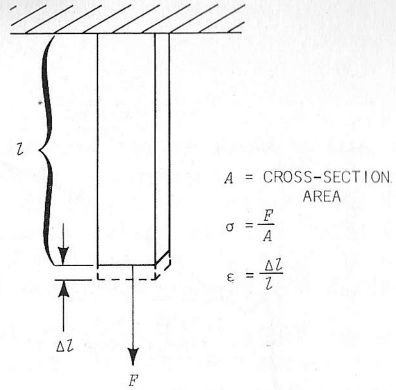



Fig. 3-21. Uniaxial tension.

strength with the least amount of material. This cannot be accomplished without accurate knowledge of *magnitude*, *direction* and *location* of *maximum stresses* to which that structure or machine is subjected under loaded conditions.

Strain magnitudes vary from infinitely small dimensions to those visible to the naked eye. For centuries, scientists and engineers had only crude and expensive tools to determine these magnitudes. Measurement of the smaller strains was completely beyond their capabilities. With the advent of the modern bonded strain gage, this situation has rapidly improved. As evidence, it is only necessary to point out that strain is now measured in microinches/inch or *microstrains*.

micro-
strains

It is not possible in a publication of this kind to provide more than a cursory examination of the physical basis of strain measurement. Unlike most of the measurands described in this chapter, stress and strain cannot be satisfactorily explained in terms of common experience. Nevertheless, armed with certain concepts, the reader can make effective use of strain-measurement devices and correctly interpret the results.

In the special case where a force is applied along the longitudinal axis of a member whose cross-sectional area is constant throughout its length, the stress-strain relationship is fairly simple.

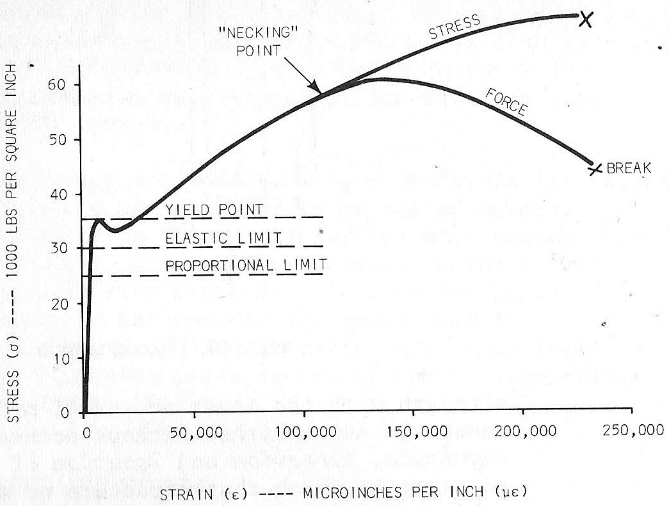



Fig. 3-22. Stress-strain curve of low-carbon steel.

Hooke's law

Young's modulus

According to *Hooke's law*, the ratio of stress to strain in materials having the property of elasticity is constant. This constant is known as the *modulus of elasticity* or *Young's modulus* and is a characteristic of that particular material. This relationship is expressed mathematically

$$E = \frac{\sigma}{\varepsilon} \qquad (3\text{-}1)$$

Where $E$ = Young's modulus

$\sigma$ = stress

$\varepsilon$ = strain

Stress is commonly expressed in $lbf/in^2$ (PSI). Strain, as stated earlier, is usually measured in $10^{-6}$ inches/inch. Strain therefore is a *dimensionless number*. Young's modulus is expressed in the same units as stress, usually $lbf/in^2$.



Although not so stated in Hooke's law, the simple proportional relationship between stress, strain and the modulus of elasticity exists *only in the special case of uniaxial stress* and then *only in the direction of maximum stress*, which in this case is also the direction of the applied force.

Another qualification which Hooke neglected to include is that the ratio of stress to strain remains constant *only within limits*, which vary from one material to another. This is illustrated by a graph of the stress versus strain relationship in low-carbon steel under the conditions shown in Fig. 3-22.

Up to about 25,000 $lbf/in^2$, the stress-strain relationship is constant. The slope of this linear portion of the curve represents Young's modulus. (The linear portion also extends through zero in the minus direction for compression strains.) At the point labeled "*proportional limit*," the curve begins to fall off -- that is, the ratio of stress to strain begins to decrease. Beyond the point labeled "*elastic limit*," the material will fail to return to its original dimensions when stress is removed. At the point marked "*yield point*," the material exhibits a degree of "plasticity" where elongation increases at a constant stress. In this area, carbon steel (but not all materials) tends to harden (called strain- or work-hardening). The material then resists further plastic deformation and stress increases with strain (at a decreased ratio) until the material ruptures. The dotted line in this diagram represents the force required. As the material elongates, a localized reduction in cross-sectional area called "necking" takes place at some point. Since stress is defined as $\frac{F}{A}$, less force is required to produce a given stress at that point.

yield strength

Hard steels and other brittle metals have no yield point, passing directly from proportional to nonproportional behavior (Fig. 3-23). To determine the *yield strength* of such materials, the *offset method* is used. In practice, the metal is stressed beyond its proportional limits, leaving the material with a permanent set when the stress is removed. The effect provides a basis for classifying the brittle materials. Stress is brought to point Y, then slowly reduced to zero. The stress-strain characteristic will follow the line Y-X, approximately parallel to the proportional portion of the first curve. The horizontal distance between point X and the origin represents the permanent set or "offset" of the material *at the particular value of stress which produced it.* "*Percent offset*" is found from the equation

offset

$$\% \text{ offset} = 100 \times \frac{\text{offset in microinches/inch}}{10^6}$$

Yield strength of stainless steel, as shown in Fig. 3-23, is 47,000 $lbf/in^2$ at 0.1% offset.

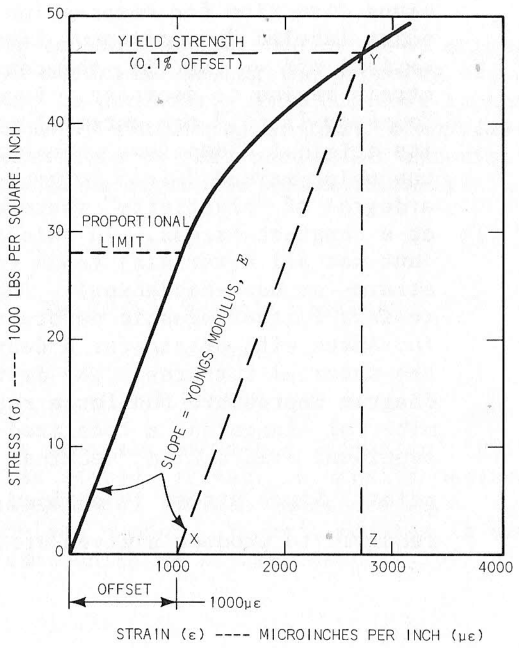



Fig. 3-23. Stress-strain curve of stainless steel.



The modulus of elasticity remains essentially constant for a certain metal, regardless of treatment, alloying, or manufacturing technique; for example, Young's modulus for steel of all kinds is approximately 3 x $10^7$ $lbf/in^2$ and aluminum is $10^7$ $lbf/in^2$.

In the remainder of this discussion, it will be assumed that *all stresses examined are within the proportional limits.*

In the case of simple uniaxial stress presented above, it can be shown that in addition to the tensional strain along the longitudinal axis, another strain occurs at right angles to the axis, even though no stress exists in that direction. Such strain can be explained by observing the behavior of a strand of rubber under increasing tension. It is quite apparent that as the band stretches, it becomes thinner; that is, its cross-sectional area decreases. Since the volume of rubber in the strand remains constant, the cross-sectional area of the strand *must* decrease as the length of the strand increases. This change in lateral dimension is, according to the definition, a kind of strain.

Such lateral strain always accompanies the primary strain, and is always of opposite sign; that is, tension produces transverse compression strain, while compression results in transverse tension strain. This phenomenon is called the *Poisson effect*; the relationship between the transverse and primary strain is called the *Poisson ratio* (μ), and is relatively constant within the proportional limits. This relationship is expressed

Poisson ratio

$$\mu = \frac{\text{lateral strain}}{\text{longitudinal strain}} \qquad (3\text{-}2)$$

Since compression is *negative* tension, μ is always a negative number.

The theoretical value of this ratio, about -0.25, has been confirmed quite closely by experimental evidence. Structural steel, for instance, exhibits a Poisson ratio of about -0.3.

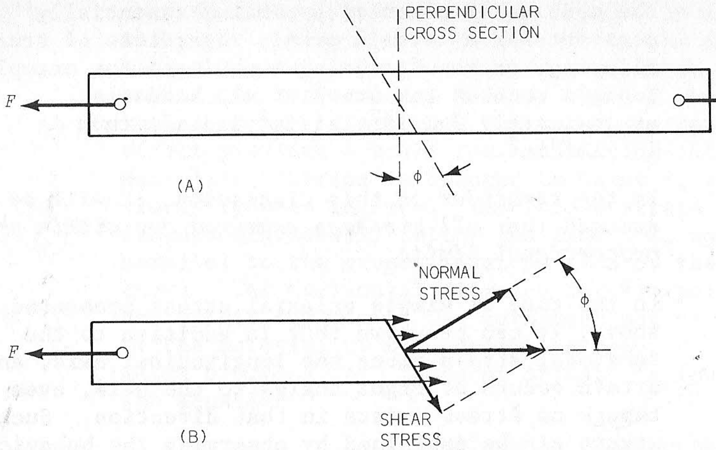



Fig. 3-24. Conditions of stress at oblique cross section.

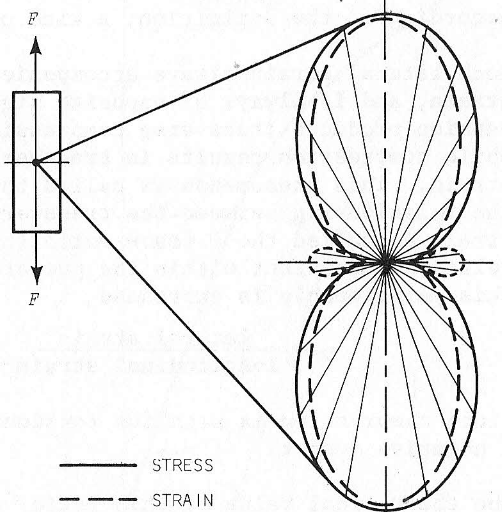



Fig. 3-25. Stress-strain field at point in stressed member.



To complete the picture of uniaxial stress, the concepts of normal and shear stress must be introduced. If the state of stress at an oblique cross-section of the tensionally loaded member is vectorially analyzed, it will be seen that two stresses are present at any point in that cross-section, one normal to the cross-section and one tangent to it (Fig. 3-24). The value of the *normal stress* is $\frac{F}{A}\cos^2 2\phi$ and that of the tangential or *shear stress* is $\frac{F}{A}\sin 2\phi$. A brief examination will reveal that normal stress is maximum and shear stress is zero when $\phi$ is zero, while shear stress is maximum when $\phi = 45°$. These stresses and their corresponding strains together with the Poisson strains, combine to form a so-called stress and strain field, as shown in Fig. 3-25. The scale of the diagram has been chosen so that the stress and strain vectors are equal in the direction of the maximum stress. It can be seen that if the relationship $\sigma = E\varepsilon$ is true in this direction, *it cannot be true in any other.*

normal stress

shear stress

When *two or more* forces are applied to the same member, the resulting stress fields assume a variety of shapes, depending on their relative angles and magnitudes. Nevertheless, in any such field the *maximum and minimum values of stress will always be at right angles to each other.* These stresses are called the *principal stresses*, their axes are the principal axes, and the planes on which they act, the *principal planes.*

principal stresses

It should be clear now why, as emphasized earlier, the simple Hooke's law relationship is not valid in cases of multi-axial stress. The combination of various strains, including those due to the Poisson effect, results in principal strains, which must *both be taken into account in calculating either of the principal stresses.*

Fortunately, the problem can be solved through analytical geometry. Although space does not permit a presentation of such an analysis in this volume, a graphic solution, based on a construction called Mohr's circle, will be demonstrated shortly. Since the analysis yields values of shear strain, as well as principal strain, however, it may be advantageous to first point out the significance of shearing forces in the study of stress.

shear

The concept of shear strain was introduced earlier in explaining the existence of a strain field in a stressed body. Many materials behave differently under shearing forces than under tension and compression. Glass, for instance, has a very high *tensile strength*, exceeding that of most steel alloys. Its *shear strength*, however, is extremely low. Thus it is often very important to determine the extent of shearing strain in a given structure.

Shearing strain, $\gamma$, is expressed in radians, rather than in units of length. This is illustrated in Fig. 3-26. A shearing force $F$ is applied to the cross-section ABCD of a block of material anchored firmly on side AD. This force causes distortion of the block so that its cross-section now occupies a position AB'C'D. For very small displacements, the dimension AB can be considered unchanged, and the sine of the small angle $\gamma$ can be considered equal to the angle itself. Thus

$$\gamma = \frac{BB'}{AB'}$$

As in the case of tensional strain, $\gamma$ is a dimensionless quantity.

In the particular case of biaxial stress where $\sigma_x = -\sigma_y$, as shown in Fig. 3-27, a unique situation exists. Along the 45° planes of maximum shear stress, the normal stresses cancel out, while the tangential stresses equal $\pm\sigma_x$ (or $\pm\sigma_y$). It follows then, that the small square element ABCD oriented at 45° to the directions of principal stress is in a state of shear *only on its edges*. This condition is described as one of *pure shear* and is of particular interest in stress analysis.

pure shear

Experiments have demonstrated that in cases of pure shear within the elastic limit of a material, shearing strain is proportional to the shearing stress $\tau$ that produces it. Thus, the relationship

$$\gamma = \frac{\tau}{G} \qquad (3\text{-}3)$$

where $G$ is a new constant of proportionality called the *shear modulus*. Like the tension modulus $E$, it has the dimensions of stress, lb/in$^2$.



An examination of Fig. 3-27 will reveal that there is a geometrical relationship between the linear strains $\sigma_x$ and $\sigma_y$ and the shearing strain $\gamma$. An analysis of this relationship reveals that, in theory,

$$G = \frac{E}{2(1 + \mu)} \qquad (3\text{-}4)$$

Experiments have supported this theoretical relationship quite closely, and it is thus possible to find the shear modulus of elasticity using the theoretical value of Poisson's ratio (-0.25) and Young's modulus for a given material.

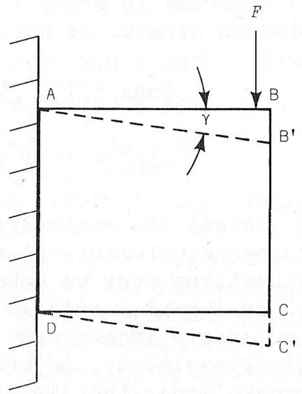



Fig. 3-26. Shear strain.

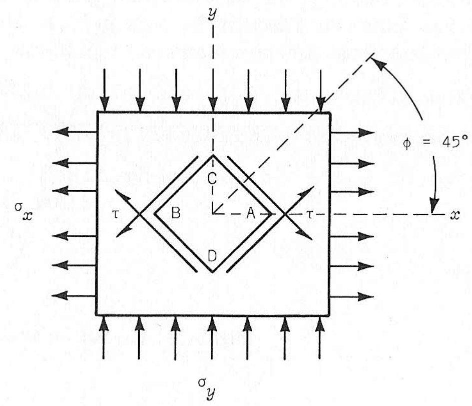



Fig. 3-27. Strain conditions when $\sigma_x = \sigma_y$.

Now that the basic concepts of stress and strain, both tensional and shear, have been set forth, it is possible to present the graphical solution to a typical stress problem, as promised earlier.

In the case of plane, or two-dimensional, stress (to which this discussion is limited), the maximum principal stress is a function of both maximum and minimum principal strains. The same is true for the minimum principal stress. Thus, both strains must be measured in order to calculate either maximum or minimum stress, or both. The applicable equations are:

$$\sigma_{max} = \frac{E}{1 - \mu^2}(\varepsilon_{max} + \mu\varepsilon_{min}) \qquad (3\text{-}5)$$

$$\sigma_{min} = \frac{E}{1 - \mu^2}(\varepsilon_{min} + \mu\varepsilon_{max}) \qquad (3\text{-}6)$$

Mohr's circle

To obtain the necessary data for this solution, three measurements of strain in three different directions must be taken from the member under test. An arbitrary $x$ axis is laid out on the test member and strain is measured at angles $\phi_1$, $\phi_2$ and $\phi_3$. The first angle, $\phi_1$, is usually made equal to zero for convenience; that is, the first strain measurement, $\varepsilon_1$, is made along the selected $x$ axis.

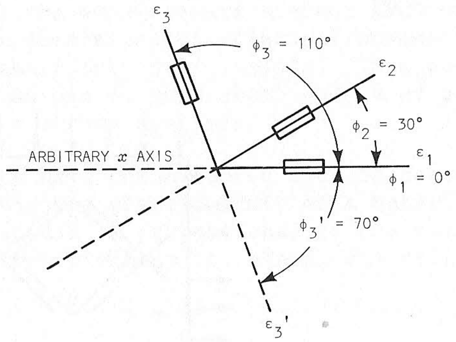



Fig. 3-28. Layout for strain measurement.



The first step of the graphical solution is to lay out the strain axes on paper as they were on the test member (Fig. 3-28). Then, selecting the axis of the strain of *intermediate magnitude* as the arbitrary $x$ axis, the angles to the adjacent axes are determined. Thus, if the three measured strains are:

$$\varepsilon_1 = 200 \times 10^{-6}$$

$$\varepsilon_2 = 350 \times 10^{-6}$$

$$\varepsilon_3 = -100 \times 10^{-6}$$

the intermediate strain is $\varepsilon_1$. (Negative strains are always considered to be *smaller* than positive strains even though their magnitudes may be numerically larger.) The nearest axes are thus $\varepsilon_2$ at an angle 30° counter-clockwise and $\varepsilon_3$ at angle $\phi_{3'}$ clockwise. By examination, $\phi_{3'}$ = 180° - 110° = 70°. Note that lines $\varepsilon_1$, $\varepsilon_2$ and $\varepsilon_3$ represent only the axes and not the magnitudes of the respective strains.

The next step is to set up a coordinate system in which the horizontal scale is graduated in convenient multiples of normal strain and the vertical scale in corresponding multiples of shear strain. The value $\frac{\gamma}{2} \times 10^{-6}$ is usually used in graduating the vertical scale to preserve axial symmetry. Positive values of $\frac{\gamma}{2}$ are below the horizontal axis.

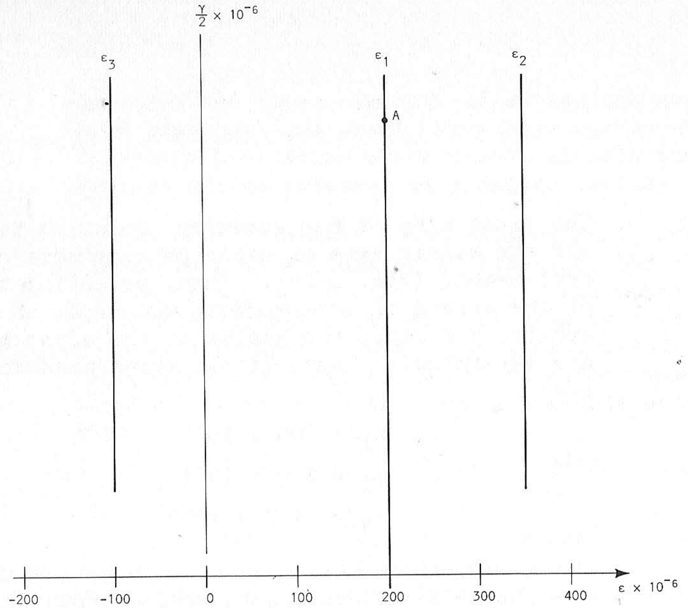



Fig. 3-29. Established strain magnitudes.

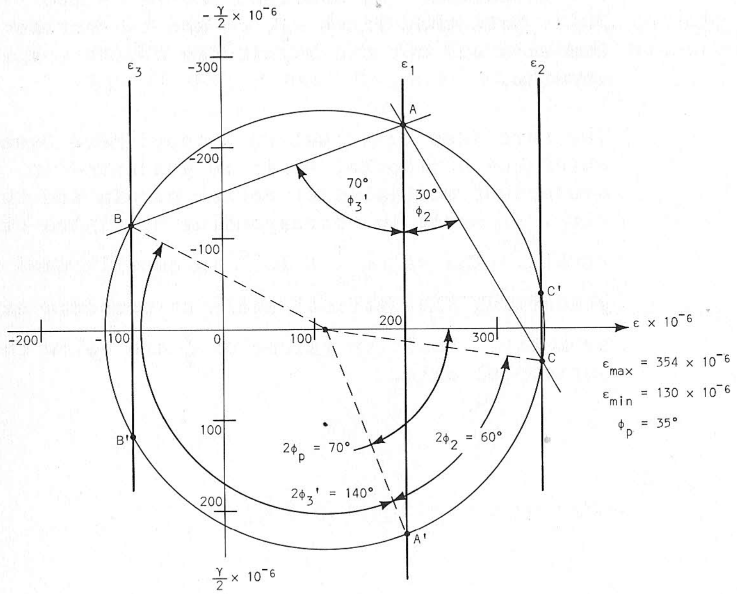



Fig. 3-30. Mohr's circle solution.



In constructing Mohr's circle, only the vertical axis is initially established (Fig. 3-29). Parallel to this axis three lines are drawn at distances corresponding to the magnitudes of $\varepsilon_1$, $\varepsilon_2$ and $\varepsilon_3$. On the line representing the strain of intermediate magnitude a point A is arbitrarily selected. From this point, lines are drawn at the *same angles* and in the *same relative positions* as the greater and lesser strains axes in Fig. 3-28. Thus, in Fig. 3-30, one line is laid out 70° clockwise from the $\varepsilon_1$ line, intersecting the $\varepsilon_3$ line at point B, and the other line is drawn 30° counter-clockwise, intersecting the $\varepsilon_2$ vertical at point C. Points A, B and C all lie on Mohr's circle, and the $\varepsilon$ axis passes through the center, which is located at the intersection of the perpendicular bisectors of lines AB and AC.

After drawing the $\varepsilon$ axis through the center, the vertical scale can be filled in on both sides of the origin, remembering that positive values read downward.

It is now possible to determine the magnitude and direction of the maximum and minimum principal strains, as well as the complete state of strain (shearing as well as normal strain) along the axes of the actual *measured* strain. It will be remembered, however, that point A was chosen arbitrarily. As a result, the points which define the true state of strain may lie on either the upper or lower half of the circle. In the present example, for instance, the circle intersects $\varepsilon_1$ at point A' as well as point A and $\varepsilon_2$ at C' and C. To determine the correct values of shearing strain along the measurement axes, it is only necessary to apply a simple rule.

Returning to the initial construction in Fig. 3-28 and proceeding counter-clockwise from $\varepsilon_3'$ through $\phi_3'$ and $\phi_2$, the sequence is $\varepsilon_3$, $\varepsilon_1$, $\varepsilon_2$. On Mohr's circle, the *same sequence exists* between the true points of strain but, due to the geometrical characteristics of the construction, the *included angles are doubled*. Thus in Fig. 3-30, proceeding counter-clockwise from point B on line $\varepsilon_3$ through an angle of 140°, one arrives at A', then through an angle of 60° to point C. These points represent the true state of strain on the *respective* measurement axes.

The maximum and minimum principal strains occur where the circle intersects the $\varepsilon$ axis, since the shearing strain at these points is zero. The corresponding maximum and minimum stresses are found by inserting these values in equations 3-5 and 3-6. Assuming that the material of the member is steel, having $E$ = 30 x $10^6$ PSI and $\mu = -0.3$, the results would be:

$$\sigma_{max} = \frac{30 \times 10^6}{1 - 0.3^2} (354 - 0.3 \times -130) \times 10^{-6} =$$

$$\frac{30}{.91} (393) \simeq 13{,}000 \text{ PSI}$$

$$\sigma_{min} = \frac{30 \times 10^6}{1 - 0.3^2} (-130 - 0.3 \times 354) \times 10^{-6} =$$

$$\frac{30}{.91} (-241) \simeq -6600 \text{ PSI}$$

The direction of maximum principal strain, $\phi_p$, is found by proceeding counter-clockwise from point A' around the circle to the point representing $\sigma_{max}$. This angle equals $2\phi_p$. (If point A represented the *true* state of strain on the $\varepsilon_1$ axis, the angle would, of course, be measured from that point.) Referring to the construction just completed, it is seen that $\phi_p$ = 35°. The direction of the minimum principal strain is, of course, 90° from this point, or 125°. Fig. 3-31 shows the relationship between the original strain measurements and the calculated stresses.

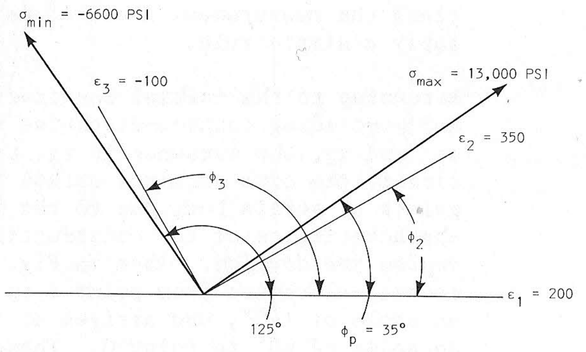



Fig. 3-31. Establishing direction of principle stresses.



Consider a circular shaft, anchored firmly at one end (Fig. 3-32A). To the other end a bar is attached. Two equal and opposing forces are applied perpendicular to this bar and in a plane perpendicular to the axis of the shaft. This pair of forces is known as a *couple* and the rotational force applied to the shaft is called torque ($T$). In the example shown, $T = Fl$, or the product of either of the forces and the distance between them. This is a case of *pure* torque.

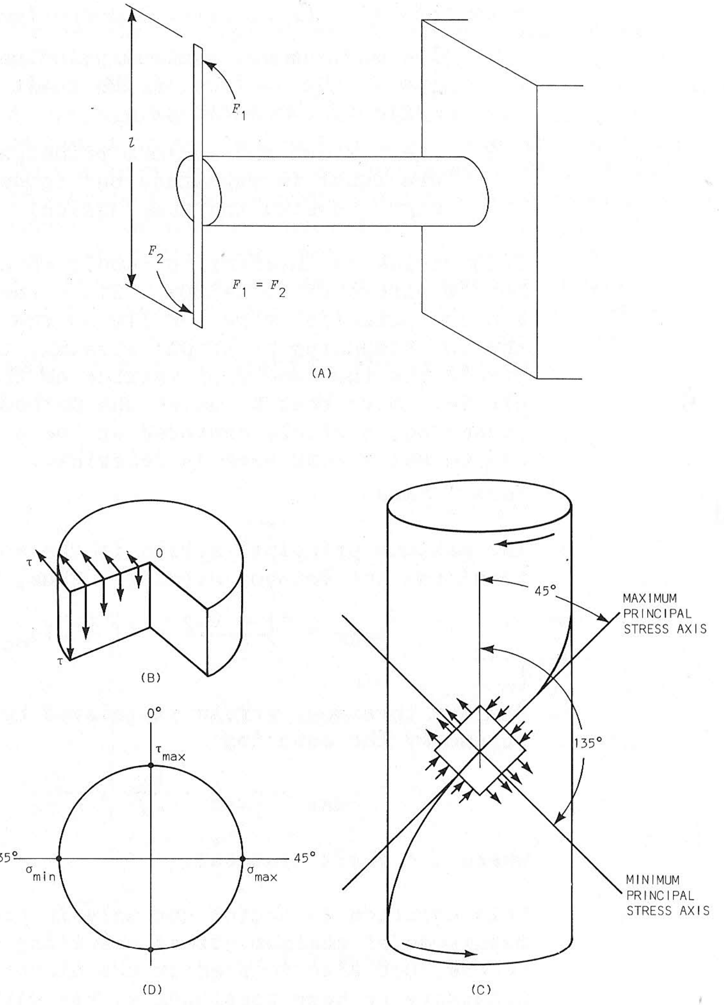



Fig. 3-32. Torque.

Two important relationships remain to be examined at this point. The first of these is the relationship between *torque* and *torsional strain.*

The twisting effect of torque upon the shaft sets up both longitudinal and shearing stresses in the shaft, which vary directly with the distance from the center (Fig. 3-32B). From the previous discussion of pure shear, it is evident that at an angle of 45° with the shaft, a segment taken at the surface is in a state of *compression* in one direction and *tension* in the other (Fig. 3-32C). From this situation, several deductions can be made.

1. The maximum and minimum principal stresses lie at the surface of the shaft at a 45° angle to the shaft axis.
2. The maximum and minimum principal stresses are equal in magnitude but opposite in sign (tension and compression).

This yields an interesting result when applied to Mohr's circle (Fig. 3-32D). Since the maximum and minimum principal stresses lie on the same axes as the corresponding principal strains, the *stress circle* has the same conformation as the strain circle. Note that by using the methods just presented, a circle centered at the origin of shear and normal stress axes is described. Thus, $\tau_{max} = \sigma_{max}$.

The maximum principal strain is the sum of the tensional and Poisson strains. Thus,

$$\varepsilon_{max} = \frac{\sigma 1 - \mu\sigma 2}{E} = (1 + \mu)\sigma_{max} \qquad (3\text{-}7)$$

Maximum torsional stress is related to the applied torque by the equation

$$\tau_{max} = \sigma_{max} = \frac{16T}{\pi d^3} \simeq \frac{T}{0.2d} \qquad (3\text{-}8)$$

where $d$ = shaft diameter.

This equation is useful not only in predicting the magnitude of maximum stress resulting from a given torque, but also to predict the diameter of a shaft necessary to keep torsional stress within desired limits of stress or strain.



twist angle

It is often useful to relate the angle of twist, θ, of the shaft to the torque which caused it. The approximate equation is

$$\theta = \frac{32Tl}{G\pi d^4} \qquad (3\text{-}9)$$

where $l$ = length of the shaft

$d$ = diameter of the shaft

$G$ = shear modulus

bending strain

The remaining type of strain to be examined is that called *bending strain.* Fig. 3-33A illustrates the basic elements of a typical bending strain situation. A rectangular beam of some elastic material is anchored at one end and free to move at the other. Such a beam is called a cantilever. Width $b$ and thickness $h$ are constant over its entire length. A force $F$ is applied perpendicular to the surface at the end of the beam, point P. A point P' is arbitrarily selected between P and the anchored end. The distance between these points is represented by $l$. In response to the applied force, the beam will be bent downward by the amount $\Delta s$.

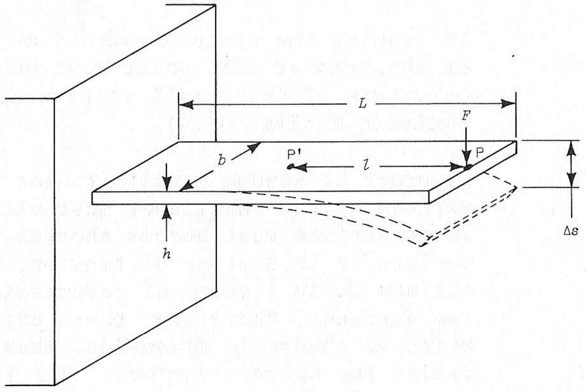



Fig. 3-33. Bending stress.

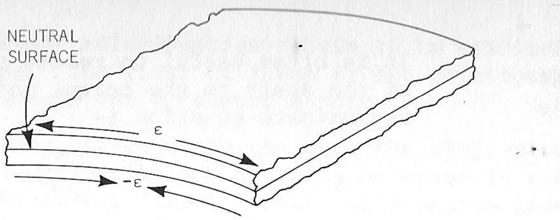



Fig. 3-34. Expanded section of Fig. 3-33 beam after force is applied.

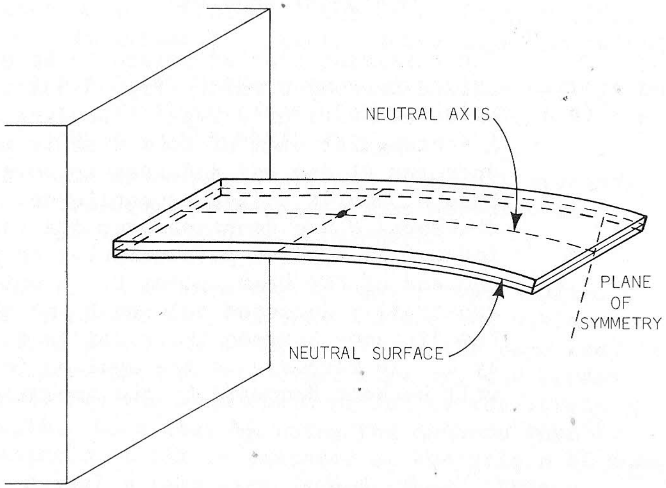



Fig. 3-35. Geometrical components of bending stress problem.

To examine the state of stress at P', a small section of the beam at that point must be examined. The curvature of this small section approximates a semicircle (Fig. 3-34).

In order to assume a semicircular shape, the upper surface of the cantilever must elongate, while the lower surface must become shorter. Thus, the upper surface is in a state of tension, while the lower surface is in a state of compression. Between the two surfaces, therefore, there exists a plane in which no change in dimension takes place. This is called the *neutral surface*. The intersection of this surface with the plane of symmetry is called the *neutral axis* of the beam and its intersection with the plane of any cross section becomes the neutral or Z axis of that cross section (Fig. 3-35).

neutral surface

neutral axis



If the cantilever beam is regarded as consisting of an infinite number of longitudinal fibers, it can be seen that the stress on a single fiber varies directly with its distance from the Z axis. It has been proven experimentally that the relationship between stress and strain in these fibers is the same as that for simple tension and compression. Thus

$$\sigma_x = E\varepsilon_x$$

moment of inertia

The summation of the areas of all the individual fiber cross sections with respect to the Z axis is known as the *moment of inertia* and is expressed

$$I = \int y^2 dA \qquad (3\text{-}10)$$

where, in a rectangular beam, $y = \frac{h}{2}$. Performing the integration

$$I = \int y^2 dA = b\int_{-\frac{h}{2}}^{+\frac{h}{2}} y^2 dy \quad \text{(See Fig. 3-36)}$$

$$I = b\left[\frac{y^3}{3}\right]_{-\frac{h}{2}}^{+\frac{h}{2}} = b\left(\frac{h^3}{24} + \frac{h^3}{24}\right)$$

$$I = \frac{bh^3}{12}$$

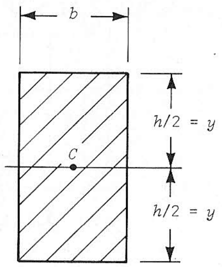



Fig. 3-36. Rectangular beam—geometry of cross-section.

bending moment

It can be shown that the stress on the fibers of the beam varies directly with the distance $l$ and the applied force $F$. Their product is called the *bending moment* ($M$). Thus the bending moment is zero at the free end of the beam and maximum at the anchored end, varying linearly along the beam. When the concepts presented above are combined, and bending stress $\sigma_x$ is defined as the stress at the surface of the beam parallel to the longitudinal neutral axis, the relationship emerges

$$\sigma_x = \frac{My}{I} = \frac{My}{\frac{(bh^3)}{12}}$$

When, as in the present case, the beam has a cross section that is symmetrical about the horizontal axis, the equation can be further simplified. Note that the expression $\frac{bh^3}{12}$ can be written $\frac{bh^2}{6} \times \frac{h}{2}$ or $\frac{bh^2y}{6}$. The equation thus becomes:

$$\sigma_x = \frac{M}{\frac{(bh^2)}{6}} \qquad (3\text{-}11)$$

section modulus

The expression $\frac{bh^2}{6}$ is known as the *section modulus*, $Z$, and applies to all rectangular shapes. Thus,

$$\sigma_x = \frac{M}{Z}.$$

This form of the equation is very useful when other cross-sectional shapes are involved, since *$y$ does not always equal* $\frac{h}{2}$. It has been proven that for all cases of pure bending, the neutral axis passes through the *centroid* or *geometric* center of the cross section. This point corresponds to the *center of mass* ($C$).

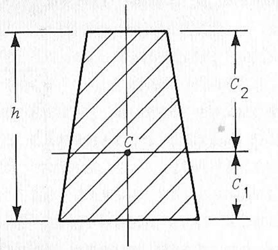



Fig. 3-37. Trapezoidal cross-section.



In a beam of trapezoidal cross section (Fig. 3-37), the geometric center is so located that the dimension $C_2$ is greater than $C_1$. If such a beam were bent downward, the tensional stress at the upper surface would be greater than that on the lower surface. It would therefore be necessary to know the value of $C_1$ and $C_2$ in order to determine the respective surface stresses from the equation $\sigma_x = \frac{My}{I}$. However, tables giving the numerical value of $Z$ for common structural shapes of all dimensions may be found in many professional publications such as *Steel Construction*, American Institute of Steel Construction, New York, 1959. Fig. 3-38 shows the location of the geometric center and neutral surface in a few of these shapes.

Another important relationship in cases of bending is that between the vertical displacement ($\Delta s$) of the beam, and bending strain. It can be shown that the maximum vertical deflection of a cantilever beam (Fig. 3-33) under a force concentrated at its free end is given by the equation

$$\Delta s = \frac{FL^3}{3EI} \qquad (3\text{-}12)$$

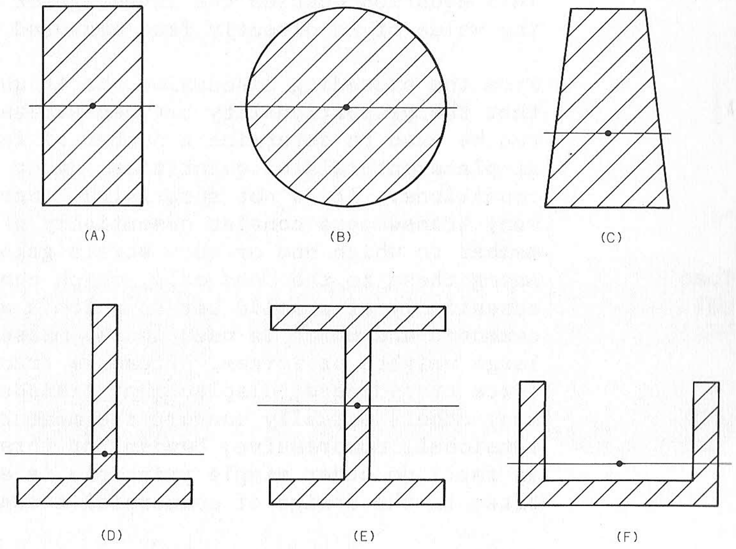



Fig. 3-38. Z-axes and geometric centers of structural shapes.

The state of stress at point P' has been determined to be

$$\sigma_x = \frac{My}{I} = \frac{Fly}{I}$$

Rearranging this expression,

$$F = \frac{\sigma_x I}{ly}$$

Equation 3-12 can also be expressed

$$F = \Delta s \left(\frac{3EI}{L^3}\right)$$

Therefore,

$$\frac{\sigma_x I}{ly} = \frac{3EI\Delta s}{L^3}$$

And since $\sigma_x = E\varepsilon$ and $y = \frac{h}{2}$

$$\frac{2E\varepsilon_x I}{lh} = \frac{3EI\Delta s}{L^3}$$

and $$\Delta s = \frac{2}{3}\,\frac{\varepsilon_x L^3}{lh} \qquad (3\text{-}13)$$

This equation enables the investigator to determine the value of $\Delta s$ directly from measured strain.

From the preceding discussion, it is quite apparent that the proportionality between stress and strain can be used to determine a number of force- or displacement-related quantities, under controlled conditions. It is not surprising, therefore, that many transducers consist essentially of an elastic member to which one or more strain gages are affixed.

load cell

Among these is the *load cell*, which consists essentially of a solid bar to which a strain gage is cemented and which is used in the measurement of large weights or forces. Pressure transducers, force transducers, displacement transducers, and many others actually convert the measurand to tensional, compressive, bending or torsional strain. In fact, no other single principle is employed more often in the design of commercial transducers.

Strain measurement with Tektronix instruments is discussed in Chapter 6.



## MEASURANDS OF VOLUME

volume

Volume is a three dimensional quantity and is thus expressed as the cube of some linear dimension ($cm^3$, $in^3$, $ft^3$, etc.). Other units, principally those of liquid measure (pint, gallon, liter), are also used to express volume but are still *defined* in cubic linear units.

Volume obviously cannot be measured *directly* by a single transducer; however, in any system where two of the three cubic dimensions are held constant, volume will vary directly and proportionally with the third dimension, and can therefore be measured with any displacement transducer (Fig. 3-39A). Nonporous objects can be measured simply by immersing them in a liquid and measuring the change in level of the liquid, provided of course that the area of the containing vessel's cross section is constant (Fig. 3-39B). Also, since density is defined as weight per unit volume, the volume of homogenous materials of known density can be measured simply by determining their weight. Therefore, many volume measurements are actually made with level transducers or load cells.

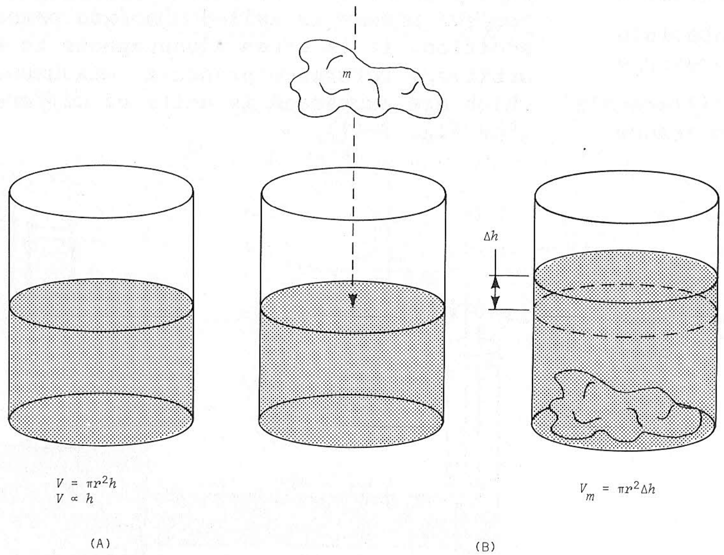



Fig. 3-39. Volume measurements.

The term "pressure" is another of those terms subject to misinterpretation through variations in usage. In engineering practice, the terms "pressure" or "total pressure" are used alternatively with the term "force.". However, the physicist defines pressure as *force per unit area.*

$$p = \frac{F}{A}$$

In this context, pressure is a function of force *and area.* The distinction is an important one. Otherwise, it would be hard to explain how a force of 100 lbs applied to a hydraulic jack will lift an automobile weighing more than a ton (Fig. 3-40).

Although it is not incorrect to refer to the "pressure" exerted by one solid object on another (provided the area of contact is specified), the term is more commonly used with reference to liquids (hydraulic pressure) or gases. Since the surface of the earth is subjected at all times to the pressure of the atmosphere, a pressure gage set at zero on the earth's surface is actually calibrated to measure the *difference* between atmospheric and some other pressure. This difference is referred to as *gage pressure*, while that measured with respect to a *perfect vacuum* is called *absolute pressure*. In addition, it is often advantageous to select some arbitrary reference pressure, measurements from which are expressed in units of *differential pressure* (See Fig. 3-41).

gage pressure

absolute pressure

differential pressure

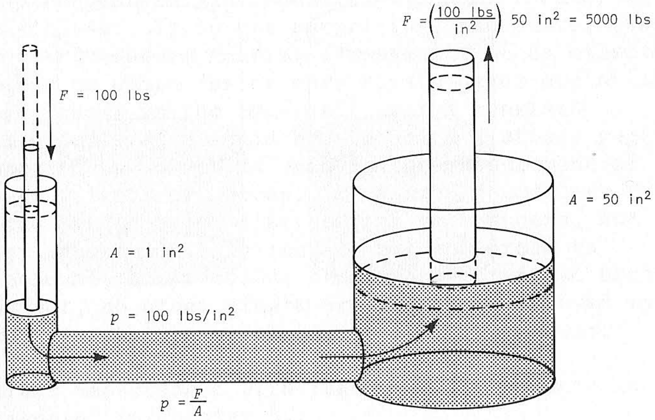



Fig. 3-40. Principle of hydraulic lift.



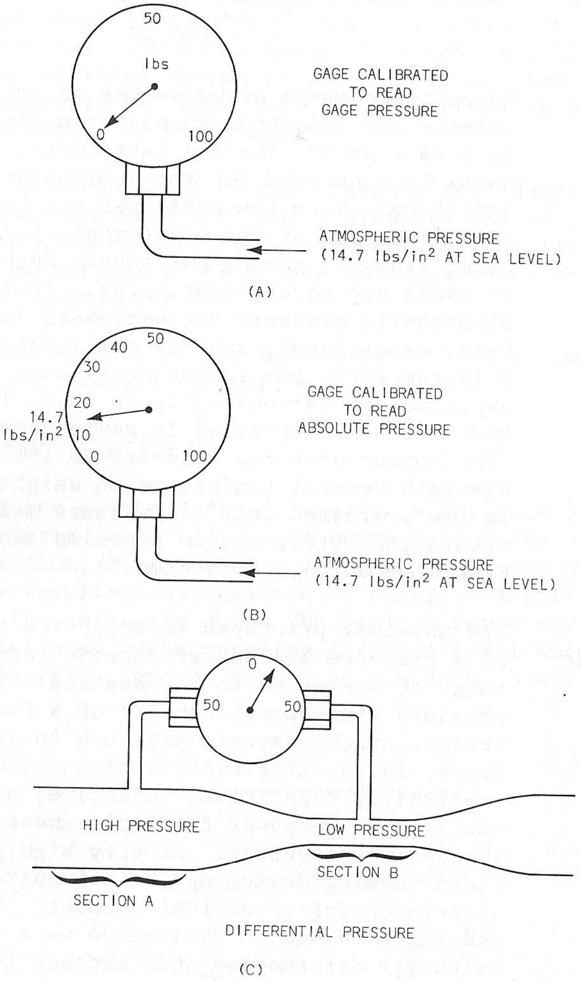



Fig. 3-41. Pressure gages.

| | | | |
|---|---|---|---|
| 1 | lb/in$^2$ | = 6.895 x $10^3$ NEWTONS/m$^2$ | |
| 1 | mmHg(0°C) | = 133.322 NEWTONS/m$^2$ | = 1.933 x $10^{-2}$ lbs/in$^2$ |
| 1 | BAR | = $10^5$ NEWTONS/m$^2$ | = 14.5 lbs/in$^2$ |
| 1 | in $H_2O$(4°C) | = 245.082 NEWTONS/m$^2$ | = 3.57 x $10^{-2}$ lbs/in$^2$ |
| 1 | ATMOSPHERE | = 1.0133 x $10^5$ NEWTONS/m$^2$ | = 14.70 lbs/in$^2$. |
| 1 | kgF/m$^2$ | = 9.81 NEWTONS/m$^2$ | = 1.42 x $10^{-3}$ lbs/in$^2$ |
| 1 | PASCAL | = 1 NEWTON/m$^2$ | = 1.45 x $10^{-4}$ lbs/in$^2$ |
| 1 | TON | = 133.32 NEWTONS/m$^2$ | = 1.933 x $10^{-2}$ lbs/in$^2$ |

Table 3-1.

units of pressure

Because the range of pressures of interest to science and industry extends from less than $10^{-12}$ to more than $10^6$ lbs/in$^2$ (absolute), a profusion of units have evolved for the expression of pressure amplitude. Very low pressures are usually expressed in millimeters of mercury (mmHg), torrs, inches of water (in$H_2O$), pounds per square inch absolute (PSIa) or dynes per square centimeter. Those above atmospheric pressure are expressed in pounds per in$^2$, bars, atmospheres, newtons per square meter or kilogram force per square centimeter. The relative amplitude of various units is shown in Table 3-1, where each is expressed in newtons/meter$^2$ and PSI. (The former unit was selected in 1960 by the Eleventh General Conference on Weights and Measures as the preferred unit of pressure measurement, within the metric system known as the International System of Units, "*SI* System.")

transducer types

The physical principle incorporated in the design of a pressure transducer depends largely on the range of pressures to be measured. The majority of pressure transducers consist of a force-summing device, which converts pressure to displacement or force, and an electrical transduction element (resistive, capacitive, inductive, piezoelectric, etc.) which responds to displacement or force with an electrical output. At very high pressures, the force-summing device may be eliminated in favor of a direct-sensing electrical element. Certain alloys undergo a change in resistance as a result of molecular deformation when exposed to very high pressures. Piezoelectric materials are also used in direct-sensing devices at high pressures. Pressure-sensitive transistors have recently appeared, yielding high outputs for very small pressure changes. Very low-pressure (high vacuum) devices are based on the same principle as the ordinary vacuum tube. For a given potential between plate and cathode, the better (higher) the vacuum, the more current in the external circuit.



Gas pressure measurements can often be used to gain information about other quantities. For example, temperature and volume are related to pressure by the Boyle's law equation $\frac{pV}{t}$ = k (constant) for "perfect" gases. Pressure varies with both altitude and ocean depth so that either can be measured by pressure transducers. Also, according to Bernoulli's theorem, the total energy in a moving fluid within an enclosed system is a constant, so that the velocity or "flow" of a fluid becomes an inverse function of its pressure.

The versatility of the pressure transducer, together with the ease with which pressure can be converted to an electrical output, accounts for the large number and variety of this type as compared to other types of transducer.

Measurement of pressure with Tektronix instruments is discussed in Chapter 6.

## MEASURANDS OF FORCE AND TORQUE

Force may be defined loosely as the push or pull exerted on a body which tends to set the body in motion, or to cause a deformation of the body, with a resultant expenditure of energy. A third case also exists in which the applied force may be balanced by an opposing force of equal magnitude, in which case no motion occurs (Fig. 3-42).

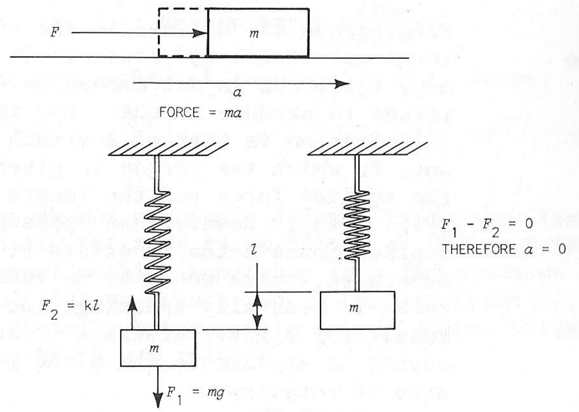



Fig. 3-42. Force.

The mathematical definition of force comes from Newton's second law of motion; an *unbalanced* force, acting on a body, causes that body to accelerate in the direction of that force and with an acceleration *directly proportional* to the *applied force* and *inversely proportional* to the *mass* of the body. Thus

$$a \propto \frac{F}{m}$$

or

$$F = kma$$

where k is the constant of proportionality. If the appropriate units are chosen, k becomes unity and $F = ma$.

Since mass may also be expressed $\frac{W}{g}$, another useful equation is

$$F = \frac{W}{g} a$$

which reveals that the force exerted on a body of weight ($W$) under the acceleration of gravity ($g$) is

$$F = \frac{Wg}{g} = W$$

load cell

Thus, many "force" transducers presently in use are designed to measure weight or "load." A "load cell" is simply a transducer whose principal elements are a column of some material of known elastic modulus, and a strain gage which measures the compression of the column under load.

torque

Pure torque was defined in the discussion of torsional stress and strain. It should be noted that many textbooks do not emphasize the necessity of two forces to produce torque. For instance, a common illustration is that of a wrench applied to a bolt or nut, in which the torque is given as the product of the applied force and the length of the moment arm (Fig. 3-43). However, an opposing force equal to the applied force actually exists at the nut itself -- otherwise, there would be no tendency for the nut to rotate. Generally speaking, the same torque will result for a given distance ($l$) no matter where the couple is applied in the plane perpendicular to the axis of rotation.



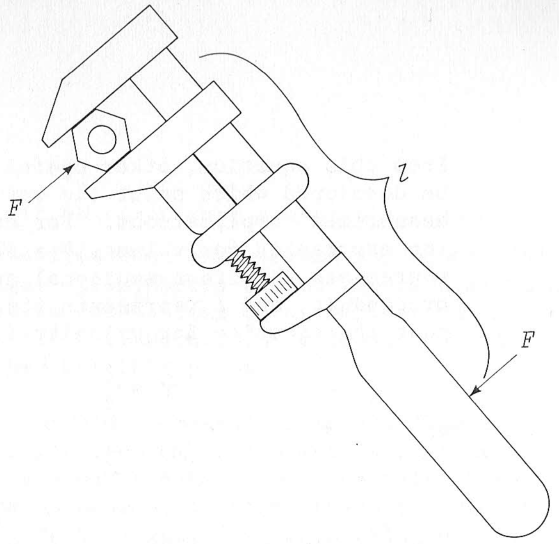



Fig. 3-43. Torque couple.

angular acceleration

If the body to which torque is applied is free to move, it will rotate around its center of mass with an acceleration proportional to the torque. Since the center of mass is also the moment of inertia, $I$, the equation for angular acceleration becomes

$$\alpha = \frac{T}{I}$$

Another useful equation involving torque is

horsepower

$$\text{Horsepower} = \frac{2\pi nT}{33{,}000}$$

where $n$ = number of revolutions per minute.

## MEASURANDS OF FLOW

Although not precisely defined in physics texts, the quantity referred to as "*flow*" or "rate of flow" is of considerable importance in a large number of industrial processes and in certain areas of research. The quantity has two primary variables, volume and time, which are related:

$$\text{Flow} = \frac{V}{t} \qquad (3\text{-}14)$$

From this equation, other useful relationships can be developed which point the way for transducer measurement applications. For example, consider the expression for volume, $V = Al$, where $A$ (3-15) represents the cross-sectional area of a tube, pipe, or conduit, and $l$ represents its length. Note also that the equation for velocity is expressed

$$v = \frac{l}{t}$$

or

$$t = \frac{l}{v} \qquad (3\text{-}16)$$

Substituting equations 15 and 16 in equation 14 yields the equation

$$\text{Flow} = \frac{Al}{\frac{l}{v}} = Av \qquad (3\text{-}17)$$

showing that flow can be measured at any point in a conduit system (provided the cross-sectional area of the conduit is known at the point of measurement) by simply measuring the *velocity* of the flowing material.

The term *mass flow* is often encountered in applications where the flowing material is not homogeneous but exhibits inconsistencies in density. A typical example is the pumping of "slurries," (aggregates suspended in a fluid) where the user is primarily interested in the weight of the transported solid, rather than the total volume of liquid and solid. Another example is found in the petroleum and chemical industries where highly volatile materials, existing in an unstable liquid-vapor phase mixture must be accurately measured as they pass through a piping system. Since volume is related to weight in the expression for density,



$d = \frac{W}{V}$, it is clear that a determination of mass flow requires that both volume and density be measured. Transducers called inferential mass flowmeters, consisting of a combination of density and velocity transduction systems, have been developed for this purpose.

inferential mass flowmeters

Another method of measuring liquid flow utilizes Bernoulli's theorem, which states that as an incompressible liquid flows, the total "head" remains unchanged; that is, the total energy (disregarding losses due to friction and turbulence) in a moving fluid is constant. This means that if in the course of its flow a fluid encounters an obstacle of some sort, its potential energy is transformed to kinetic energy, with a corresponding increase in velocity. This principle is illustrated in Fig. 3-41C. In a given time, equal volumes must flow in both the large diameter portion (section A) and the small diameter portion (section B) of this device, called a venturi tube. The velocity of the liquid in section B must therefore exceed that in section A. At the same time, the fluid pressure in section A will be higher than that in section B since the potential energy of the slower moving fluid has been converted to kinetic energy in section B. The *difference* in pressure increases in proportion to the rate of flow and can be measured with a differential pressure transducer. Because gases are compressible, their density changes with pressure. The effects described above are therefore somewhat modified; however, the *general* effects are the same and can be utilized to measure gas flow.

differential pressure measurements

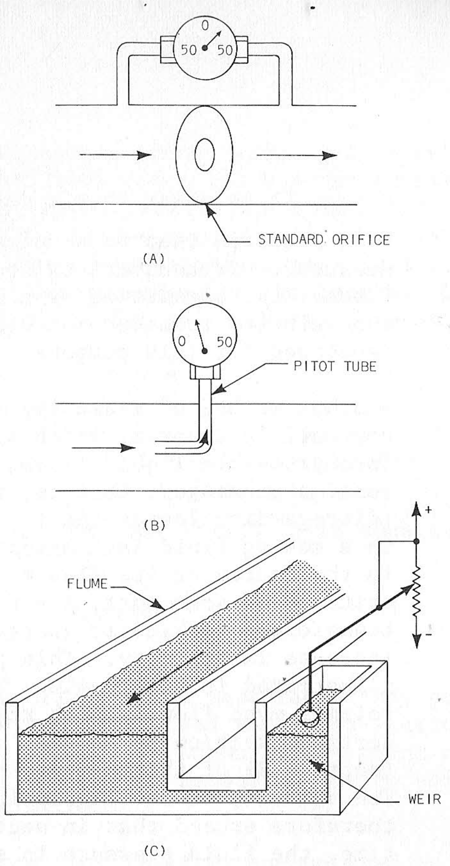



Fig. 3-44. Flow measurement.

Other devices which operate on the Bernoulli principle are *standard orifices*, *Pitot tubes*, and *weirs*. Standard orifices, like the venturi tube, constrict the cross-sectional area of the pipe and permit differential pressure measurements (Fig. 3-44A). Pitot tubes, Fig. 3-44B, simply measure the head pressure created by fluid flow. The weir (Fig. 3-44C) is useful in measuring rate of flow in open flumes. Here the fluid is not fully confined, so velocity remains constant while volume (cross-sectional area of the stream) increases with rate of flow in the flume. A small weir, or stilling chamber, is connected to the flume. By Bernoulli's theorem, the level in the weir will always equal the level in the flume.



Thus, a float placed in the weir will rise or fall with changes in the volume of liquid flowing in the flume per unit time. Float displacement can be converted to an electrical signal by any displacement transducer.

thermistor flowmeter

Still another method of fluid flow measurement involves the use of a thermistor transducer. The thermistor is inserted in the pipe or flume and heated by passing current through it. At the same time, the surrounding liquid tends to cool it. The two effects are brought into equilibrium by adjusting the heating current. As flow increases, a greater cooling effect is felt by the thermistor, increasing its resistance. Changes in current can thus be read out as changes in rate of flow.

deflection flowmeter

Perhaps the simplest (although not the most accurate) way to measure flow is to insert an obstruction in the flow path and through mechanical linkage communicate the force exerted on the obstruction to a transducer located outside the conduit. Such an arrangement is shown in Fig. 3-45.

radioactive tracers

Rate of flow can also be measured by mixing radioactive ("tracer") elements with the gas or fluid and "counting" the particles with a radioactive transducer as they pass by a given point (Fig. 3-46).

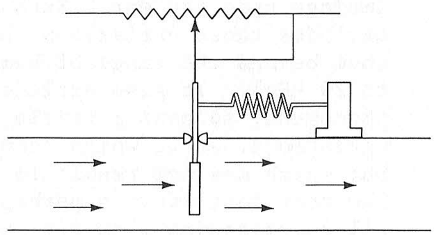


Fig. 3-45.

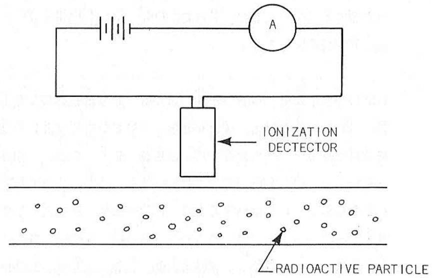



Fig. 3-46. Flow measurement.

**magnetic flow transducer**

The flow of electrically conductive fluids can be measured by a unique type of transducer which operates completely external to the flow system (Fig. 3-47). Saddle-shaped coils placed around the conduit, through which the moving fluid passes, create a powerful magnetic field at right angles to the direction of flow. Since the fluid is an electrical conductor, a potential is induced in the fluid whose magnitude is directly proportional to the velocity of flow. Length of the conductor is the diameter of the conduit which, of course, must be constructed of nonmagnetic material.

All fluid flow measurements are complicated by considerations of temperature, viscosity, volatility, and a number of other factors. Each application must therefore include measures which compensate for these variables if the final readout is to be relied upon.

Space does not permit a complete catalogue of flow transducer types. The preceding examples should, however, be sufficient to illuminate the concept of flow as a measurand.

## MEASURANDS OF SOUND

Sound is generally thought of as the auditory sensation evoked by pressure variations as they impinge upon the ear. Such a definition, however, excludes those variations whose frequency places them beyond the range of human hearing (about 20 Hz to 20 kHz). It also excludes certain other related phenomena, such as particle displacement, stress variations, etc., which occur at audio frequencies but which may not result in a hearing sensation. The term *acoustics* is perhaps a more useful and all-encompassing term for these phenomena and is finding increasing usage in the field of scientific measurement. Frequencies below the range of human hearing are termed *infrasonic* and those above, *ultrasonic*.

Acoustic waves are essentially longitudinal mechanical waves, propagated in solids, liquids or gases. Regardless of the medium, all sound waves are a direct result of particle displacement. In gases, acoustic waves are regarded as a train of alternating high and low pressure regions (Fig. 3-48) while in liquids and solids it is more convenient to speak of density or stress variations.



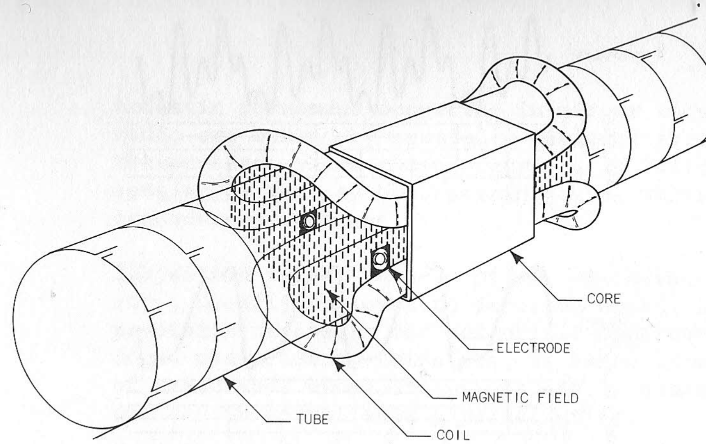



Fig. 3-47. Flow measurement – conductive fluids.

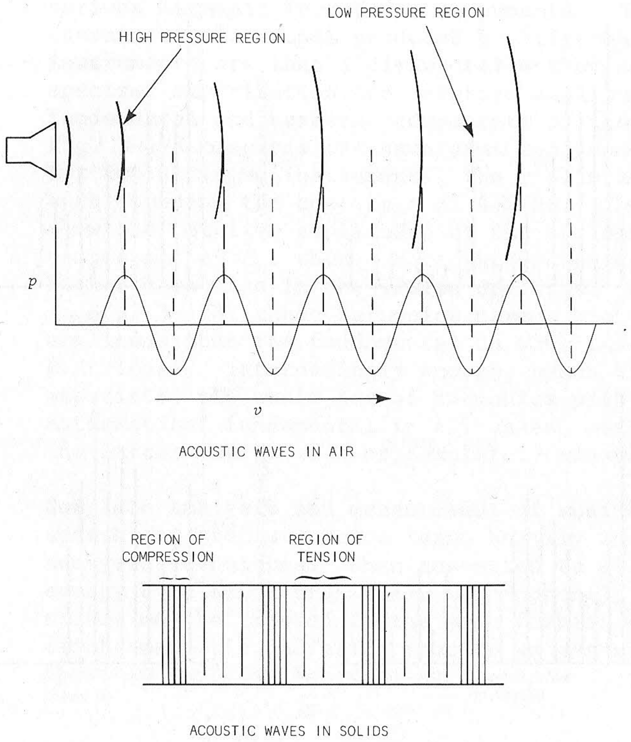



Fig. 3-48. Acoustic wave propagation.

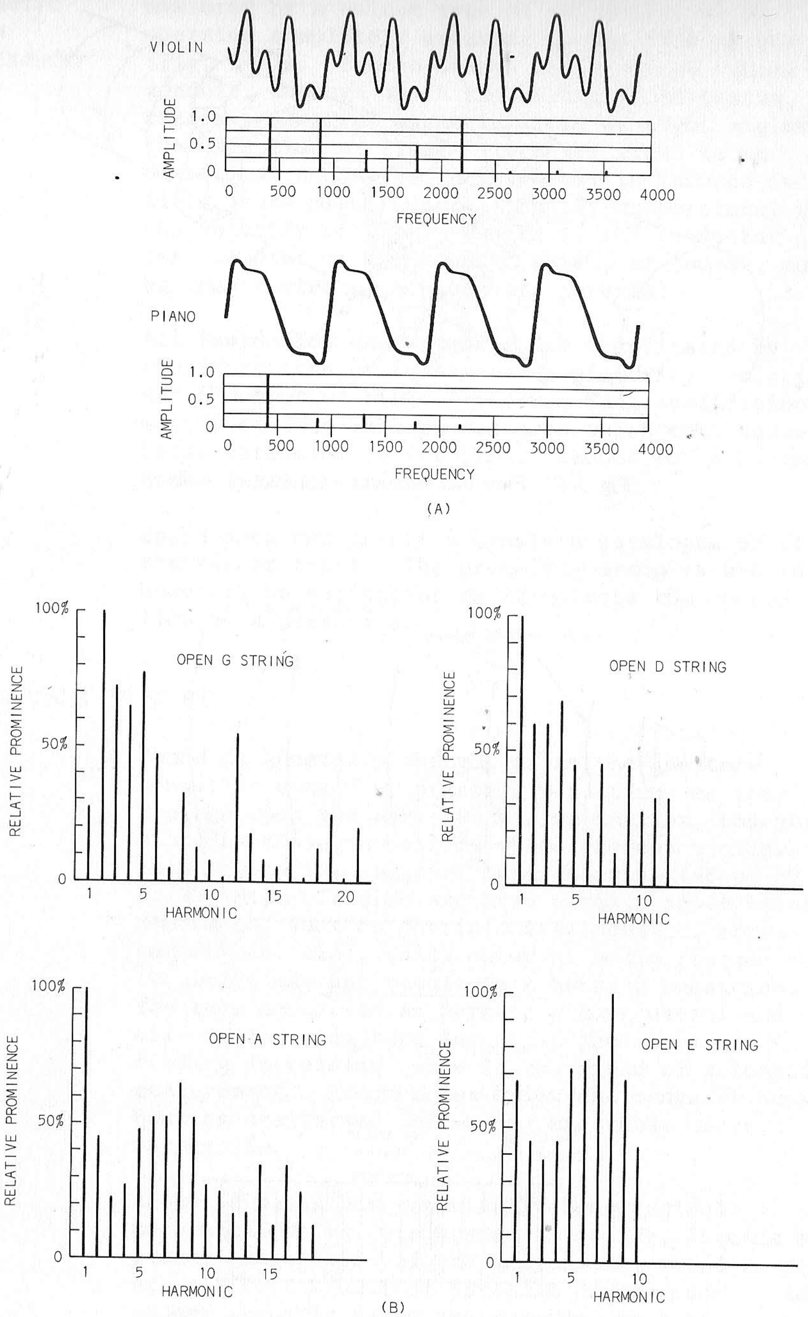



Fig. 3-49. Characteristic waveforms of musical instruments.



Acoustic phenomena occurring in air or liquid media are sensed by specially designed pressure transducers, while those occurring in solids require sensing devices such as strain gages, vibration transducers, etc.

Subjective terms, such as *pitch*, *loudness*, *tone*, etc., usually employed to describe sound, lack the precision necessary for scientific application. Sound measurement, therefore, is based upon a group of measurands whose dimensions can be quantitatively defined in established physical units.

frequency

Simplest of these measurands is that of frequency, which gives rise to the auditory sensations of pitch and tone. Few sounds familiar to the ear are evoked by "pure" sinewaves. Most sound waves are highly complex, consisting of a fundamental and various harmonic (overtone) components. The characteristic sounds produced by different musical instruments are thus a direct reflection of the spectral distribution and relative amplitude of fundamental and harmonic components of these sounds. Fig. 3-49A compares the waveforms and sound spectra for two stringed instruments, the violin and piano, both sounding the concert A of 440 Hz. The spectra show the relative amplitudes of the various harmonic components of the wave. Note the presence of loud higher harmonics in the violin spectrum. As seen in Fig. 3-49B, these harmonics have a higher amplitude than the fundamental in some cases (G and E strings). Interestingly enough, human hearing associates the whole set of harmonics with the mathematical fundamental in all cases, even though the latter may be weak or completely missing.

Complete analysis and measurement of musical sounds, speech and ordinary noise leans heavily on spectrum analysis techniques. When converted to electrical energy by a sound transducer (microphone), such sounds may be treated in the same fashion as electromagnetic radiation spectra as described in *Spectrum Analyzer Measurement Concepts*.

velocity

Sound velocity refers to the speed of propagation of a sound wave and is a constant for a given medium. A definite relationship exists between sound velocity and the density ($d$) and bulk modulus ($E$) of elasticity of the medium through which it is propagated. With regard to liquids and solids, this relationship is expressed:

$$v = \sqrt{\frac{E}{d}}$$

where $E$ is the bulk modulus and $d$ is the density. When $E$ is expressed in dynes/cm$^2$ and $d$ in grams/cm$^3$, $v$ will be in cm/s. In the British system, $E$ is given in poundals/ft$^2$, $d$ in pounds/ft$^3$ and $v$ in ft/s. When considering the propagation of sound along a solid rod, Young's modulus is substituted for the bulk modulus.

The same relationship applies to sound propagation in gases, but must include the effect of pressure ($p$) on the density of the medium. If temperature were to remain constant during compression and expansion, a change in pressure ($\Delta p$), according to Boyle's law, would result in a corresponding change of volume $\Delta V$ so that

$$pV = (p + \Delta p)(V - \Delta V)$$
$$= pV + \Delta pV - p\Delta V - \Delta p\Delta V$$

and since the quantity $\Delta p\Delta V$ is negligible,

$$p\Delta V = V\Delta p$$

or

$$p = \frac{\Delta p}{\Delta V/V} = E$$

Therefore, under isothermal conditions,

$$V = \sqrt{p/d}$$

However, in actual sound production, the heat generated during compression of the gas cannot escape quickly enough to maintain uniform temperature, so that except at very high frequencies the compression and expansion must be considered an adiabatic process. In an adiabatic process, the pressure change $\Delta p$ that causes a given volume change $\Delta V$ is $\gamma$ times as great as it would be in an isothermal process. ($\gamma$ represents the ratio of the specific heat of a gas at constant pressure to that at constant volume.) Thus the velocity of sound in a gas becomes



$$V = \sqrt{\frac{\gamma p}{d}}$$

Since changes in barometric pressure of the atmosphere cause corresponding proportional changes in density, the velocity of sound is unaffected by such pressure changes. Changes in the temperature of the atmosphere, however, cause changes in density without affecting the pressure, and thus cause changes in the velocity of sound propagation. As a rule-of-thumb figure, the velocity of sound in air is about 1100 ft/s. Other values are presented in Table 3-2.

acoustic power

sound energy

To describe and define some of the other important measurands of sound, it will be helpful to consider a simple sound source -- one which radiates uniformly in all directions. The *acoustic power* of the source is the total *sound energy* radiated by the source per unit time. The sound energy in a given portion of the medium is the total energy of that part of the medium, minus the energy that would exist there if no sound were present. *Sound energy density* at a point in a sound field is the sound energy in an infinitesimal part of the medium, divided by the volume of that part, and is usually expressed in ergs/cm$^3$. The most commonly used unit of sound energy is the erg/second, but the power may also be expressed in watts.

| MEDIUM | TEMPERATURE °C | VELOCITY | |
|---|---|---|---|
| | | METERS/s | ft/s |
| HYDROGEN | 0 | 1,286 | 4,220 |
| OXYGEN | 0 | 317.2 | 1,041 |
| WATER | 15 | 1,450 | 4,760 |
| LEAD | 20 | 1,230 | 4,030 |
| ALUMINUM | 20 | 5,100 | 16,700 |
| COPPER | 20 | 3,560 | 11,700 |
| IRON | 20 | 5,130 | 16,800 |
| GRANITE | | 6,000 | 19,700 |
| VULCANIZED RUBBER | 0 | 54 | 177 |

Table 3-2.

Assuming that no energy is lost to the propagating medium, the *sound energy level* will decrease in proportion to the distance from the source. The sound power passing through a *unit area* is called the *sound intensity*. Thus, for a spherical sound "surface" $S$, the sound intensity at all points on the surface is

$$I = \frac{\omega}{S}$$

where $\omega$ represents the total sound power radiated by the source. Also, from the equation for the area of a sphere, the relationship

$$I = \frac{\omega}{4\pi r^2}$$

is inferred, when $r$ represents the distance from the omnidirectional source.

Neither acoustic power, sound energy density, nor sound intensity can be sensed directly by a transducer. It is therefore necessary to employ some relationship between these measurands and *measurable* parameters of sound. With a single exception, the only sound-related quantity of practical value for this purpose is *sound pressure*. As an acoustic wave is propagated through an elastic medium, a train of alternating high- and low-amplitude pressure, stress or particle-displacement regions is set up in the medium. The root-mean-square value of the instantaneous values of these disturbances is the *effective sound pressure*, $p$, as they pass through a certain point. In the case of *periodic* alternations, the time interval used in the calculation must be an integral number of periods, or an interval long with respect to a single period. In the case of nonperiodic alternations, the interval must be long enough to make the value obtained essentially independent of small changes. Units are usually given in newtons/meter$^2$. *Sound intensity* is related to sound pressure

sound pressure

sound intensity

$$I = \frac{kp^2}{\rho c}$$

where $p^2$ is the *mean-square sound pressure*, $\rho$ is the density of the propagating medium, $c$ is the speed of propagation in that medium, and k is the constant of proportionality. In the mks system, k equals unity.



Therefore, when density is given in kilograms/meter$^3$, $c$ in meters/s and $p$ in newtons/meter$^2$, sound intensity is measured in watts, and the equation simplifies to

$$I = \frac{p^2}{\rho c}$$

sound pressure level

Since most acoustic measurements are made in terms of effective sound pressure, it is convenient to express such pressures on a decibel scale. On this scale, the *sound pressure level*

$$L_p = 20 \log_{10} \frac{p}{P_r}$$

where $p_r$ is the reference sound pressure.

Acoustic measurements in air usually are based on a reference pressure of 0.0002 microbar, (1 microbar = 1 dyne/cm$^2$ ≃ 1.45 x 10$^{-5}$ PSI ≃ 10$^{-6}$ atmospheres) and standard sound level meters are calibrated in decibels relative to this reference pressure.

Determination of sound intensity provides the necessary information for the calculation of sound energy density and total sound power.

Investigations of sound phenomena fall into two broad categories. The first category covers those devoted primarily to sound reproduction and includes such subjects as the design and manufacture of musical instruments, construction of acoustically efficient auditoriums, and the development of "hi-fi" electronic equipment. The secondary category includes all activities in which sound is used as a tool rather than being the center of interest itself. In this category are sonar (sound echo-ranging devices), infrasonics and ultrasonics. Even a brief survey of either category would demand more space than is available in a book of this kind.

Many sound phenomena can be analyzed through analogies to electrical or electromagnetic phenomena. Terms such as "acoustic impedance," "acoustic filter," etc. reflect the fact that many fundamental laws of electricity can, with proper modification, be applied to the behaviour of sound. In a similar fashion, terms such as "sound absorption," "sound refraction," "sound reflectance," etc. point up the similarity between the behavior of sound waves and those of light or other electromagnetic waves.

ultra-sonics

Perhaps the most recent advances in the study of acoustics have been made in the field of ultrasonics. Not only have ultrasonic sound waves proved a highly versatile tool in the testing of materials, but through the analogies mentioned above, a number of problems relating to electromagnetic radiation have been solved by employing acoustic models of the electromagnetic problem.

## MEASURANDS OF TEMPERATURE

As a physical quantity, temperature is very difficult to define with simultaneous accuracy and simplicity. Intuitively one knows it has something to do with heat, but then what is heat? To quote one authority, "The temperature of a body is its thermal state with reference to its power of communicating heat to other bodies." This admittedly unsatisfactory definition emphasizes the difficulties of treating the whole concept of temperature. Perhaps the most appropriate course in a book of this kind is to settle for a practical, if oversimplified version, at the same time admitting the limitations imposed by the simplifying process.

thermal agitation

All matter consists of atoms and/or molecules which exist in a more or less agitated condition. The degree of agitation determines whether such matter is in its solid, liquid or gaseous state. The kinetic energy of the individual particles acts in opposition to the cohesive forces which tend to bind the particles together. It is possible, within the limitations acknowledged above, to regard temperature as the degree of activity attained by the particles in a body of matter. Thus, empty space has no "temperature" since there are no agitated particles to define it, but a body in which "thermal" agitation was totally absent would have an *absolute* temperature of zero.



The act of temperature measurement also requires careful consideration. If a common mercury-bulb thermometer is lowered into a liquid of unknown temperature, what actually happens? Depending upon the thermal state of the thermometer (before immersion) and that of the liquid, heat will flow from one to the other until the thermometer and liquid are in a state of equilibrium. That is, the thermal agitation in the warmer body increases the thermal agitation of the cooler one until the two are equal in degree of kinetic activity. Thus, if the thermometer is warmer than the liquid, the temperature of the liquid rises slightly in the process, while the opposite situation occurs if the thermometer is cooler. As the mercury in the thermometer acquires or loses heat, it expands or contracts. When the thermometer is removed from the liquid, the height of the mercury column is read against an inscribed *scale*, and this reading is said to reflect the temperature of the liquid.

The fallibility of this process is not difficult to discern. In the first place, it is clear that except in the unique circumstance where thermometer and liquid are at the exact same temperature before the measurement, the original temperature of the liquid cannot be determined, since the measuring process itself imposes a change in the liquid's original temperature. This effect is further aggravated if the volume of the liquid is not many times larger than the volume occupied by the immersed portion of the thermometer.

Still another source of error is introduced by radiation or absorption of heat by the unimmersed portion of the thermometer during the measurement. Other errors are introduced by large differences between the specific heats of the liquid and thermometer, thermal conduction in the glass surrounding the liquid column, and so forth. About the only accurate statement that can be made about the entire process is that the height of the column is a fairly accurate indication of the temperature *of the liquid in the column.*

Despite the fact that 100% accuracy in temperature measurement is impossible to attain, once the sources of error are recognized the errors themselves may be minimized through a number of fairly simple techniques. Other problems remain to be solved, however, before a satisfactory system of temperature measurement can evolve.

temperature scale

The most important of these is the matter of establishing a *temperature scale*. The discussion in the previous paragraph assumed that such a scale existed; however, the only fact revealed by the thermometer was whether the liquid was hotter or colder than the liquid in the thermometer. *How much* hotter or colder is a concept that also requires examination.

Most measurement systems begin with a zero reference of some kind and the units chosen are based upon tradition, convenience, or some quantity occurring in nature. In such a system, a given measurement is simply the total number of units (including fractions) between the zero reference and the point under examination. However, there seems to be no convenient *natural* unit of temperature, and only a theoretical zero reference. That is, up to this time it has been impossible to induce a condition of *absolute zero*, where thermal activity completely ceases.

In the face of these difficulties, the international scientific community has adopted an International Temperature Scale, based upon the zeroth law of thermodynamics; that two systems in thermal equilibrium with a third are in thermal equilibrium with each other. The scale is developed from an operational procedure based upon a series of *fixed points* (freezing or boiling), to which specified values have been assigned, and a specified means of interpolation and extrapolation. The points selected (Table 3-3) are easily reproducible and are assigned values on the Celsius (Centigrade) scale. Interpolation is performed using specified instruments and equations; for example, the range between the boiling point of liquid oxygen and the triple point of water (the state where the three phases, gas, liquid and solid are in equilibrium -- roughly, the melting point of ice) is established with a standard platinum resistance thermometer and Van Dusen's formula for relative resistance to temperature. Much research is currently being performed in the high and low temperature ends of this scale to extend the limits of true temperature definition.



Other temperature scales, including the familiar Fahrenheit scale, have played their parts in scientific history and are still very much in use. A comparison of the four most commonly used scales is presented in Fig. 3-50.

| FIXED POINT | TEMPERATURE °C |
|---|---|
| OXYGEN (BOILING) | -182.970 |
| TRIPLE POINT OF WATER (MELTING ICE) | 0.01 |
| STEAM, FUNDAMENTAL (BOILING WATER) | 100 |
| SULFUR (MELTING) | 444.600 |
| ANTIMONY* (MELTING) | 630.5 |
| SILVER (MELTING) | 960.8 |
| GOLD (MELTING) | 1063.0 |

* NOT A PRIMARY FIXED POINT

Table 3-3.

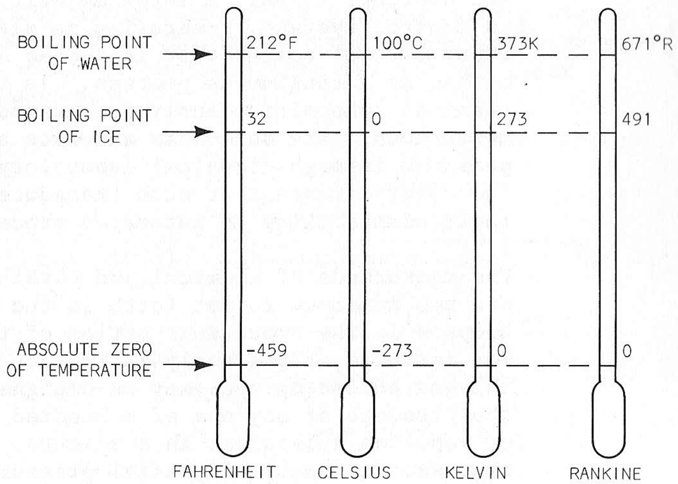



Fig. 3-50. Standard temperature scales.

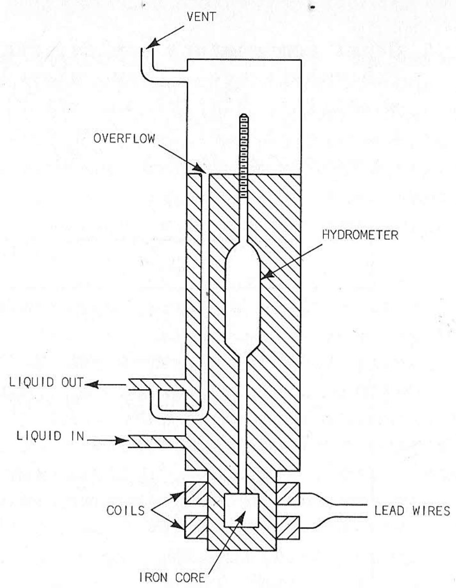



Fig. 3-51. Specific gravity transducer.

## MEASURANDS OF CHEMICAL AND PHYSICAL COMPOSITION

Transducers for chemical and physical analysis play two distinct roles. A large majority are employed in control systems, generating an electrical or other type of output that initiates a corrective action in a continuous process. In the field of chemical composition analysis, transducer measurements are seldom as accurate as those possible through classical laboratory techniques. The chief advantage of such transducers lies in their adaptability to automated processes.

The measurands of chemical and physical composition are too numerous to set forth in the same manner adopted in the preceding portion of this chapter. For instance, a gas analysis transducer, such as the gas chromatograph, may be designed to detect the presence of any one of a hundred or more gaseous or vaporous substances in a mixture. Readouts are expressed in units of partial pressure, weight percent, mole percent, parts per million (ppm), etc., which are usually familiar only to the chemist or chemical engineer.



A detailed exposition on these subjects would be of questionable value to the user of an oscilloscope transducer system and will not be undertaken here. However, a few measurands of special interest are described below to illustrate the variety represented by this field of measurement.

density

The density of a material is the ratio of its mass to its volume. It is measured in units of $lbs/ft^3$, $gm/cm^3$, etc., or on a relative scale called *specific gravity*. In the latter case, the quantity is a pure numeric and indicates the density of a material relative to (pure) water. Since one cubic foot of water weighs 62.4 lbs, a material with a specific gravity of 3 would weigh 187.2 $lbs/ft^3$.

Liquid density may be remotely measured by sensing the displacement of a hydrometer (much like those used to test the strength of electrolyte in an automobile battery) through magnetic transducers of the inductive type (Fig. 3-51). The density of translucent mixtures, both liquid and gaseous (including smoke) can be measured by projecting a beam of light through the containing vessel or duct and sensing the light intensity with a photoelectric type of transducer (Fig. 3-52). Opaque materials or material in opaque vessels or ducts can be measured for density in much the same manner using beams of radioactive energy rather than light. Ionization type transducers are used in place of photoelectric devices for these measurements.

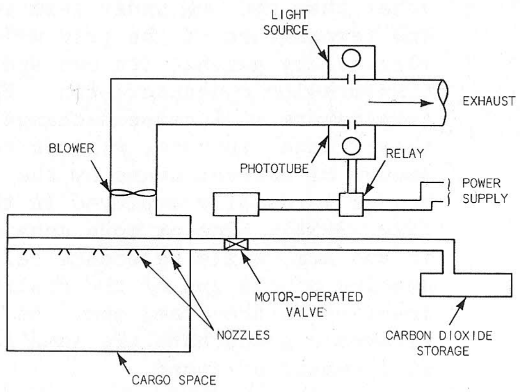



Fig. 3-52. Automatic sprinkler system.

**electrical conductivity**

Electrical conductivity is the ability of a material to conduct electrical current. The conductivity of liquids and solutions varies with the ability of the molecules of the liquid and (or dissolved materials) to disassociate into ions. Within prescribed limits, the conductivity of a solution is proportional to the number of free ions, and therefore of the concentration of dissolved material in the solution. Fig. 3-53 is a diagram of one type of transducer designed to measure electrical conductivity. Alternating current (to prevent ion collection) is applied to two electrodes immersed in the solution. The electrons are usually made of platinum to prevent chemical reactions between electrode and solution, but in some applications may be made of other materials. The electrical current permitted to flow in the circuit by the solution is a measure of the solution's conductivity and is measured in mho's. Because any dissolved substance tends to increase the conductivity of water, conductivity tests are often made to determine the purity of boiler feed water, distilled water, etc., and to check the extent of chemical reactions.

**gas composition**

Gases may be analyzed for purity by sensing changes in their thermal conductivity. This is accomplished by passing the gas through one or more cells containing fine wire grids, through which an electric current is passed. The grid wire is usually made of tungsten or platinum, which exhibit a specific temperature/resistance characteristic. If a gas other than the one under test enters the chamber, the temperature of the grid will change slightly, since every gas has its own specific heat transmission characteristic. The change in grid temperature will cause a change in its resistance; this change, in turn, will be reflected in the amount of current drawn by the grid. A Wheatstone bridge is usually employed in this application (Fig. 3-54). One or more sensing cells are placed in one arm, while reference cells, containing samples of the gas of the desired purity, are inserted in the other arm. As long as the test and reference gases have the same composition, the bridge will remain balanced.



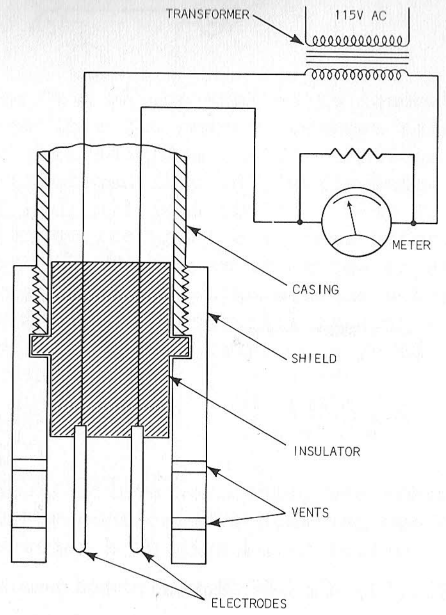



Fig. 3-53. Electric conductivity transducer.

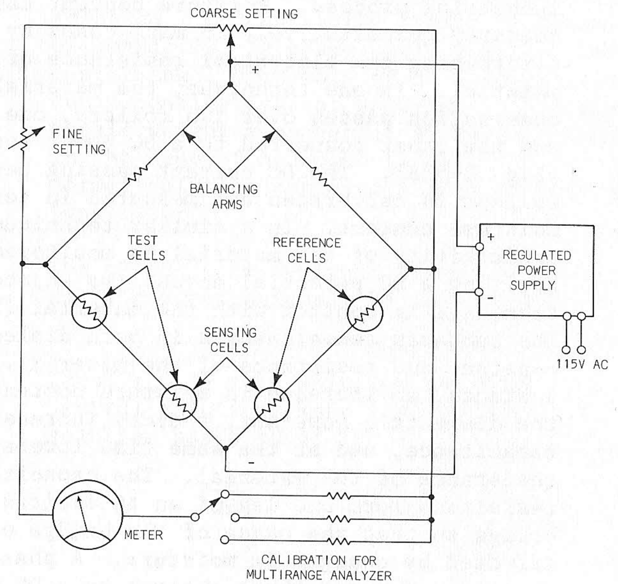



Fig. 3-54. Gas composition analyzer.

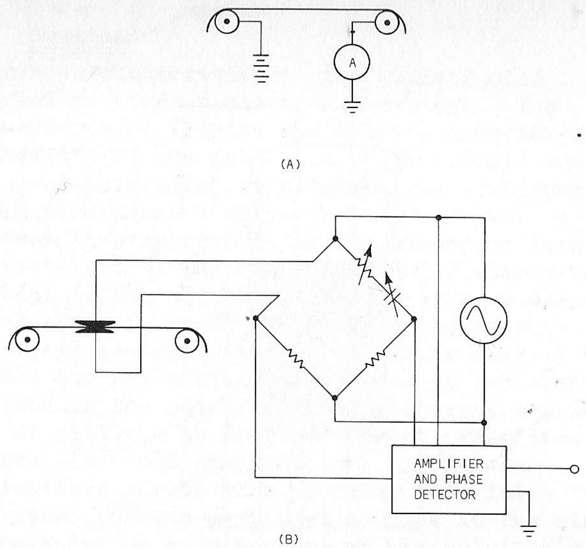



Fig. 3-55. Moisture content measurement.

moisture content

The moisture content of a material is often an indication of its state of evolution in an industrial process. Moisture content can be measured quantitatively in many cases by determining the electrical resistance of the material. In one technique, the material under observation passes over two rollers, one grounded and the other connected to a DC power source (Fig. 3-55A). The DC current passing between the rollers is calibrated and measured in terms of moisture content. In a similar technique, the conductivity of the material is monitored by applying a DC potential across two adjacent terminals in contact with the material (Fig. 3-55B). The contacts sense changes in both dielectric constant and resistance of the material. For instance, an increase in moisture content increases the dielectric constant, thereby increasing capacitance, and at the same time lowers the resistance of the material. The capacitance and resistance form one leg of an AC-excited Wheatstone bridge so that the *phase* of the bridge output is affected by changes in moisture. A phase-sensitive detector converts these changes to a DC signal that varies with moisture content.



acid-to-alkali balance (pH)

The term pH, as applied to aqueous solutions, describes the balance between acid and alkali (base) in that solution. Acid solutions have an excess of hydrogen ions ($H^+$) while bases have an excess of hydroxyl ions ($OH^-$). These ions have a strong tendency to combine to form water. One type of ion can only be increased at the expense of the other. In pure water, or an aqueous solution, a state of equilibrium thus exists between water, free hydrogen and hydroxyl ions which must satisfy the condition:

$$\frac{(H^+)(OH^-)}{H_2O} = k$$

In all dilute solutions, the concentration of water can be considered a constant and combined with the constant k to give $k_w$ as follows:

$$k(H_2O) = k_w = (H^+)(OH^-)$$

The value of $k_w$ has been determined as $1.0 \times 10^{-14}$. Since the product of the ion concentrations is a constant, the concentration of either ion can be used to express the acidity or alkalinity of a solution. Concentration itself is measured in terms of *normality*. A normal acid solution is one containing 1 *gram mole* of $H^+$ ions per liter (1000 cubic centimeters) of solution. (One gram mole = atomic weight x number of atoms in formula x 1 gram.) In the case of hydrogen (atomic weight = 1), a normal solution contains 1 gram of hydrogen ions/liter.

The pH scale is designed primarily for work with small concentrations. By definition,

$$pH = -\log_{10}(H^+)$$

Thus, a 0.1N acid solution has a pH of 1. All neutral solutions have a pH of 7 and a 0.1N base solution has a pH of 13.

$$\left(\frac{k}{OH^-} = H^+ \text{ or } \frac{10^{-14}}{10^{-1}} = 10^{-13}\right)$$

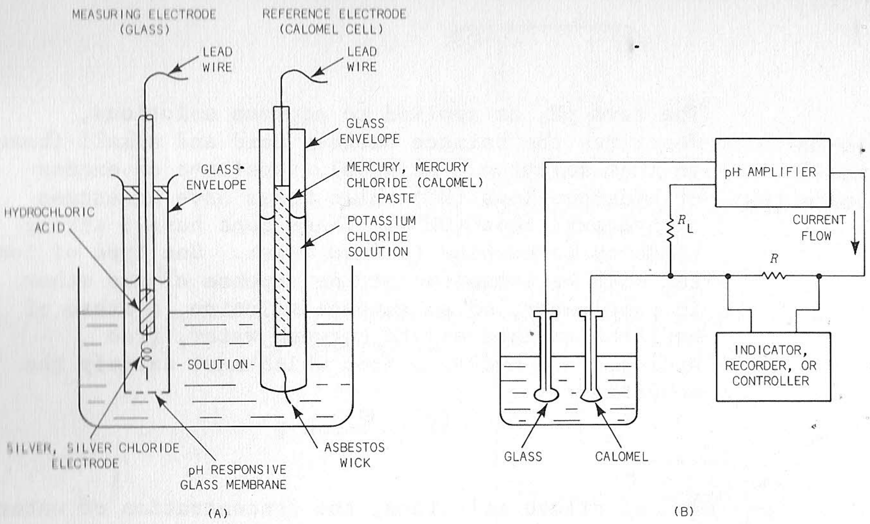



Fig. 3-56. Measurement of pH.

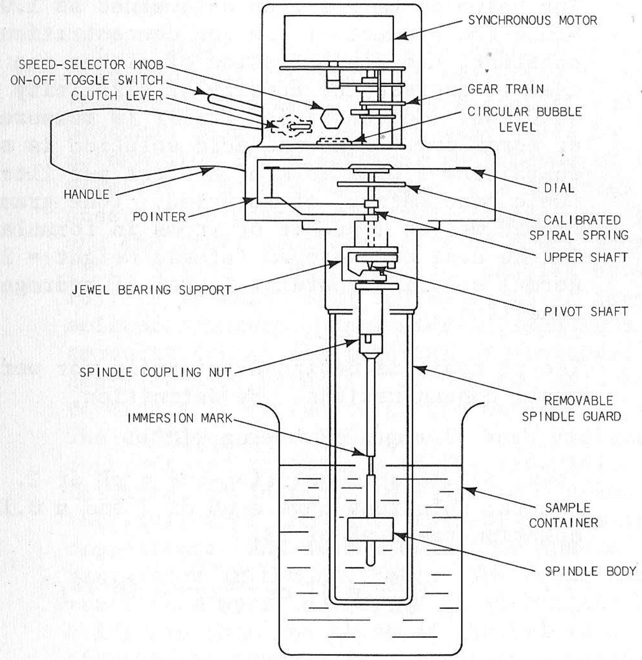



Fig. 3-57. Viscosity measurement.



pH is measured by determining the electrical potential generated by the solution, across electrodes of special composition (Fig. 3-56). These electrodes are sensitive only to the presence of $H^+$ ions in the solution, generating a voltage which is proportional to the $H^+$ ion concentration. Current is kept very low in order to prevent polarization of the electrodes. The voltage developed across current-limiting resistor $R_L$ also tends to balance the voltage generated in the solution.

Control of pH is an important factor in manufacturing and waste disposal techniques. The output of a pH cell is often used as a control signal for automatic processing machinery (Fig. 3-56B). pH meters are also used as precision laboratory instruments.

turbidity

Turbidity is the property of a fluid containing a suspension of very small particles. "Muddy" water is a good example. Measurements of turbidity play an important part in many industrial processes involving liquid concentrates. The simplest method of measuring turbidity is to shine a light through a sample and measure the light intensity with a photoelectric transducer. This technique can also be used in automatic control applications.

viscosity

Viscosity is the *flow resistance* or "stickiness" of a fluid. Its measurement is of particular importance in the petroleum, paint, and similar industries. An example of a transducer-aided viscosity measurement is shown in Fig. 3-57. A motor-driven spindle is immersed to a prescribed depth in the liquid under test. The spindle and motor shafts are connected through a flexible spring coupling. Resistive or capacitive transducers sense the degree of spring deformation when the motor is driven at the prescribed speed. Resistance or capacitance changes cause changes in excitation current, which are calibrated and measured in terms of viscosity.

## MEASURANDS OF TIME

Time is perhaps the least understood and yet one of the most critical quantities with which scientists and engineers are concerned. The "flow" of time is an abstract concept, rooted in change or motion, and perceived intellectually rather than physically. There are two aspects of time, both of which require accurate determination; the *epoch* and the *interval*. The epoch is related to the question, "*What time* (of day, year, century, eon) is it, or did (will) such-and-such an event happen?" The interval is related to the question, "*How many* (seconds, days, years) have elapsed (or will elapse) between two events?"

epochal time

Epochal time was established early in man's history, using the *apparent* motion of the moon, sun and stars. Daily events were timed by the position of the sun overhead, while crops were planted and harvested in rhythm with the sun's equinoctial excursions. Centuries later man began to count the intervals within cycles so that he could predict "how many" days, months, etc., passed between recurring events.

interval time

Early attempts at scientific investigation were often severely hampered by the lack of even roughly accurate timekeeping devices. Galileo made his famous experiments on falling bodies by weighing the amount of water collected from a fine stream during the intervals between events, or by counting his heartbeats. Since that time, instruments for time measurement in both the epochal and interval sense have undergone continuous, if somewhat sporadic refinement. Strangely enough, epochal time is still kept in the same old way, although with vastly increased precision. Interval time, on the other hand, is now established by *frequency standards* (since frequency is simply an inverse function of time) of such accuracy that they must be periodically adjusted to conform with the *less* "accurate" rotation of the earth on its axis and around the sun.



time standards

Units of time measurement are too well known to merit lengthy discussion here. It is interesting to note, however, that the present international definition of the *second* (the basic time unit) is 1/31,556,925.9747 of a year, for January 0, 1900 at 1200 hours, Ephemeris (celestial) time. This corresponds to 9,192,631,770 ±20 transitions of the cesium beam "clock" which now serves as the United States Frequency Standard. This standard has an accuracy of ±1.1 parts in $10^{11}$ and can even be used in frequency measurements with a precision of only a few parts in $10^{12}$.

Most secondary time and frequency standards employ highly stable crystal-controlled oscillators. The temperature and pressure of the oscillator's environment are strictly controlled, giving them a stability (but not accuracy) of better than one part in $10^{11}$ per day. Oscillators of this type are used to generate time signals and carrier frequencies which are broadcast by the National Bureau of Standards. The NBS also publishes corrective information monthly as a part of its services.

It is necessary to stretch the meaning of the term "transducer" in order to include time and frequency measurement instruments in the transducer category. However, in the sense that such instruments "convert" time to an electrical signal whose characteristics bear a known relation to the *flow* of time, such an inclusion may be justified. In this sense, the oscilloscope itself may be considered an excellent time transducer. In fact, together with sensitivity and bandwidth, time-measurement capability ranks high in the determination of an oscilloscope's quality.

## MEASURANDS OF ELECTROMAGNETIC RADIATION

Electromagnetic (EM) radiation is the term applied to the propagation of electrical energy in the form of waves, which consist of mutually perpendicular electric and magnetic fields, both of which are perpendicular to the line of propagation.

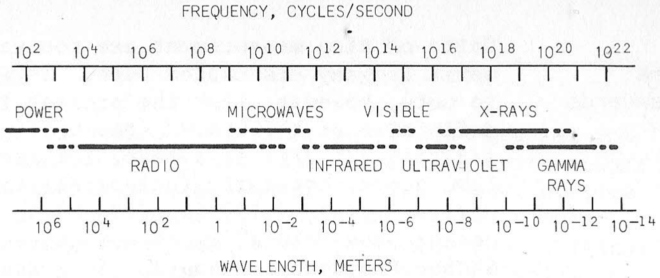



Fig. 3-58. Electromagnetic spectrum.

electro-magnetic spectrum

As shown in Fig. 3-58, the electromagnetic spectrum ranges from the very low-frequency (long-wave) radiations such as those from power transmission lines to the very high-frequency radiation associated with nuclear disintegration, and it includes a rather narrow range of frequencies (light radiation) visible to the human eye.

From the measurement standpoint, interest is primarily centered on the *wavelength* and the *magnitude* of electromagnetic radiation. However, both the terminology involved and the method of determining these parameters vary with the type of radiation.

frequency

wavelength

In radio frequency measurements, the term wavelength is usually replaced by its reciprocal, *frequency*, although in the microwave area, terms such as "centimeter waves" and "millimeter waves" are standard usage. At the frequency of infrared and above, wavelength becomes the preferred term, since the interpretation of measurement data is much less cumbersome in units of this dimension.

field strength

A similar situation exists with regard to the *magnitude* of electromagnetic radiation. In the measurement of radio frequency radiation, it is most practical to measure the electrical component, or *field strength* of the radiation. Since the field strength of radiated energy is proportional to the energy density *at the point of measurement*, much can be learned about the pattern of energy distribution around a source of radiation. These measurements are very important to research and development in the field of communications, telemetry and radar antennas.



Field strength is measured in volts or microvolts per meter. This unit of measurement has its origins in the concept that one volt will be developed across a dipole antenna one meter in length, oriented in the plane of electric polarization if the electric field of radiation is 1 volt/meter in magnitude. All field strength transducers, regardless of operating principle or associated measurement technique, are calibrated in these units.

frequency

Measurement of radio frequencies is accomplished principally through one of a number of types of spectrum analyzers or through familiar oscilloscope techniques. See *Spectrum Analyzer Measurement Concepts*.

magnitude

intensity

Measurement of the magnitudes of infrared, visible, and ultraviolet radiation are all made in terms of radiation *intensity*. The concept underlying this dimension was explained earlier in the discussion of sound. In the case of EM radiation, it is the energy, or number of photons passing through a unit area per unit time that defines the term. Infrared and ultraviolet radiation intensity are simply measured in watts/cm$^2$. Visible EM radiation (light) is measured in different units, the governing concepts of which require a brief digression.

light

candlepower

luminous intensity

flux density

lumen

The earliest investigations of electromagnetic radiation were made at the visible frequencies, long before it was recognized that light was simply a special kind of EM radiation. One of these early efforts was an attempt to establish a quantitative basis of measurement for the "brightness" of different light sources. A spermaceti candle, burning at the rate of 120 grains per hour, was chosen as the standard source and was assigned an intensity of one international *candlepower* (when viewed in a horizontal plane). Note that this definition of *luminous intensity* refers to the intensity of the *source*, not the flux density of the radiation. For the latter quantity, the term "lumen" was later applied. One lumen is the amount of light flux radiated from a 1 candlepower source through a solid angle whose dimensions are such as to surround a unit area at a unit distance from the source. In concrete terms, a 1-cp source produces

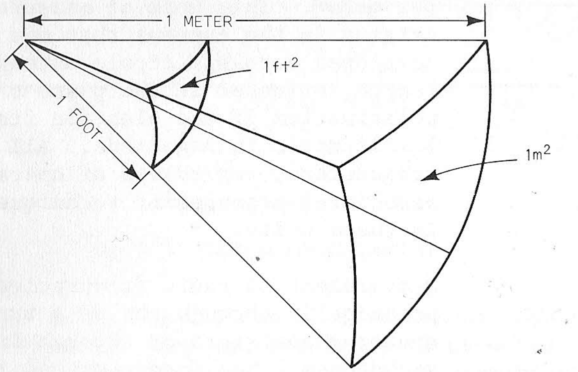



Fig. 3-59. Geometry of candlepower definition.

1 lumen of illumination on a surface of 1 square meter at a distance of 1 meter, or upon a surface of 1 square foot at a distance of 1 foot (See Fig. 3-59). Thus, if the source is regarded as being surrounded by a spherical shell of radius $r$, the area of the surface would be $4\pi r^2$ and each portion of the surface of area $r^2$ would be illuminated by 1 lumen. Thus, the total light flux emitted by a 1-cp source is $4\pi$ lumens.

A primary standard of luminous intensity was developed by the National Bureau of Standards at Washington and adopted by the International Committee on Weights and Standards, effective January, 1948. This standard consists of a glowing flask operated at the temperature of solidifying platinum, 2046°K. A cross section of the flask is shown diagramatically in Fig. 3-60. The brightness within the sight tube is taken as 60 cp/cm$^2$. The new *candle* has thus one-sixtieth the luminous intensity of one square centimeter of the area of the sight tube opening.

color

luminosity

Since light measurement transducers depend on comparisons made with the human eye, and since visual response is considerably influenced by the color (wavelength) of light, a *luminosity factor*, established through repeated experiments, must be applied when comparing the brightness of different colors.



The wavelength of infrared, visible, and ultraviolet radiation is expressed in microns ($10^{-6}$ meters) or angstroms ($10^{-10}$ meters).

Like many other physical phenomena already mentioned in previous pages, electromagnetic radiation interacts with a number of other physical phenomena, so that it often plays the part of an investigative tool, rather than constituting the primary measurand.

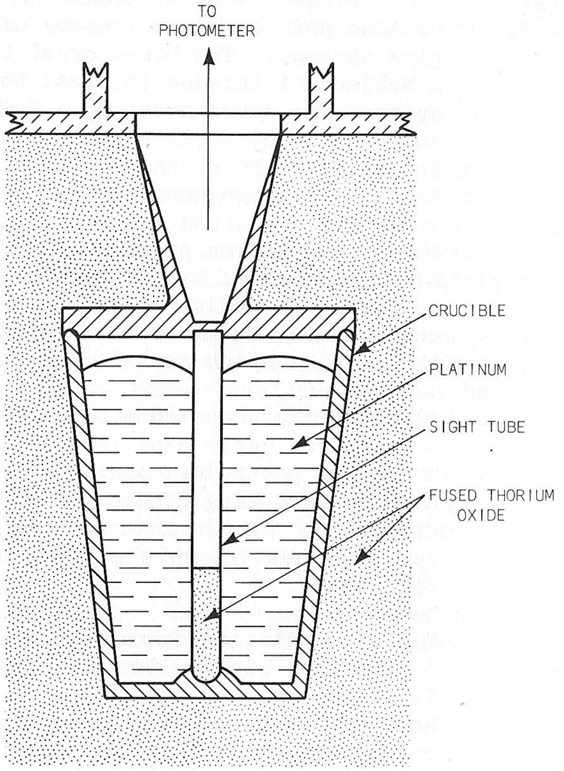



Fig. 3-60. Apparatus for establishing light intensity standards.

## MEASURANDS OF NUCLEAR AND PENETRATING RADIATION

Nuclear radiation is the emission of particles or photons (rays or "energy packets") from the nucleus of an atom. Such radiation occurs spontaneously in certain elements and isotopes as a result of their *natural radioactivity*, a process involving the "decay" of the nucleus from an unstable to more stable state. Radiation can also be produced *artificially* by bombarding the nucleus with high energy particles in giant "atom-smashing" machines. These devices accelerate atomic particles of various kinds to extremely high velocities. Upon colliding with the nucleus of a target atom, these tiny "projectiles" overcome the forces binding the nucleus and release a variety of esoteric particles plus photons. The behavior of these particles is a subject of intense interest to science, and has spurred the development of a number of interesting techniques and tools of investigation. Many of the latter might be classed as transducers, since they permit the measurement of such quantities as velocity, mass, charge, etc., through some kind of energy conversion process. However, at the present time, commercial transducers are limited in function to simple detecting and counting of individual emissions or to generating outputs proportional to the rate at which such emissions occur.

radio-activity

Although the phenomenon of nuclear radiation is most conveniently explained in terms of charged and uncharged particles, or rays, it also fits into the more encompassing concept of electromagnetic radiation. Within this concept, it occupies the upper extreme of the frequency spectrum (See Fig. 3-58).

Nuclear radiation characteristically produces ionization, either directly or indirectly, in matter. It is convenient, therefore, to group x-rays, which have the same capability but do not arise as the result of atomic disintegration and nuclear radiation, in a single category designated *nuclear and penetrating* radiation. X-rays, like gamma rays, are classed as photons and are generated by the collision of high velocity electrons with an atom. X-ray emission increases with electron velocity and weight of the atom involved.

ionization



Units for this kind of measurement, based on the activity of a radioactive substance, are expressed simply in *numbers of nuclear disintegrations* occurring per unit time, or in units called *curies*. One curie of radioactive material is that *amount* exhibiting a decay rate of $3.7 \times 10^{10}$ disintegrations/second (the decay rate of one gram of radium). In addition, special transducer-type instruments have been designed to detect radiation and give a readout in another unit called the *roentgen*. This unit is based on the destructive effect of nuclear and penetrating radiation on the tissues of living organisms and is defined as the amount of radiation that releases by ionization one electrostatic unit of charge of either sign in one $cm^3$ of air at normal temperature and pressure.

curie

roentgen

## MEASURANDS OF HUMIDITY

The term "humidity" originally appeared in the lexicon of meterology where it referred to the moisture content of the atmosphere. The term broadened to include the air in artificial environments, as well as any gas or gaseous mixture. Determination of humidity is becoming increasingly important in military, industrial, and scientific fields, since moisture content affects ballistics, aerodynamics, radio-wave propagation, health and comfort, and many manufacturing processes.

There are a number of ways to describe the moisture content of air, each of which constitutes a different measurand for the humidity transducer. The commonly employed terms are:

*Mixing ratio:* Mass of water vapor per unit *mass* of associated dry gas. Typical unit is grams/kilogram.

*Vapor concentration:* Mass of water vapor per unit *volume* of associated dry gas. Typical unit is gms/meter$^3$.

*Specific humidity:* Mass of water vapor per unit *mass* of *moist* gas (mixture of gas and water vapor). Typical unit is gms/kgm.

*Absolute humidity:* Mass of water vapor per unit *volume* of *moist* gas (mixture of water vapor and gas). Typical unit is gms/meter$^3$.

*Volume ratio:* Volume of water vapor per unit volume of associated dry gas. Typical unit is cm$^3$/meter$^3$ (also parts per million -- ppm).

*Dew point:* The *temperature* to which a mass of moist gas at a given pressure must be cooled in order to achieve a *saturated* condition with respect to water; that is, the point where any further cooling will initiate condensation of some of the water vapor. Typical unit is °C.

*Frost point:* The *temperature* to which a given mass of moist gas at a given pressure must be lowered to be saturated with respect to ice at that same pressure. Typical unit is °C.

*Vapor pressure:* The *partial pressure* of the water vapor in a moist gas. Partial pressure is the difference between the pressure of a given volume of moist gas at a given temperature and the pressure which would exist at the same temperature if all the water vapor were to be extracted.

*Relative humidity:* Ratio of the partial pressure of the vapor in a moist gas to the saturation vapor pressure of water at the temperature of the moist gas.

A common type of relative humidity transducer operates on resistive principles (Fig. 3-61). Two thin-foil grids are stamped on a plastic form in such a way as to form an interlaced pattern but without actual contact between them. The whole form is then coated with a hygroscopic material such as lithium chloride. Resistance between the grids is inversely proportional to the moisture content of the coating. Current changes in the circuit can therefore be read out in terms of relative humidity.

Most expressions pertaining to humidity encountered in daily experience are stated in terms of relative humidity.



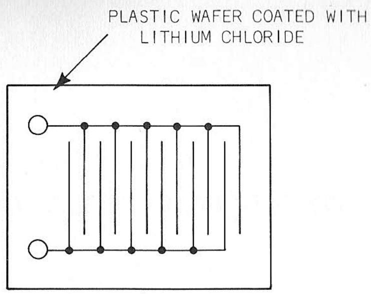



Fig. 3-61. Humidity sensor.

## MEASURAND OF LEVEL

The level of a liquid, suspension, slurry, or aggregate in a tank, vat or bin is of considerable importance in many industrial processes. Logically, this measurand falls in the category of dimension; however, it differs from other dimension quantities in one important respect: the peculiar nature of the "units" in which it is usually measured. Although it is quite possible to relate level to such quantities as volume, weight, and density, these dimensions are seldom of primary interest. In industrial processes, interest lies in the answers to such questions as "Full or empty?," "Rising or falling?," etc. For this reason it has been given separate classification.

Level transducers are used primarily as control rather than measurement devices.

4

# TRANSDUCER INSTRUMENTATION SYSTEMS

The electrical output of a transducer is rarely applied to a measuring device without previous processing. For a number of reasons which will become apparent, most transducer measurements require an *instrumentation system*. These systems vary widely in complexity and flexibility with the type of transducer, frequency and amplitude of the transducer signal, and the type of indicating or recording device used for measurement. Some systems are incorporated in a single instrument, while others are assembled from discrete components.

excitation

Passive transducers, including all resistive and capacitive devices and certain inductance types, require external excitation. The choice between AC and DC excitation depends upon the particular application and also upon the type of associated equipment available. The voltage or current of the excitation should be selected to provide the maximum output from the transducer, while at the same time, remaining within the specified operating limits of the device.

Wheatstone bridge

It is common practice to use one or more passive transducers in a bridge circuit. A number of advantages are gained through this technique; therefore, it may be helpful at this point to briefly review the theory of the *balanced* and *unbalanced* Wheatstone bridge.

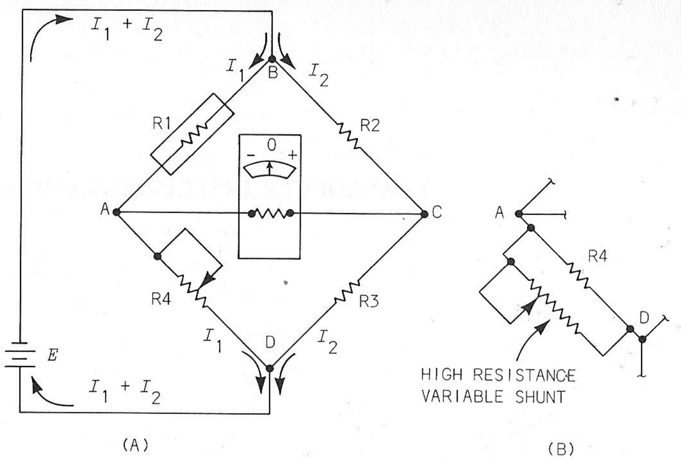



Fig. 4-1. Balanced bridge principle.

An examination of the circuit diagram in Fig. 4-1A will reveal that when the bridge is balanced (zero volts between points A and C) the individual voltage drops across R1 and R2 must be equal as well as those across R3 and R4. Thus:

$$I_1 R1 = I_2 R2 \tag{4-1}$$

and

$$I_1 R4 = I_2 R3 \tag{4-2}$$

Dividing equation (4-1) by equation (4-2),

$$\frac{R1}{R4} = \frac{R2}{R3}$$

and

$$R1 = \frac{R2}{R3} R4 \tag{4-3}$$

Thus, if R1 represents the resistance (or reactance) of the transducer, and if the ratio $\frac{R2}{R3}$ as well as the value of R4 are known with precision, the impedance of the transducer can be accurately determined.



In practice, the transducer is inserted in the bridge in the R1 position and R4 is adjusted for zero output. (For more precise control, a high-resistance potentiometer is usually connected in shunt with R4, as shown in Fig. 4-1B.) When the quantity being measured causes a change in the resistance of R1, a voltage is developed across the output terminals, causing deflection of the readout device. R4 is readjusted for zero output, and if R4 is provided with a calibrated scale, a value ΔR can be determined. From equation (4-3) it can be seen that

$$\Delta R1 = \frac{R2}{R3} \Delta R4$$

gage factor

The value ΔR1, of course, represents the actual measurement and when inserted in the appropriate equation, together with the transducer's conversion constant (*gage factor*) will yield a solution in the desired units.

It is evident that this null-balance technique is useful only for *static* measurements. However, the method for making dynamic measurements was implied in the foregoing description. It is evident that the amplitude of the output voltage developed across the bridge bears some relationship to the magnitude of the measurand at the transducer's input. To find this relationship a rather lengthy analysis involving the application of Kirchoff's laws is required. It can be shown that if the input resistance of the device connected to the bridge output is assumed to be infinite, the following approximation is sufficiently accurate for small changes in transducer resistance to yield practical results.

$$E_o = \frac{E_i \Delta R}{4R} \quad \text{where } \Delta R << R$$

where R is the resistance of the transducer. This is the highest output voltage that can be obtained from a bridge with a resistance change in a single leg. If the load resistance on the bridge is not considerably higher than the transducer resistance, $E_o$ falls off rapidly and linearity errors become significant.

From the same analysis it can be shown that if resistance changes occur in each leg of the bridge (again assuming an infinite load resistance)

$$E_o = \frac{E}{4}\left(\frac{\Delta R1}{R1} - \frac{\Delta R2}{R2} + \frac{\Delta R3}{R3} - \frac{\Delta R4}{R4}\right)$$

From this equation it is evident that if R2 and R4 represent transducer resistances which react to the measurand by the same degree of magnitude, but with opposite sign from that of R1 and R3, the bridge output voltage will be

$$E_o = \frac{E}{4}\left(\frac{4\Delta R}{R}\right) = \frac{E\Delta R}{R}$$

or 4 times the magnitude attained by a single transducer. If R1 and R3 are fixed resistors, $E_o$ will still have twice the magnitude achieved through a single transducer.

The use of two or more transducers connected in bridge conformation is a common practice in certain types of measurement. For example, if strain gages are cemented to a cantilever beam as shown in Fig. 4-2, the resistance of each will change in proportion to the bending strain imposed on the beam. The changes will be of opposite sign (tension and compression), however, so the gages are inserted in the R1 and R4 positions. The bridge output will thus be twice that achieved by a single gage.

**temperature compensation**

As an added advantage, the Wheatstone bridge offers an excellent opportunity for temperature compensation of the transducer. In Fig. 4-2 for instance, an increase in temperature would cause the beam to expand, increasing the tension on both gages by an equal amount. The ratio $\frac{R1}{R4}$ is thus unaffected by changes in temperature.

It sometimes happens that it is convenient to use "dummy" gages for temperature compensation. In such situations, the gage is positioned so that it shares the same environment as the active gage and is connected in the bridge so as to offset the effects of temperature on the active gage. Thus, if R1 is the measuring gage and R2 is the dummy, any temperature effect on R1 will be duplicated by R2.



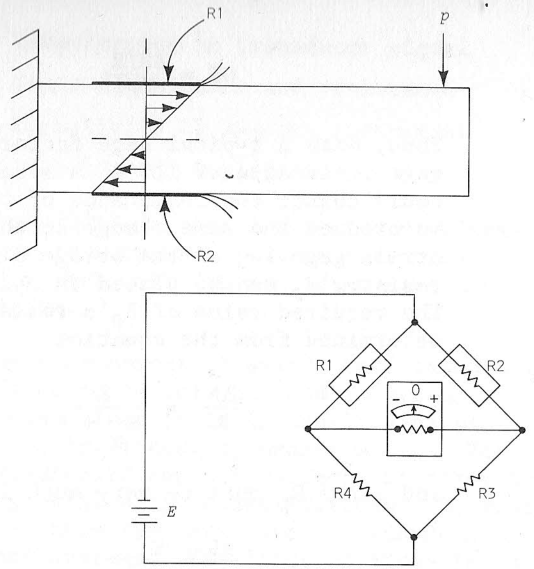



Fig. 4-2. Measuring bending strain with Wheatstone bridge.

The ratios $\frac{R1}{R4}$ and $\frac{R2}{R3}$ will therefore be affected equally and $E_o$ will exhibit no change attributable to temperature effects.

**Wheatstone bridge**

In a number of commercial transducers a Wheatstone bridge is included as an integral part of the design. Auxiliary bridge fixtures are also available and are designed to facilitate a wide variety of bridge-transducer configurations. These bridges also include provisions for calibration of the bridge output. This is accomplished by shunting one of the bridge arms with a "calibration resistor" (sometimes built right into the transducer). The resulting change in resistance is equivalent to a specified resistance change in the transducer, and thus a definite measurand amplitude. The readout device can thus be calibrated in the actual units in which the measurand is expressed.

**gage factor**

Before giving an example of this technique, the concept of *gage factor* must be expanded. This term pertains to the *sensitivity* of the strain gage and is a measure of the *transfer function* of strain-sensitive resistance materials; that is, the ratio of *unit change in resistance* to unit strain, and is expressed numerically.

$$GF = \frac{\Delta R/R}{\Delta l/l}$$

Thus, with a typical gage factor of 2 and strain gage resistance of 120 Ω, a strain of 1000 μin/in would change the resistance of the gage by 0.24 Ω. To produce the same change in the resistance of the strain gage leg of the bridge circuit, a calibrating resistor $R_p$ can be placed in shunt with the gage. The required value of $R_p$'s resistance can be determined from the equation

$$\frac{\Delta R}{R} = \frac{R}{R_p + R}$$

and since $R_p$ must be very much larger than R

$$\frac{\Delta R}{R} \simeq \frac{R}{R_p}$$

$$\text{and } R_p = \frac{120}{2 \times 10^{-3}} = 60 \text{ k}\Omega$$

Thus, when a 60-kΩ calibrating resistor is placed in shunt with the gage (under no-load conditions), the readout device should indicate 1000-μ strains.

capacitive and inductive transducers

Although the foregoing discussion was based upon the use of resistive transducers with the Wheatstone bridge, the arguments are valid for capacitive and inductive transducers also, provided AC excitation of the bridge is employed. In this case, values of $X_C$ or $X_L$ at the excitation frequency may be substituted for the corresponding resistance values.

amplifiers

In all but a few instances, the transducer or bridge output signal requires amplification before it is applied to a readout instrument. The design of the amplifier is determined by many factors, some of which conflict. The more important design considerations are:

1. Amplitude and frequency of the transducer output signal
2. Output impedance of transducer
3. Passive or self-generating transducer



4. Interference in transducer signal
5. Cable capacitance and resistance
6. Sensitivity of readout instrument
7. Stability of amplifier

These considerations have led to the development of several distinct types of transducer-signal amplifiers, each with its own advantages and disadvantages.

Before the development of solid-state technology, DC amplifiers could only be used in dynamic measurements, since their instability caused errors in static or low-frequency measurements. For this reason, AC-coupled amplifiers were the first to be used for general purpose applications. Several versions of this type are used in transducer measurement systems. The first of these is called the *DC carrier amplifier* (Fig. 4-3).

DC carrier amplifier

In the DC carrier amplifier the input signal is generated by a DC-excited bridge. (In theory, the transducer itself can be used as a signal source, but inevitable minor variations of conversion gain at the modulator make this application impractical for transducer signals below about 100 millivolts in amplitude.) The input signal first passes through a low-pass filter to remove any interference that may be present in the signal. The filtered signal, together with the audio oscillator output or *carrier*, is applied to a linear modulator. Another oscillator output provides the reference for the phase-resistive demodulator. The output of the modulator is an amplitude-modulated AC signal. This signal is applied to a narrow bandpass AC amplifier,

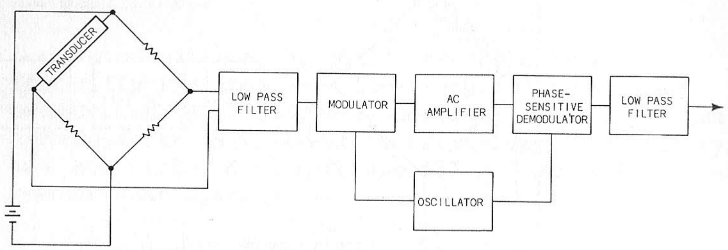



Fig. 4-3. DC carrier amplifier with modulator.

then passes to a phase sensitive demodulator. The demodulated output, reflecting both the phase and amplitude of the input signal, is then filtered to remove undesired modulation products and passes on to the readout device as an amplified reproduction of the transducer signal.

The same effect is achieved by the DC carrier amplifier shown in Fig. 4-4. Here the bridge output is applied to the oscillator in such a fashion that it modulates the carrier. This eliminates the need for a separate modulator. However, to preserve phase information, the bridge must be initially unbalanced in the "no load" condition.

AC carrier amplifier

The AC carrier amplifier (usually referred to simply as a carrier amplifier) operates on the same principle as the DC type, except that the carrier is applied as excitation power to the bridge (Fig. 4-5). Thus the carrier is modulated in the bridge and passes directly to the AC amplifier. The oscillator signal is applied to a phase-sensitive demodulator where it acts as the demodulator reference.

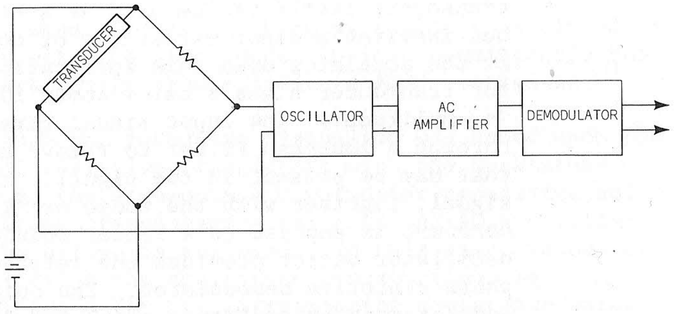



Fig. 4-4. DC carrier amplifier – direct carrier modulation.

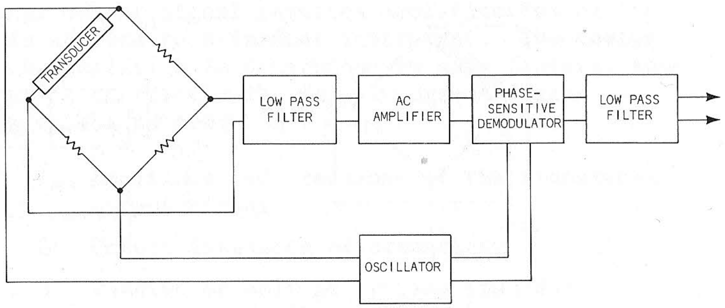



Fig. 4-5. AC carrier amplifier.



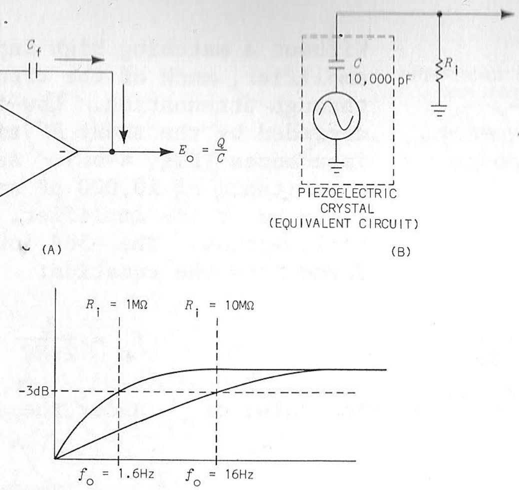



Fig. 4-6. Charge amplifier.

The carrier amplifier, both AC and DC versions, possesses several advantages. Since it uses an AC-coupled amplifier it has all the stability inherent in this design. Its filters and narrow bandpass amplifier provide excellent rejection of 60 Hz and other interfering signals picked up by the connecting cables to the transducer. On the other hand, the input signal frequency must be no higher than one-fifth of the carrier frequency, limiting the bandwidth of the carrier amplifier. Also, cable capacitance, which becomes significant with long leads, is seen as parallel capacitance to the bridge arm resistors, and must be compensated for in achieving bridge balance. Phase adjustments to the reference signal are also necessary when capacitive transducers are used. Thus, the carrier amplifier requires considerably more adjustment than DC amplifiers.

As stated earlier, DC amplifiers of adequate stability for static or low-frequency transducer measurement were only made possible by fairly recent developments in solid-state technology. Several types are now employed in both special and general purpose measurement systems.

charge amplifier

The *charge amplifier* (Fig. 4-6A) is specially suited for use with high-impedance transducers, such as the piezoelectric type. Transducers of this sort may be regarded as equivalent *current sources* due to the high impedance of the crystal capacitance (Fig. 4-6B).

low-frequency response

Without a matching high input impedance in the amplifier, much of the transducer signal is lost through attenuation. Low-frequency response is also degraded by the short *RC* time of the combined impedances (Fig. 4-6C). Assuming a typical crystal capacitance of 10,000 pF and an input resistance of 1 megohm at the amplifier, the *RC* time will be 10 milliseconds. The -3dB low cutoff frequency $f_o$ is found from the equation:

$$f_o = \frac{1}{2\pi RC}$$

The value of $f_o$ under the assumed conditions will be

$$\frac{1}{2\pi RC} = \frac{1}{2\pi \times 10^{-2}} \simeq 16 \text{ Hz}$$

However, if the input resistance is increased to 10 MΩ, $f_o$ will fall to 1.6 Hz, a much better low-frequency response.

The charge amplifier is essentially an integrating operational amplifier. This type is characterized by an input impedance approaching infinity. Thus, $f_o$ approaches zero Hz (DC). All the signal current acts as charging current for feedback capacitor $C_f$. The output voltage is the integral of $I_i$, so that

$$E_o = \frac{1}{C}\int Idt = \frac{Q}{C}$$

where $Q$ = charge in coulombs
$C$ = capacitance in farads

In addition to its excellent low-frequency response, the charge amplifier has the advantage of being unaffected by cable capacitance. This accrues from the fact that the cable-to-ground voltage remains relatively constant, in spite of signal current variations. The only significant disadvantage offered by this amplifier is encountered when designing a multipurpose instrument. To function as a charge amplifier, the input must obviously be entirely isolated from ground. Signal *voltages* from other types of transducers could thus not be applied to this input, so another amplifier or complex switching and attenuation circuits would be required in a multipurpose instrument.



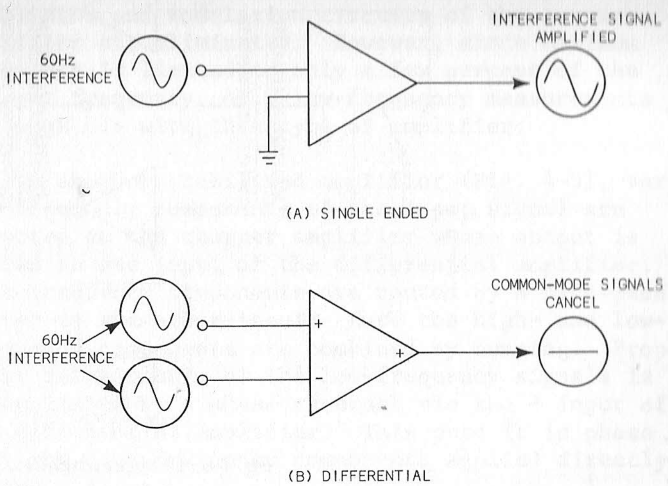



Fig. 4-7. DC amplifiers.

DC amplifier

The *DC amplifier* can be designed to accept any type of transducer signal with a minimum of additional circuitry. Used in conjunction with a bridge, it will amplify the output of all passive transducers without imposing limitations on signal frequencies. Self-generating transducers can be connected directly to the input. High-impedance transducers can be provided with separate high-impedance input circuits to provide adequate low-frequency response for the majority of applications.

single-ended

differential

common-mode rejection

In many cases the *single-ended* DC amplifier (Fig. 4-7A) proves adequate to the measurement requirements. Its chief disadvantage is its inability to reject 60-Hz and ground-loop interference, picked up by the connecting cable. The problem can be avoided, however, by using a *differential amplifier* (Fig. 4-7B), which amplifies only the difference in voltage between the signal and signal-return leads. Since interference signals are in the same phase on both leads, they are not amplified. This is known as *common-mode rejection* and is one of the principle advantages of the differential amplifier. Effects of cable capacitance are also minimized by the differential input.

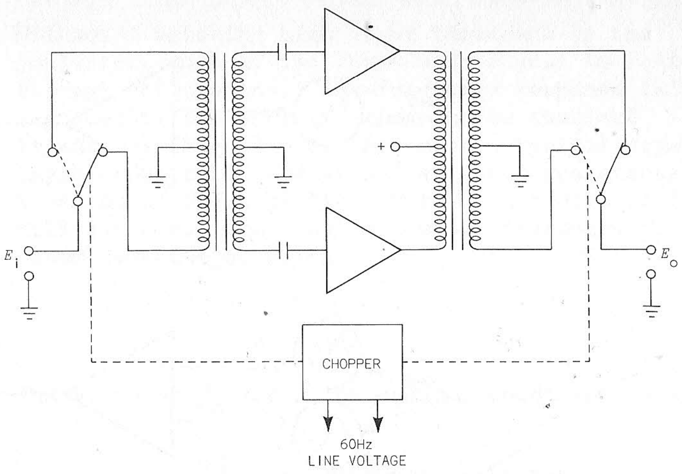



Fig. 4-8. Chopper amplifier.

Although the stability of DC amplifiers has been extended to the point where voltage drifts of 3μV/°C are not unusual, offset current and current drift can still remain problems in a few applications. At the same time, the relatively narrow bandwidth of AC amplifiers may eliminate them from consideration in the same application. By combining the advantages of both types, the *chopper-stabilized amplifier* is able to exceed the capabilities of either when used alone.

**chopper amplifier**

The *chopper amplifier* is not a new development in transducer instrumentation. Its chief recommendation is its extreme stability, even as compared to the carrier amplifier. A typical example of this kind of amplifier is shown in Fig. 4-8. The transducer signal is applied directly to the primary of a transformer "chopper" which alternately reverses the direction of current through the input transformer. (In this case the chopper is a single-pole, double-throw reed switch, driven by a 60 hertz AC voltage. Chopping is also accomplished with electronic switches, however.) The secondary of the transformer feeds a push-pull amplifier with alternate positive- and negative-going rectangular pulses whose amplitude reflects the level of the transducer signal. These pulses are coupled to the secondary of the output transformer, where another set of contacts of the same chopper restores the train to a single polarity, providing an amplified and demodulated output for the readout instrument.



Thus, the chopper acts as both modulator and demodulator and instabilities introduced by the oscillator and modulation circuits of the carrier amplifier are eliminated. However, since maximum

**frequency limitations**

bandwidth is limited to only a few percent of the chopper frequency, only low-frequency measurements are possible with this type of amplifier.

**chopper stabilized amplifier**

In the chopper stabilized amplifier (Fig. 4-9), very low-frequency components of the input signal are directed to the chopper amplifier whose output is routed to one input of the differential amplifier. High-frequency components are routed by a high-pass filter to the other input. Here the high- and low-frequency components are combined by summing. Proper phase relationship of the low-frequency signals is accomplished by a phase reversal via the + input of the differential amplifier. This puts it in phase with the high-frequency components applied directly to the - input.

The advantages gained by these techniques are evidenced by a comparison of the typical offset current and thermal drift characteristics of unstabilized differential amplifiers with those of chopper stabilized amplifiers. Unstabilized amplifiers show offset currents and current drift on the order of 1 nA and 50 pA/°C respectively and this over a limited temperature range. Chopper stabilized amplifiers on the other hand show 50 pA and .5 pA/°C for the same characteristics and over a much wider range of temperatures.

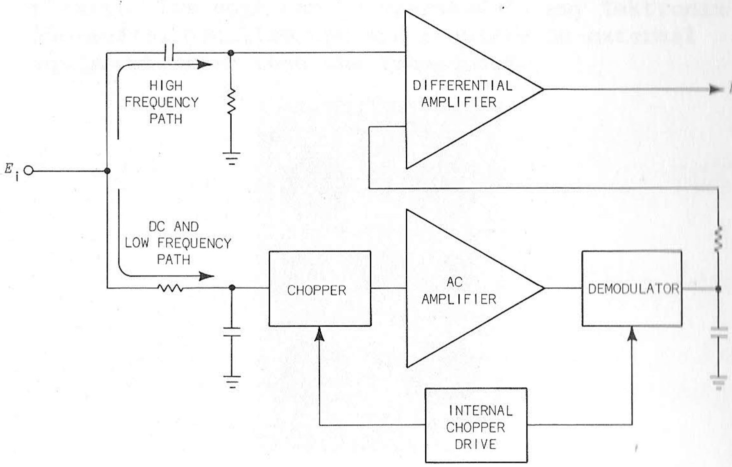



Fig. 4-9. Chopper-stabilized amplifier block diagram.

readout

Readout of static transducer signals can be accomplished with relatively simple galvanometer-type instruments. Such instruments usually consist of an internal bridge provided with terminals for the transducer and calibrating resistor, an excitation power supply, an amplifier, and a galvanometer movement. Some operate on the null-balance principle, while others are direct-reading types. An oscilloscope can also be used as the readout instrument for static measurements. Unless the oscilloscope is used for other purposes, however, its capabilities will be largely wasted.

Dynamic transducer measurements up to about 100 hertz in frequency can be made with pen-recorder type instruments, and up to 5 kHz with light galvanometers. Above this frequency, the oscilloscope proves to be about the only readout instrument capable of providing the desired accuracy and frequency response for dynamic measurements.



# 5

# TEKTRONIX TRANSDUCER INSTRUMENTATION

The oscilloscope has been used as a readout device in transducer measurement systems for many years. Its advantages were not fully utilized, however, until Tektronix extended its revolutionary plug-in concept to instruments designed specifically for transducer measurements. With these plug-ins, a complete transducer measurement system can be housed in a single oscilloscope mainframe, eliminating the problems created by component incompatibilities, interconnecting cabling and overlapping controls. With one of the systems described below, almost any physical quantity, property or condition, whether static or dynamic in nature, can be measured from remote locations with precision and accuracy.

## TYPE 3C66 CARRIER AMPLIFIER

The 3C66 (Fig. 5-1) is a carrier amplifier designed primarily for strain measurement, although it can be used with many other types of passive transducers, including resistive, capacitive and inductive varieties. It can also be calibrated for direct reading of capacitance from 0.2 pF/div to 10,000 pF/div. The unit can be operated in any Tektronix 560-series oscilloscope and requires no external equipment other than the transducer.

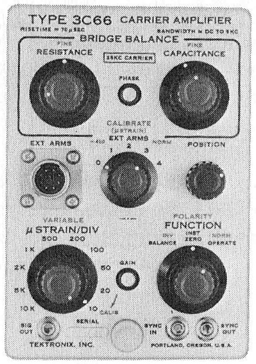



Fig. 5-1.

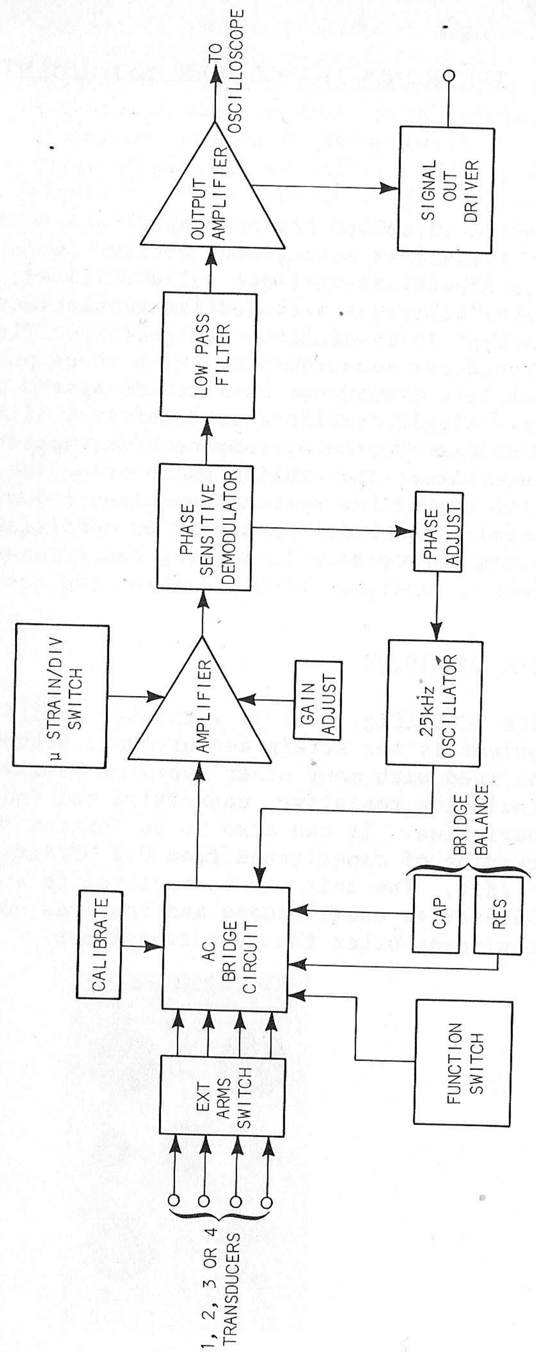



Fig. 5-2. Block diagram, Type 3C66.



**block diagram**

A block diagram of the 3C66 circuitry is shown in Fig. 5-2. With minor exceptions, it is essentially the same as that shown in Fig. 4-5. The AC bridge circuit is a conventional 120-ohm Wheatstone bridge, modified to give it additional flexibility. Excitation power at about 5 V RMS is supplied to the bridge by the 25 kHz oscillator, which also provides a reference signal for the phase-sensitive demodulator. Changes in resistance, capacitance or inductance of the transducer or strain gage(s), acting as one or more arms of the bridge, modulate the 25 kHz carrier by unbalancing the bridge. When the bridge is balanced, the carrier is suppressed. The amplifier passes modulation frequencies from DC to 6 kHz, rejecting unwanted frequencies.

In the phase-sensitive demodulator, the 25 kHz carrier is added to the modulated signal so that the output reflects not only the amplitude but the phase of the bridge signal. After passing through a filter circuit to eliminate undesired modulation products, the signal passes to the oscilloscope.

**controls**

The convenience and flexibility of the 3C66 is revealed by the front panel controls.

The EXT ARMS switch makes it possible to connect from one to four transducers or strain gages as arms of the Wheatstone bridge. (The term "strain gage" will be used in the rest of this discussion to avoid needless repetition. In almost all cases, however, the term "passive transducer" can be substituted whenever it appears.) The 0 EXT ARMS position permits a check of the instrument for normal operation without an external transducer. In position 4 EXT ARMS, the switch connects a standard 4-arm strain-gage transducer directly to the amplifier.

The BRIDGE BALANCE controls adjust shunt capacitance and resistance in the arms of the bridge to offset unbalances caused by the transducer, cable resistance, and capacitance.

The CALIBRATE switch connects a built-in calibrating resistor in parallel to one arm of the bridge, causing a deflection of the trace proportional to the amount of equivalent strain. The GAIN ADJUST control is then manipulated to give the correct vertical deflection of the trace for direct reading in μ strains/div. This adjustment can be used to compensate for different gage factors between strain gages. A provision is also made for changing calibration resistors when the range of the GAIN ADJUST controls is insufficient to achieve the desired deflection. This is only required for other than 120 Ω strain gages.

The μSTRAIN/DIV switch adjusts the sensitivity of the amplifier in ten calibrated steps from 10 to 10,000 με/division of vertical deflection. With active strain gages in all four arms of the bridge, the maximum sensitivity is increased to 2.5 με/div. When the VARIABLE control is activated, the sensitivity may be continuously varied between steps.

The PHASE control permits changes in the phase of the reference signal supplied to the demodulator. The range of adjustment is sufficient to permit use of both resistive, capacitive and inductive transducers.

The FUNCTION switch makes the necessary connections to allow bridge balancing or to completely disconnect the instrument from the system.

The EXT ARMS terminal is a connector to which a shielded four-conductor cable is connected to the strain gages.

gages

The 3C66 can be operated successfully with strain gages ranging from 50 ohms to 2,000 ohms in resistance. Optimum performance and ease of operation are achieved in the 120- to 500-ohm range.



When capacitive transducers are used in conjunction with the internal bridge, the maximum useful sensitivity of the 3C66 is 1.0 pF/div. An external higher impedance bridge increases this sensitivity.

Inductive transducers can be used with good results, although differential transformers designed to operate at 60 Hz are only partially satisfactory at 25 kHz.

Operation of the 3C66 is virtually noise and drift free.

## TYPE Q PLUG-IN UNIT

The Q unit (Fig. 5-3) is designed to be used with Tektronix 530-, 540-, or 550-series oscilloscopes. Its design, operation and capabilities are essentially the same as those of the 3C66.

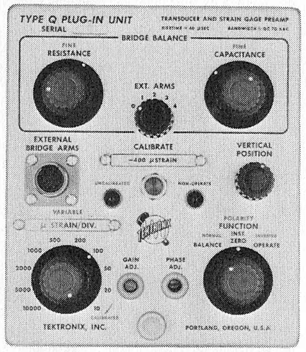



Fig. 5-3.

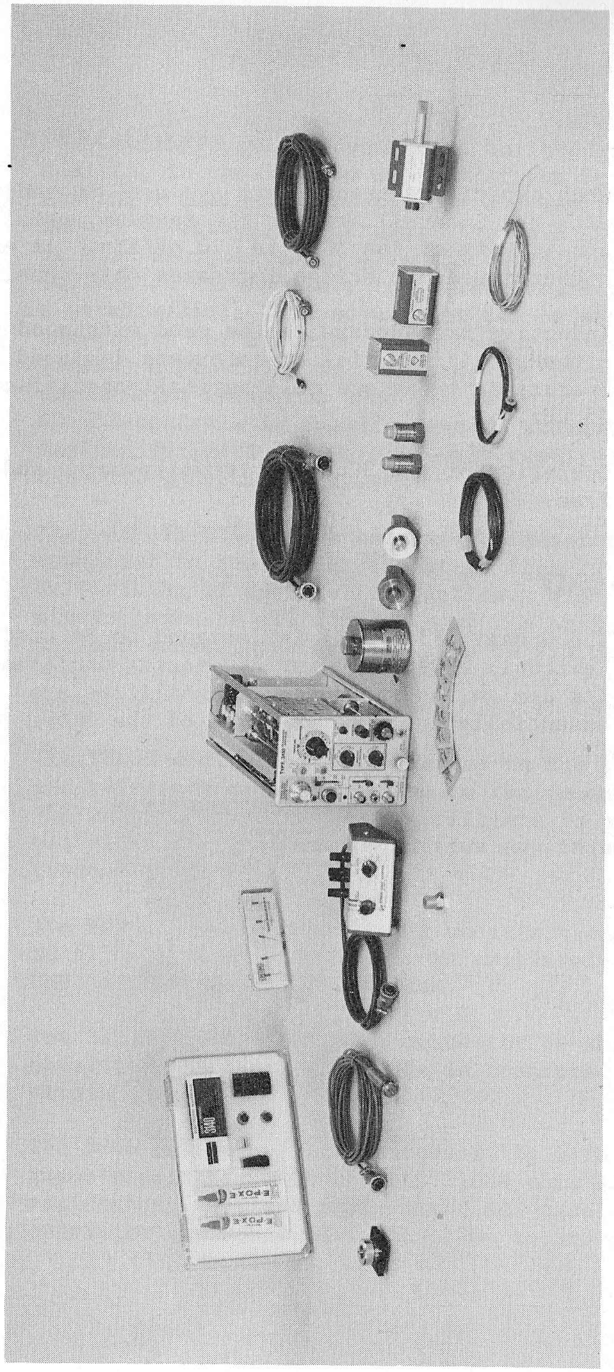


Fig. 5-4. Type 3A10 transducer system.



TYPE 3A10 TRANSDUCER AMPLIFIER

system

The Type 3A10 Transducer Amplifier is the most recent addition to the Tektronix line of transducer instrumentation. Together with its family of specially tailored transducers, it constitutes an integrated, all-purpose mechanical measurement system (Fig. 5-4). For the first time, measurement accuracy can be specified for a complete system rather than by individual components. Innovations in system design have eliminated many of the troublesome and time-consuming set-up procedures formerly associated with transducer measurements.

At the heart of the system is the 3A10 Transducer Amplifier (Fig. 5-5), a stable, low-noise, wideband DC amplifier of 100% solid-state construction. Both single-ended and differential modes of operation are provided. A 1-11 volt DC power supply (with 60 mA current limit) is included for strain-gage and other voltage-excited transducers. A 10 megohm input impedance may be selected for piezoelectric and other high impedance transducers, while a 1 megohm input permits use of standard oscilloscope probes.

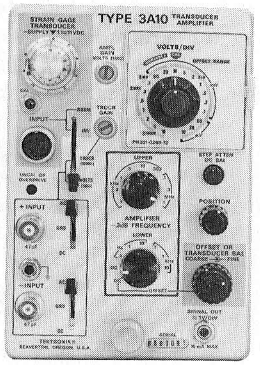



Fig. 5-5.

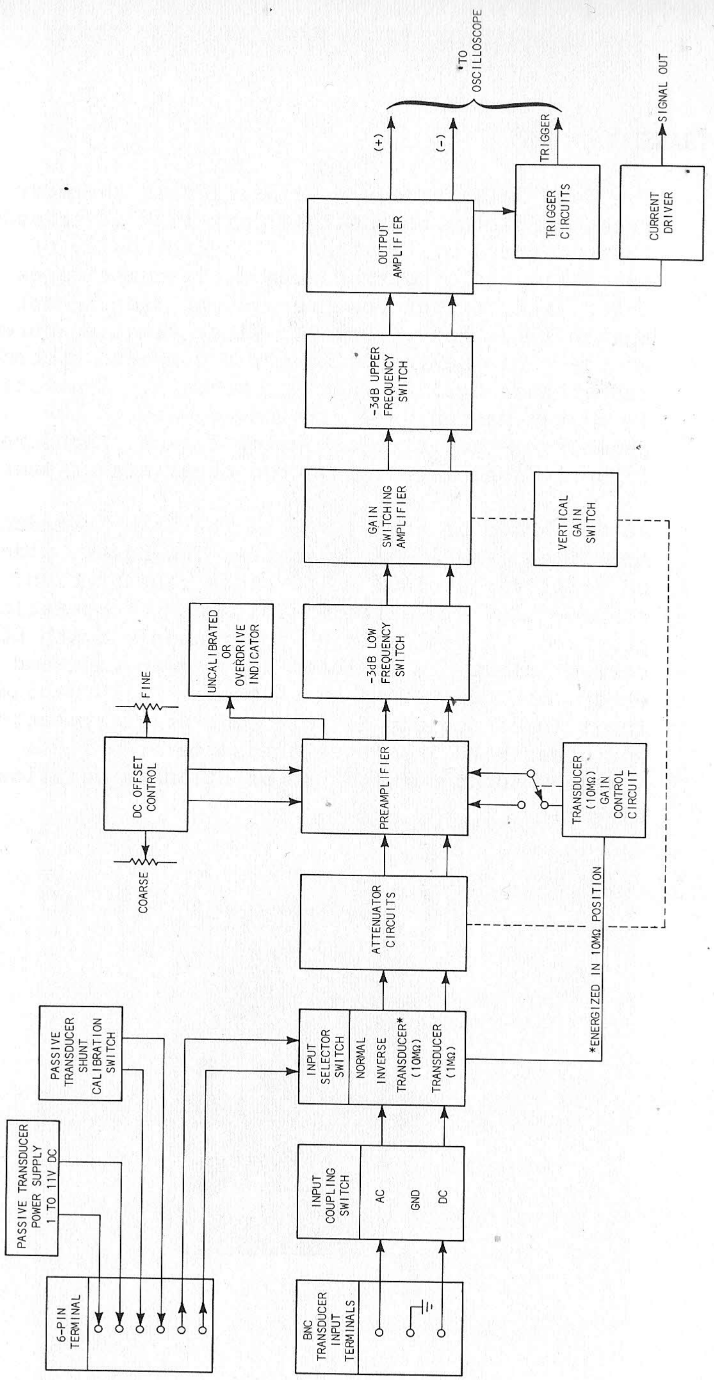



Fig. 5-6. Block diagram, 3A10 transducer amplifier.



transducers

Ten transducers, each tailored specifically for use with the 3A10, and a strain-gage adapter complete the system. With these accessories the measurands of force, relative and absolute displacement, absolute velocity and acceleration, shock, temperature, strain, pressure and many other quantities can be determined. Direct reading in measurand/division is provided by "snap-in" attenuator scales. Each scale is reversible, with appropriate U.S. units on one side and metric units on the other. All strain-gage type transducers are fitted with shunt calibration resistors, eliminating the need for lead-impedance corrections.

A block diagram of the 3A10 circuits is shown in Fig. 5-6. Two BNC terminals are provided for the differential amplifier inputs, and a 6-pin connector for the strain gage adapter and voltage-excited transducers. A Tektronix-manufactured, six-conductor, low-noise cable connects the adapter and transducers to the instrument. Two leads provide the variable bridge excitation voltage, two carry the bridge output signal, and two are used to shunt a calibration resistor in the adapter or transducer to one arm of the bridge. Input coupling switches permit AC or DC coupling, or grounding of either side of the amplifier. Thus, the amplifier can be used in the single-ended mode when desired. An INPUT selector switch controls the polarity of the bridge output signal and the input impedance of the differential amplifier. Ten megohms is presented to the bridge signal and high impedance transducers, while a one megohm impedance is provided for standard oscilloscope probes. In this position of the switch, the instrument can be used as a conventional oscilloscope vertical amplifier.

attenuator

The selected input signal is routed through a calibrated attenuator circuit which is controlled by the gain control switch. This switch also controls the gain of the amplifier. Maximum sensitivity is 10 microvolts/division. No attenuation is imposed on the input signals at sensitivities below 20 millivolts so that a common-mode rejection ratio of 100,000:1 is provided for low-amplitude transducer signals. The gain-control switch is surrounded by a fixture which permits interchanging small metal plates, scaled in appropriate units of pressure, force, velocity, acceleration, etc. Metric units are presented on one side of the plate, while traditional U.S. units are used on the other. This arrangement eliminates "mental scaling" and the attendant possibility of errors in conversion from volts/div to measurand amplitude. A volts/division scale is also provided for conventional oscilloscope measurements. The reverse side of the scale is blank, and can be marked in units of convenience.

pre-amplifier

From the attenuation circuits the signal is applied to a preamplifier where DC offset is controlled. This control acts as the balancing circuit of the amplifier and also functions to "buck out" small DC components of the input signal while maintaining the differential capability. A relay is energized when the INPUT selector switch is placed in the TRDCR position, connecting a variable-gain circuit to the amplifier. This circuit extends the amplifier gain to accommodate differences in transducer sensitivity, and permits switching between inputs without constant recalibration.

bandpass limiting

The lower and upper -3 dB limits of the amplifier bandpass are adjustable, providing selective filtering of signal frequency components. This feature gives a significant flexibility to the amplifier, especially in studies of shock and vibration, where extraneous frequencies often complicate the measurement. The lower -3 dB limit can be varied from DC to 10 kHz, while the upper limit is adjustable from 100 Hz to 1 MHz. Thus, at frequencies below 10 kHz the bandpass can be narrowed to eliminate almost all undesired frequencies, including most externally generated noise. Roll-off is approximately 6 dB per octave. Differentiation takes place on the low frequency slope, while integration may be performed on the upper frequency slope.

gain-switching amplifier

The gain-switching amplifier provides calibrated gain in 1, 2, 5 steps. As stated earlier, no attentuation is imposed on the input signal below the 20 mV/div position. The overall sensitivity range extends from 10 μV/div to 10 V/div.



output amplifier

The output amplifier processes the signal for the oscilloscope mainframe circuits and also provides outputs for the trigger circuit and SIGNAL OUT current driver. The latter circuit provides about 15 mA maximum current drive into 400 ohms, at an approximate 9 V maximum (open circuit). This signal is sufficient to drive many types of recorders without further amplification.

564B/3B4 recommended

The 3A10 amplifier can be used with any of the 560-series oscilloscopes. The 564B with a 3B4 time base is highly recommended, due to the numerous advantages accruing from the split-screen storage capability of the former, and the excellent triggering capability of the time base. The 3A10 can also be stacked in the Type 129 Plug-in Unit Power Supply for multichannel testing and recording, *X-Y* plotting and similar applications.

## SYSTEM ACCESSORIES

Strain Gage Adapter (Fig. 5-7): This device consists primarily of an incomplete 120 Ω Wheatstone bridge, the fourth arm of which is open to accept a strain gage or other passive or active transducer. The EXT ARMS switch permits the use of 1, 2, or 4 external arms. The calibration resistor is placed in shunt with the R4 arm, so that it provides an equivalent of 1,000 μ strains in the 1 and 2 EXT ARMS positions, regardless of the strain gage resistance.

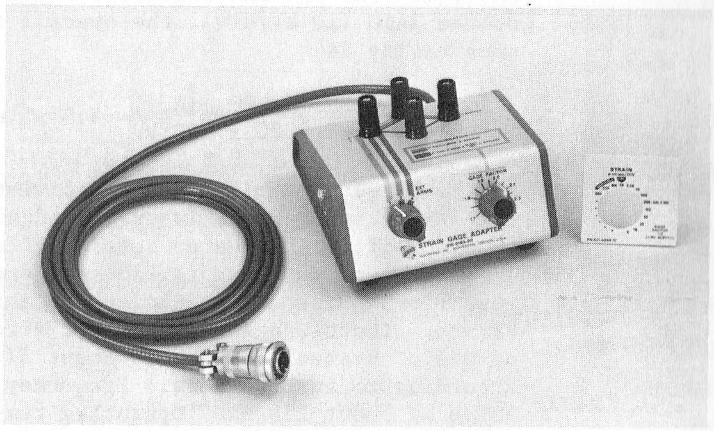



Fig. 5-7. Strain Gage Adapter.

In the 4 EXT ARMS position, of course, the equivalent strain must be calculated. Color coding provides a clear picture of the bridge configuration in all three positions of the switch. The calibration resistor itself is a variable linear precision resistor. This feature eliminates the necessity of calculating equivalent strain when gage factors other than 2 are encountered. GAGE FACTOR range is 1.7 to 2.3. The variable bridge excitation power supply can be adjusted to meet the power density conditions imposed by the particular circumstances of the application (see Appendix). In the 1 EXT ARMS position only 120 Ω strain gages can be used; in the 2 or 4 EXT ARMS positions any value of gage resistance can be used, as long as 60 mA bridge input current is not exceeded. A unique low-noise cable and connector developed and manufactured at Tektronix, connects the adapter to the 3A10.

Displacement Transducer (Fig. 5-8): The displacement transducer consists essentially of an LVDT, an oscillator, a demodulator and a noise filter, all combined in a compact, lightweight package. The DC supply voltage powers an oscillator to provide an AC voltage to the LVDT primary (Fig. 5-9). The output of the secondary winding is applied to the phase-sensitive demodulator, producing a DC output voltage whose amplitude and phase are determined by the position of the core. A simple RC filter suppresses noise in the output signal. The sensitivity of this transducer is approximately 20 mV/$10^{-3}$in. At the highest sensitivity setting of the 3A10 (10 μV/div), the overall system sensitivity is

$$\frac{10^{-5}\text{V}}{\text{div}} \times \frac{10^{-3}\text{in}}{20 \times 10^{-3}\text{V}} = 0.5 \times 10^{-6}\text{in/div}$$

or about 1/2 of a microinch per division. However, the displacement scale is graduated no lower than 10 μinch/div. At greater sensitivities, even small ambient temperature fluctuations and transducer electrical noise are sufficient to introduce sizable errors. Input range is ±0.2" for a full-throw range of 0.4". System accuracy is about 3% when used according to instructions. Frequency response is -3 dB at about 150 Hz. Operating temperature range is -50° to +60°C (for a typical application, see Chapter 6).



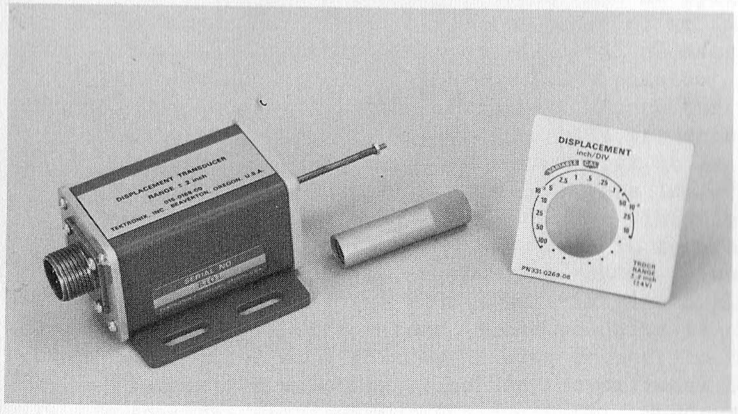


Fig. 5-8. Displacement Transducer.

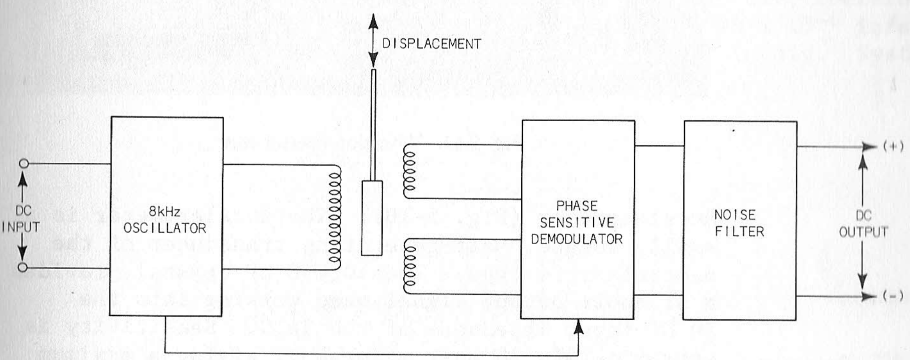



Fig. 5-9. Block diagram, LVDT displacement transducer.

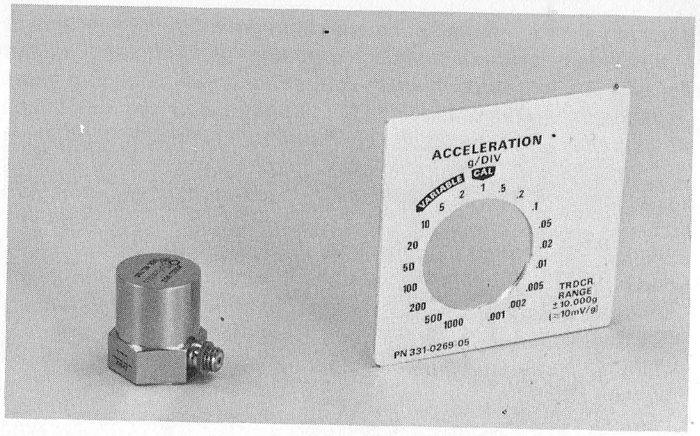



Fig. 5-10. Accelerometer.

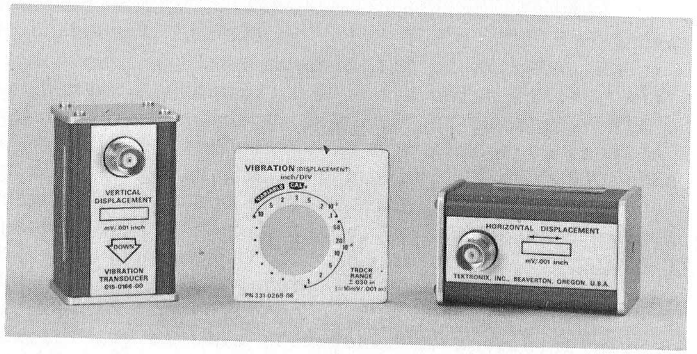



Fig. 5-11. Vibration transducers.

Accelerometer (Fig. 5-10): The accelerometer is a small, rugged, self-generating transducer of the piezoelectric type. The 10,000 pF crystal provides a sizeable output signal when working into the 10 MΩ input impedance of the 3A10. Sensitivity is approximately 10 peak mV/peak g, giving a maximum system sensitivity of about $10^{-3}$ peak g/division. System frequency response (-3 dB) is about 1.5 Hz to 6 kHz. Accuracy is about 5% for the accelerometer and about 8% for the system. Resonant frequency is above 30 kHz. The accelerometer can be used in motion studies to determine absolute acceleration or in shock and vibration studies (see Chapter 6). Special low-noise cable is provided for these applications.



Vibration Transducers (Fig. 5-11): Two vibration transducers, one for vertical and one for horizontal vibration measurements, are provided as system accessories. These devices consist of an inductive (self-generating) seismic mechanical element of very low (8 Hz) natural frequency and a passive integrating circuit (Fig. 5-12). Since the mass is a coil, suspended in the field of a permanent magnet, the coil generates a voltage whenever it is in motion. The amplitude of the voltage is, of course, proportional to the *velocity* of the vibration. This output signal is available at the BNC terminal marked VERTICAL (or HORIZONTAL) VELOCITY (not shown in Fig. 5-11). The same signal is also applied to the passive integrator. Since velocity is the first derivative of displacement with respect to time, the integrated velocity signal is proportional to the absolute displacement of vibration. Shunt resistor $R_S$ provides electrical damping which effectively eliminates the natural-frequency-peak of the device's mechanical-response curve. This provides an almost flat transducer sensitivity down to about 10 Hz. Displacement sensitivity is nominally 10 mV/.001 in, while velocity sensitivity is approximately 600 mV per inch per second. When used with the 3A10 at the highest sensitivity setting of 10 μV/div, therefore, system sensitivity for velocity is 16 x $10^{-6}$ in/s/div and for absolute displacement, $10^{-6}$ in/div. System accuracy is about 8%.

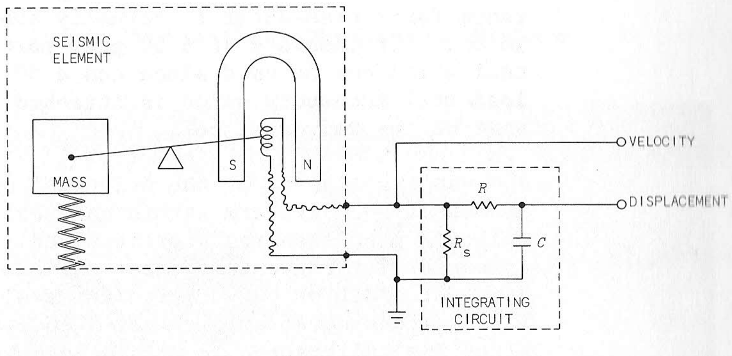
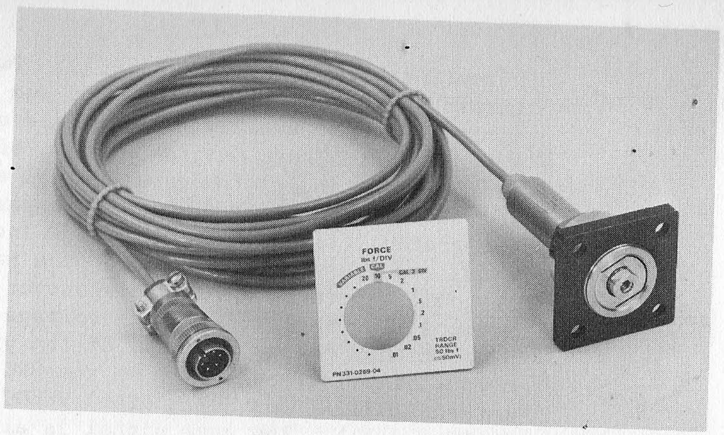



Fig. 5-12. Schematic diagram – vibration transducer.



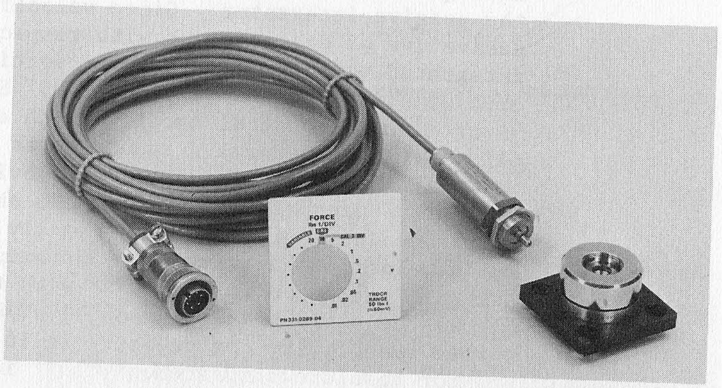


Fig. 5-13. Force transducer (Low).

Force Transducer -- Low Range (Fig. 5-13): The low-range force transducer is actually two transducers in one. It consists of a 50 gram-force universal cell which can be used alone and a 50 pound-force load cell accessory which is attached to the threaded nose of the universal cell.

The sensing element of the universal cell is an unbonded, 4-active-arm strain gage bridge. A selected precision resistor is wired into the connector for convenient shunt calibration of the gram-force/div or pound-force/div scales (Fig. 5-14). This feature considerably increases *system* accuracy, since the calibration is precisely determined for each transducer. Thus, variations in transducer sensitivity are automatically compensated for, eliminating a common source of readout error.



Maximum useful system sensitivity is 0.01 gram/div with a system accuracy of about 5%. Small displacements can also be measured with this device. Maximum displacement range is .12 mm.

The load cell accessory increases the force range to 50 pound-force. Deflection of the load cell accessory diaphragm under tension or compression is communicated to the universal cell through an adjustment screw. This screw is used to bias the load cell for tension or compression measurements. Maximum system sensitivity of the 50 pound-force configuration is 0.01 pound-force/div or 5 gram-force/div with an accuracy of approximately 5%.

Force Transducer -- High Range (Fig. 5-15): The high-range force transducer is a simple 3,000 pound-force load cell, consisting of a steel cylinder to which a strain gage bridge has been cemented, all contained in a hermetically sealed housing. Both ends of the cylinder are threaded to accept heavy duty eyebolts, or a "load button" for compressional loads.

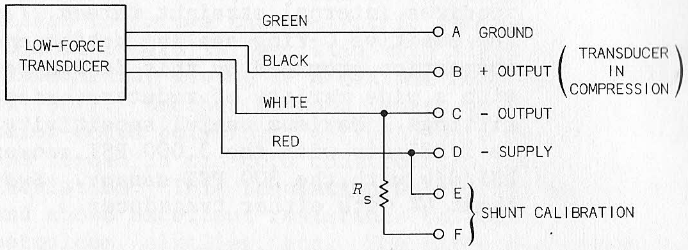



Fig. 5-14. Shunt calibration resistor installation.

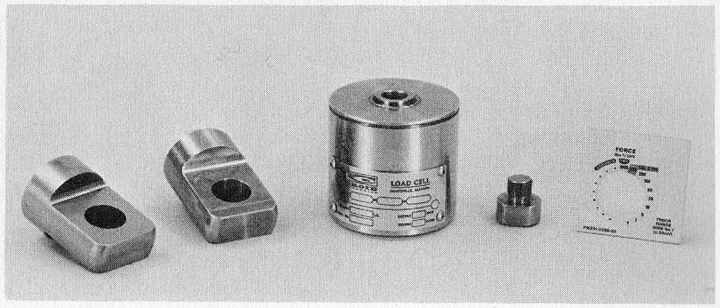


Fig. 5-15. Force transducer (High).

A manufacturer-installed half-full-scale shunt calibration resistor is also included. Bridge excitation power, bridge output signal and shunt calibration resistor leads are wired to a Bendix connector for easy hook-up to the 3A10. Maximum useful system sensitivity is 1 pound-force/div or 0.5 kilogram-force/div, with a system accuracy of about 4%.

Pressure Transducers (Fig. 5-16): Two pressure transducers of identical design but different pressure ranges are available as accessories to the 3A10. The 3,000 PSI transducer is intended primarily for hydraulic pressure measurements and high pressure compressors. The 300 PSI model will be more often used in air- or gas-pressure measurement. Construction is very simple. A strain gage bridge, bonded to a diaphragm, senses any distortion of the diaphragm due to fluid pressure. A factory-installed calibration resistor is built into the bridge. Bridge and shunt calibration leads are wired to a 6-pin connector. The pressure inlet is designed to meet Mil Spec 33649-4 (1/4" tubing, fluid connection, female) formerly Air Force Navy 10050-4, which requires internal straight thread 7/16" 20 VNJF-3B. The positive O-ring sealing action and ease of connection provided by this design can be attained with a wide variety of reducers, adapters and similar fittings. Maximum useful sensitivity of the system is 1 PSI/div with the 3,000 PSI sensor and 0.1 PSI/div with the 300 PSI sensor. System accuracy is about 4% with either transducer.

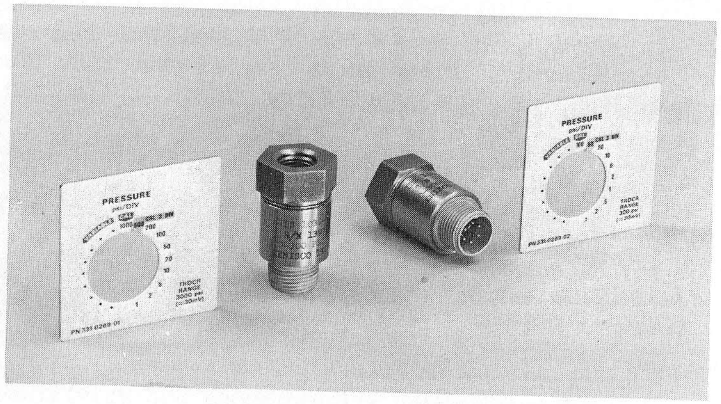



Fig. 5-16. Pressure transducers.



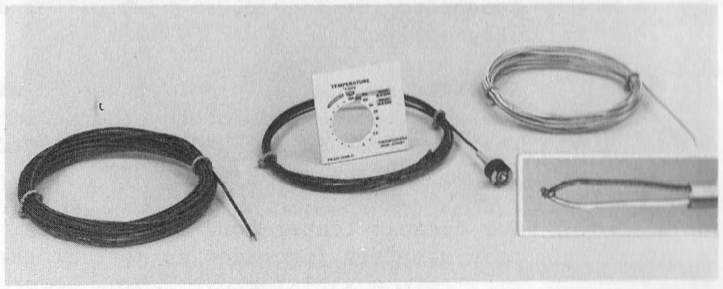


Fig. 5-17. Thermocouples.

Temperature Transducers (Fig. 5-17): Three thermocouple-type temperature sensors are available as accessories to the 3A10 system. Two of these devices consist of lengths of #30 iron-constantan thermocouple wire, one end of which has been spot-welded to form a thermoelectric junction. One 20-foot length is insulated with silicone-impregnated glass braid, giving it a maximum temperature range of 900°F. Another 20-foot length is insulated in color-coded polyvinyl, extruded onto the bare wires and bonded in rip-cord construction without further insulation. This insulation will stand up to 220°F and shows excellent resistance to abrasion, petroleum, alkalies, etc. The third thermocouple is made from #24 wire, insulated in impregnated glass braid. It is six feet long and fitted with a magnetic coupling device at the junction end. This device holds the junction in firm contact with ferrous materials while temperature measurements are made.

Each of the thermocouples generates about 30 μV/°F from 50°F to 900°F. Maximum useful system sensitivity is thus 0.5°F/div, with an accuracy of about 5%. (See Appendix.)

If a stable reference junction is required, a second thermocouple may be connected in series with the active one, and immersed in a temperature-controlled, nonconductive liquid, such as oil or distilled water (Fig. 5-18A).

A better system is to solder copper wires to the iron and constantan leads of the thermocouple and immerse the junctions in a fluid, as described above. (Fig. 5-18B).

For dynamic temperature measurements, the binding post adapters (provided as part of the thermocouple kit) form a satisfactory "cold" reference junction in almost all cases.

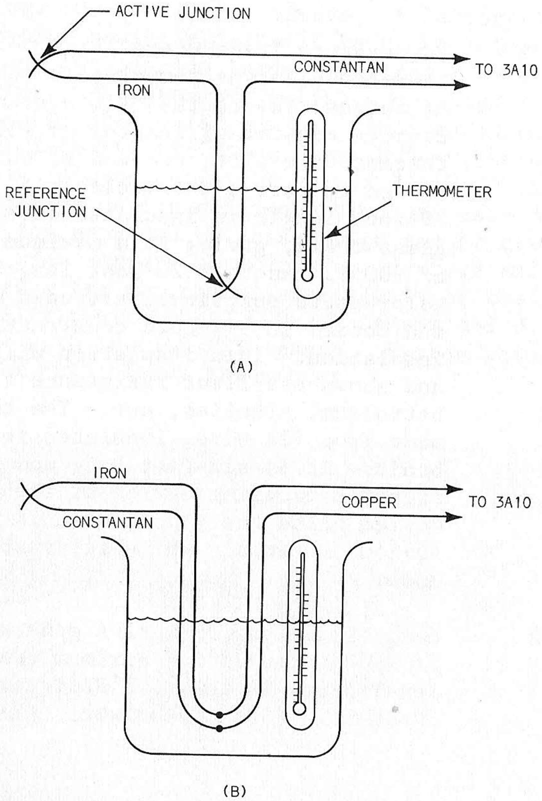



Fig. 5-18. Establishing thermocouple reference junctions.



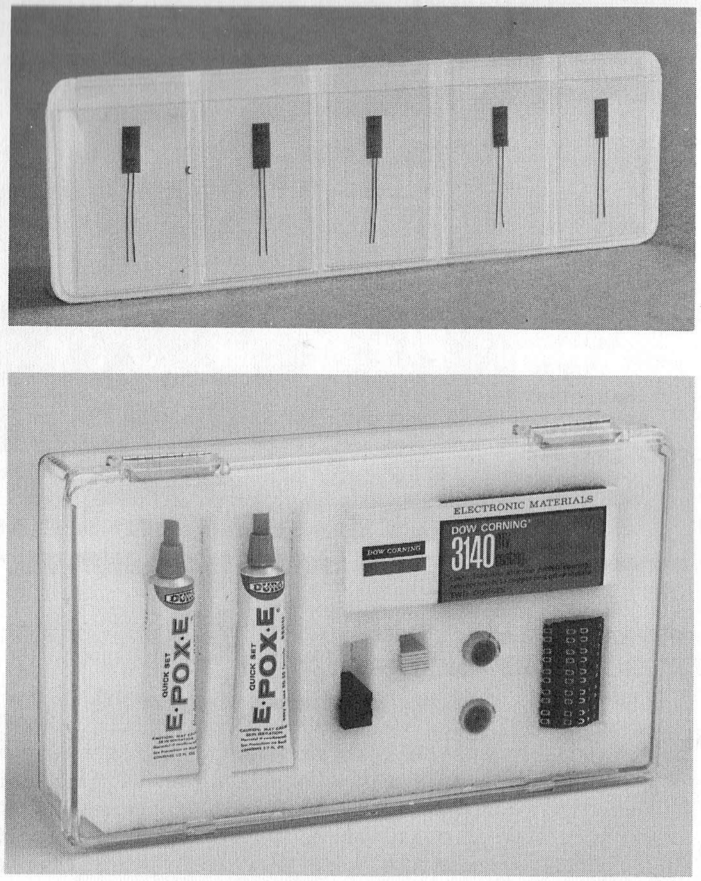



Fig. 5-19. Strain gages and strain gage kit.

Strain Gages and Strain Gage Kit (Fig. 5-19): A package of five strain gages and a complete strain-gage application kit complete the 3A10 system accessory list. The strain gages are 120 ohm, metal-foil, polymide-backing precision gages with a nominal gage factor of 2 and a gage length of 1/8". When used with the Strain Gage Adapter at 4 volts DC, the strain-gage maximum system sensitivity is 5 μstrains/div with an accuracy of about 3%. Maximum range exceeds the yield point of common metals.

The strain gage kit contains the basic materials required for cementing and waterproofing the gage and connecting the cable to the strain gages.

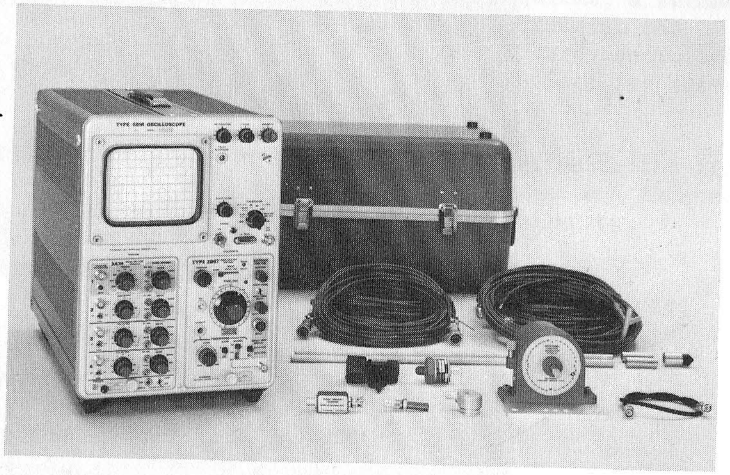


Fig. 5-20. Engine analyzer system.

## TEKTRONIX ENGINE ANALYZER SYSTEM

The Engine Analyzer System (Fig. 5-20) is a completely integrated oscilloscope system for evaluating the performance of reciprocating engines, compressors and pumps. It consists of a 561B or 564B oscilloscope, fitted with a modified 3A74 Engine Analyzer (Vertical) Amplifier and a modified 2B67 Engine Analyzer (Horizontal) Time Base, a Rotational Function Generator (RFG) and four transducers, plus the necessary connecting cables. The transducers sense cylinder pressure, ignition voltage, vibration and cylinder top dead center (TDC). The first three quantities are displayed against crankshaft angle, a function generated in the RFG and reference to TDC. A modified sinewave, representing cylinder volume, is also generated in this device. Many malfunctions such as incorrect timing, faulty ignition, valve leakage, piston slap and others can be diagnosed, by interpreting the display. Costly routine overhauls can thus be avoided and down time kept to a minimum. At the same time, serious malfunctions can be detected and corrected before damage occurs.



A complete description of the Engine Analyzer System and its components, together with helpful information on applications, may be found in the Tektronix Measurement Concepts book, *Engine Analysis Measurements*.

## TYPE 410 PHYSIOLOGICAL MONITOR

The Type 410 is a highly specialized medical transducer system, designed primarily as a patient monitor (Fig. 5-21). It consists of an oscilloscope-type display device and a number of electrical pickups for making ECG, EEG, pulse and other physiological measurements. It can be operated from AC line voltages or its own internal battery pack. It is used extensively in the operating room, intensive care unit and during patient recovery.

The Type 410 is described in the Tektronix Measurement Concepts book, *Biophysical Measurements*.


Fig. 5-21. Type 410 Physiological Monitor.

# 6

## PRACTICAL APPLICATIONS

The range of measurements which can be performed with transducer systems is limited only by the imagination and ingenuity of the user. A few examples of practical applications are presented in this chapter to illustrate the basic principles involved. The applications selected for each transducer are generally typical of those encountered in industry. All measurements were performed with the 3A10 Transducer System, using a Type 564B (Storage) Oscilloscope and a C-12 camera.

### MISCELLANEOUS APPLICATION NOTES

**bonded resistance strain gage**

Bonded resistance strain gages are the most widely used of all types of transducers. This is due primarily to their versatility, accuracy, and relatively low cost. Although initially developed for studies of stress and strain, large numbers are now used as sensing elements in the manufacture of other transducers.

Bonded strain gages were first manufactured of very fine resistance wire. Although such bonded wire strain gages are still in use, they have been largely superseded by the bonded metal-foil strain gage. Both operate on the same principle. When subjected to tension, the wire or foil filament elongates, with a resultant reduction in cross-sectional area. Since the resistivity of a given filament is a function of its length and cross-sectional area, both effects increase the resistance of the filament. When supported by a firm cement bond, the filament can also be compressed with opposite effects on its resistance.

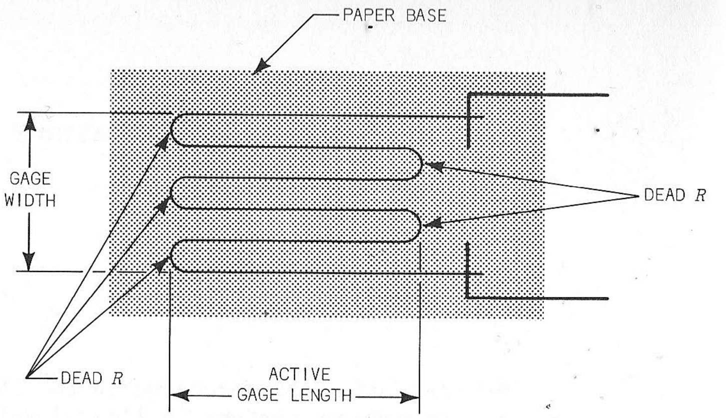



Fig. 6-1. Typical strain gage.

When the filament is folded to form a grid as in Fig. 6-1, small sections at the fold are not affected by tensional or compressive strains. This same *"dead resistance,"* however, is directly in line with Poisson strains. Since these strains are of opposite types, the "dead-resistance" change subtracts from the normal-resistance change. This effect is called *transverse sensitivity* and subtracts from the normal gage sensitivity. The manufacturer, however, tests samples of each gage lot on a calibrated test structure so that the effects of dead resistance are included in the published *gage factor*.

The majority of bonded resistance strain gages have a resistance of 120 Ω, but many other resistances are available. Gage factor for these types is nominally 2. The backing or gage-carrier is usually made of nitrocellulose paper, but bakelite is also used for higher-temperature gages.

Gage lengths vary from about 1/64" for the smallest metal foil gages to 6". Since strain is expressed $\frac{\Delta l}{l}$, it is clear that in actual measurements, the strain registered by a given gage represents the total elongation experienced by the gage *averaged over the length of the gage*. Thus, when strain is not evenly distributed in a member, the strain at any given point is most accurately determined by the *shortest* gage.



It was demonstrated in Chapter 3 that many individual strain measurements require three strain gages, placed at different angles to a chosen axis. For convenience, rosette gages consisting of three gages mounted in one of several configurations on a common carrier are available from commercial sources (Fig. 6-2). Nomograms for quick solution of the strain problem are also available.

Where conventional temperature compensation techniques cannot be employed, it may be advisable to use a single temperature-compensated strain gage. These gages are designed to give compensation over a specific range and on a specific material.

Although strain gages will function at stresses beyond the yield point of most common materials, maximum strain should be kept within 2,000 $\mu\varepsilon$ for optimum repeatability and linearity. Linearity of most gages is on the order of 0.1 or 0.2%.

Semiconductor gages are characterized by their high gage factors, ranging from 50 to 250 and above. However, these gages suffer from a high degree of nonlinearity and require special circuitry if their full potential is to be realized.

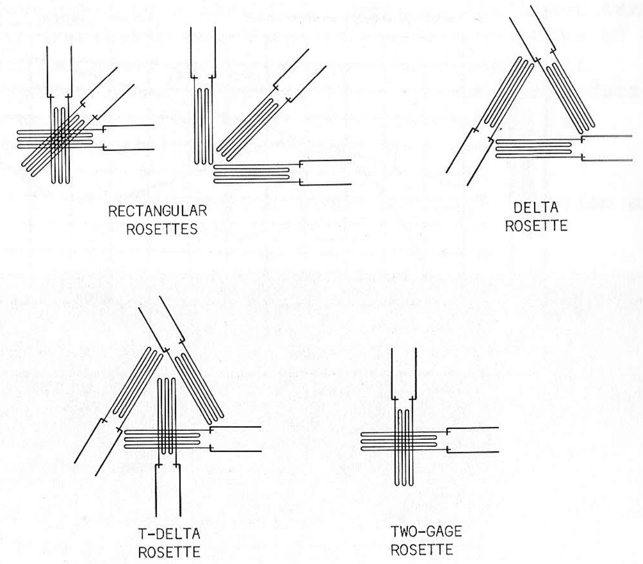



Fig. 6-2. Strain gage rosette configurations.

M-M

ENGINEERING DATA SHEET

ITEM ______
CODE ______
CHECK ______
FINAL QA ______

THE INFORMATION APPEARING ON THIS SHEET HAS BEEN COMPILED SPECIFICALLY FOR THE GAGES CONTAINED IN THIS PACKAGE. THIS FORM IS PRODUCED WITH ADVANCED EQUIPMENT & PROCEDURES WHICH PERMIT COMPREHENSIVE QUALITY ASSURANCE VERIFICATION OF ALL DATA SUPPLIED HEREIN. SHOULD ANY QUESTIONS ARISE RELATIVE TO THESE GAGES, PLEASE MENTION GAGE TYPE, ITEM NUMBER, AND LOT NUMBER.

**MICRO-MEASUREMENTS**
ROMULUS, MICHIGAN
**PRECISION STRAIN GAGES**

M-M

EA-06-125BT-120

EA-06-125BT-120
GAGE TYPE

120.0 ± .15%
RESISTANCE IN OHMS

2.11 ± 0.5%
GAGE FACTOR AT 75° F

$K_t$: +0.6%

Q-A21AD06
LOT NUMBER

5 GAGES
QUANTITY

OPTIONS

Form: B2-440
Code: 782121

GENERAL INFORMATION: SERIES EA STRAIN GAGES

APPLIES TO ALL LOT NUMBERS WITH THE PREFIX 'Q'

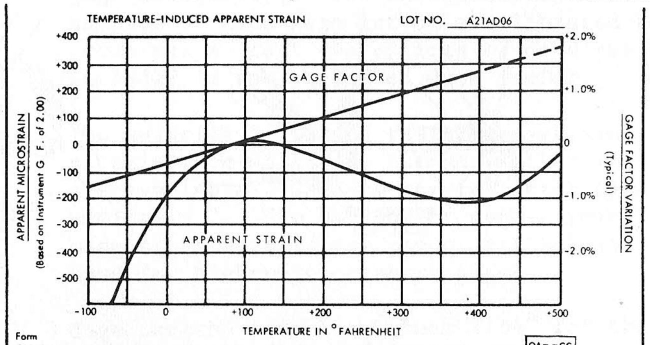
TEMPERATURE RANGE: Cryogenic to approximately +400°F for static measurements; to +500°F for dynamic strain.

SELF-TEMPERATURE-COMPENSATION: See data curve below.

STRAIN LIMITS: 30,000 to 50,000 microstrain (3% to 5%), tension or compression.

FATIGUE LIFE: Over $10^7$ cycles at ± 1400 microstrain; over $10^6$ cycles at ± 1500 microstrain or approximately 2800 microstrain unidirectional (tension or compression). Longer gage lengths and lower resistance gages show greater endurance.

CEMENTS: Particularly compatible with 'M-M' Certified Eastman 910 for fast installation. M-Bond 600 or RTC are recommended for long-term tests. M-Bond 610 is the best choice over the entire operating temperature range for elastic strains.




Form C1012-B TESTED ON: 1018-STEEL CODE: 792922 Q. A. QAm-mGG

TEST PROCEDURES USED BY MICRO-MEASUREMENTS FOR STRAIN GAGE PERFORMANCE EVALUATION

| | |
|---|---|
| OPTICAL DEFECT ANALYSIS: | M-M Procedures and Standards |
| GAGE FACTOR AT 75°F: | ASTM E251-67 (Constant Stress Cantilever Method)* |
| G. F. VARIATION WITH TEMP: | ASTM E251-67 (Step Deflection Method) |
| APPARENT STRAIN VS. TEMP: | ASTM E251-67 (Slow Heating Rate, Continuously Recorded) |
| TRANSVERSE SENSITIVITY: | ASTM E251-67 |
| INITIAL RESISTANCE: | M-M Procedure, Direct NBS Traceability on Resistance Standards |
| FATIGUE LIFE: | NAS 942 (Modified) |
| STRAIN LIMITS: | NAS 942 (Modified) |
| GAGE THICKNESS: | M-M Procedure |
| CREEP & DRIFT: | M-M Procedure (Similar to NAS 942 Method) |

*NOTE: This data is obtained in an uniaxial stress field with Poisson's ratio of approximately .285.

Form B1-431
Code: 781016

Fig. 6-3.



Most strain gages come packaged in sets of five; gages carrying the same *lot number* have common resistance values, gage factors and tolerances. To avoid complications and errors, all gages in a bridge should be from the same lot. An engineering data sheet is usually included in the package, providing the user with all the characteristics and parameters essential to proper installation and use (Fig. 6-3).

When an excitation voltage is applied to a strain gage, it dissipates power in the form of heat. The *power density* of a given gage's dissipation depends on its resistance and grid area and is expressed in watts/in$^2$. The excitation voltage must be chosen to keep power density within the limits imposed by the conditions of the test. Graphs are included in the Appendix showing the power density of common strain gages of various grid areas over a range of bridge voltages. An associated table indicates the power density limits for various materials on which the strain gage may be mounted, under static and dynamic conditions.

## installing the strain gage

The strain gage cannot be used as a precision measuring device unless it is properly bonded to the member under test. The techniques involved in bonding and waterproofing strain gages have been developed to a fine art. Several excellent texts are available which include full treatments of these subjects and should be consulted in unusual applications. However, the following procedure has been used with success at Tektronix and is recommended for most common applications.

1. Lay out scribe lines for gage location on surface (Fig. 6-4).

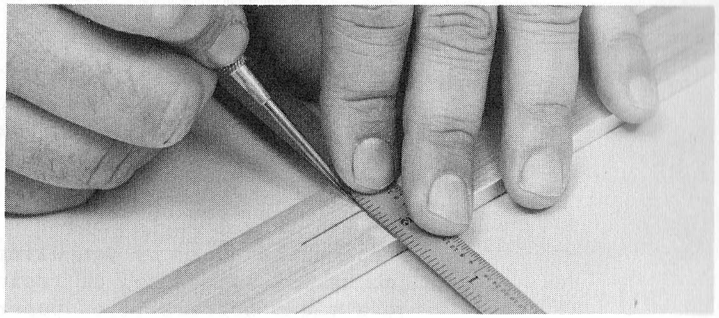


Fig. 6-4.

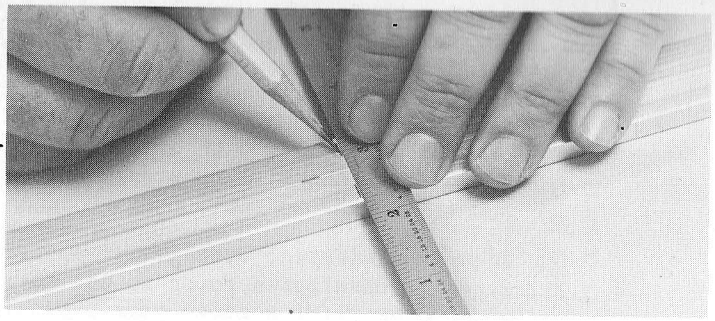


Fig. 6-5.

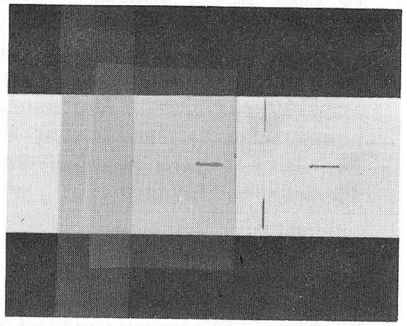


Fig. 6-6.

2. Sand with a 240 grit paper in a circular motion until scribe lines are barely visible.
3. Clean surface with solvent (alcohol, acetone or lacquer thinner) and mark in ends of scribe lines with hard pencil away from gage location (Fig. 6-5).
4. Line up gage on cross lines and mark location of lead end of gage.
5. Tape a piece of Mylar film across the above point to mask off the leads from the surface (Fig. 6-6). This prevents the leads from being glued down.
6. Clean the bottom of the gage.
7. Prepare the epoxy by squeezing out equal beads (about 1/2 inch long) of resin and hardener on a clean surface (i.e. paper) and mixing with a clean paddle until mixture is a uniform color.



NOTE: To check the epoxy, keep the paper it is mixed on. It should harden enough in 24 hours that a thin layer of it can be cracked by folding the paper.

8. With a clean paddle apply a thin coat of epoxy to the surface to wet it and a more liberal amount to the bottom of the gage.
9. Holding the gage by the leads with a pair of tweezers, place it on the surface and push it down into the epoxy with a soft instrument such as a pencil eraser and line it up with the scribed lines.
10. Place over the gage a strip of Mylar as shown and working through this strip roll out the excess epoxy from under the gage with a finger in the direction away from the leads (Fig. 6-7). When this is properly done, the gage will appear flat on the surface.
11. Once the gage is flat on the surface, it can be realigned with the scribed lines by pressing on the gage through the Mylar strip and moving the strip (both will act as one unit). When aligned, the Mylar is taped securely to the surface to prevent any more movement.

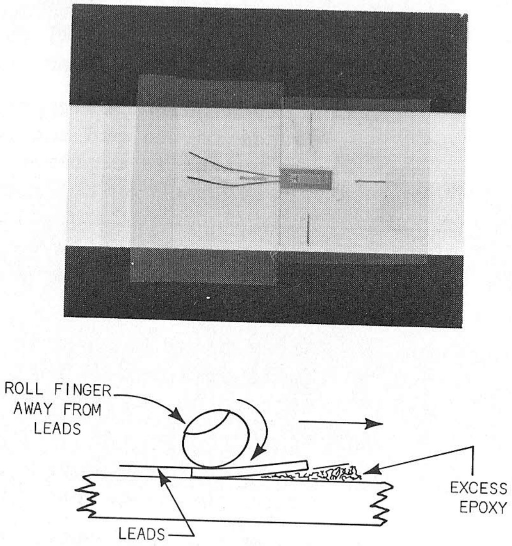



Fig. 6-7.

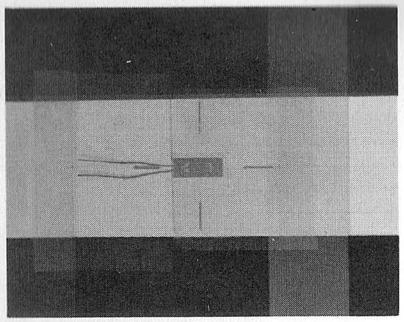


Fig. 6-8.

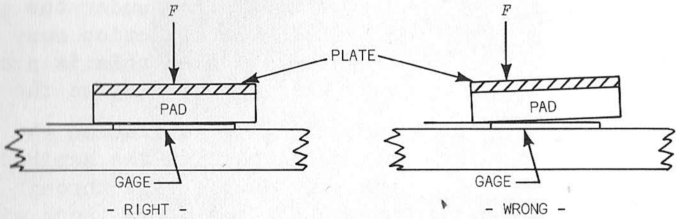



Fig. 6-9.

12. Now place another strip of Mylar over the gage and leads (Fig. 6-8) and place a neoprene pad and metal plate over the gage.
13. Apply a weight of approximately 5 to 10 pounds to the pad and plate making sure that the weight is centered on the plate so that the pressure on the gage is uniform (Fig. 6-9). One possible way to insure that the pressure on the gage is uniform is to apply the weight to the pad and plate as shown in Fig. 6-10.
14. After epoxy has set for at least 12 hours (wait at least 24 hours before use), carefully remove the weight, plate, pad and three Mylar strips.
15. Scrape off any excess epoxy from the area under the leads and rough up with sand paper.
16. Clean the area under the leads with solvent taking care not to get any on the strain gage.



17. Prepare the epoxy as before (Step 7).

    NOTE: Eastman 910 Contact Cement can be used also.
18. Wet the surface with a small amount of epoxy and apply a more liberal amount to the bottom of the terminal strip.
19. Push the strip down onto the surface and line up with the gage; keep the terminal strip close enough to the gage so that the leads from the gage to the strip can be looped (Fig. 6-11).

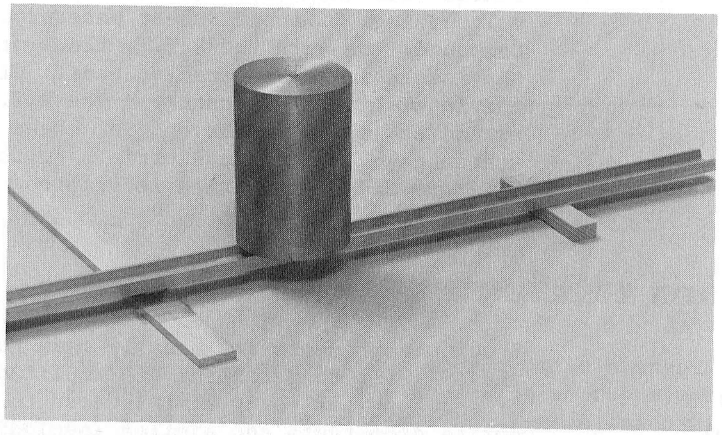


Fig. 6-10.

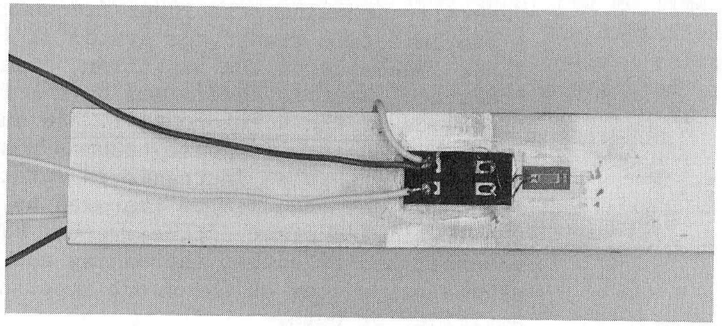


Fig. 6-11.

20. Allow about 12 hours for the strip to set on the surface and then solder the strain gage leads to the terminals. If 910 cement is used, the leads can be soldered immediately. (Leave a loop in the leads to prevent any strain at the connection on the gage.)

21. Solder the cable leads to the terminal. Connect cable to strain gage adapter.

22. The gage and strip may now be sealed, or coated with the R.T.V. (room temperature vulcanizing) Silicone Rubber Waterproofing Compound. Be sure the R.T.V. flows around the insulation of the cable leads. Clean the insulation if necessary. The R.T.V. should extend at least 1/4" beyond the edges of the strain gage and terminal strip. Further waterproofing information is printed on the R.T.V. tube.

## SHOCK MEASUREMENTS

Shock measurements are usually made for one of two reasons; (1) to determine the amplitude and duration of shock pulses being administered to an object during drop-tests and similar aperiodic acceleration studies, or (2) to observe the mechanical response of an object when subjected to various conditions of shock.

Generally speaking, the lower-frequency response of a piezoelectric transducer system is limited by the input impedance of the amplifier, while the upper frequency limit is determined by the first mechanical resonance of the accelerometer. In shock studies, the low-frequency response becomes most important as the transient pulse increases in duration. Low-frequency response can be improved by increasing the RC time constant of the system. This can be accomplished by either increasing the capacitance of the transducer or the input impedance of the amplifier or both.



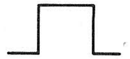
| PULSE SHAPE | $\frac{RC}{t}$ FOR 2% ACCURACY | $\frac{RC}{t}$ FOR 5% ACCURACY |
|---|---|---|
|  HALF SINE | 16 | 7 |
|  SAWTOOTH | 16 | 7 |
|  SQUARE | 50 | 20 |

Table 6-1. *RC* requirements for three common pulse shapes.

The RC requirements for three common pulse shapes are shown in Table 6-1. The square pulse represents the worst case for the system. Any system which will handle a square pulse of a given duration $t$ will handle any type of transient of the same duration. Since the accelerometer associated with the 3A10 system has a capacitance of 10,000 pF and the amplifier has a 10 MΩ input impedance, the RC time constant (ignoring cable capacity and the amplifier's input capacity) is 0.1 seconds. Thus, square pulses up to 2 milliseconds in duration can be measured with 2% accuracy and up to 5 milliseconds with 5% accuracy.

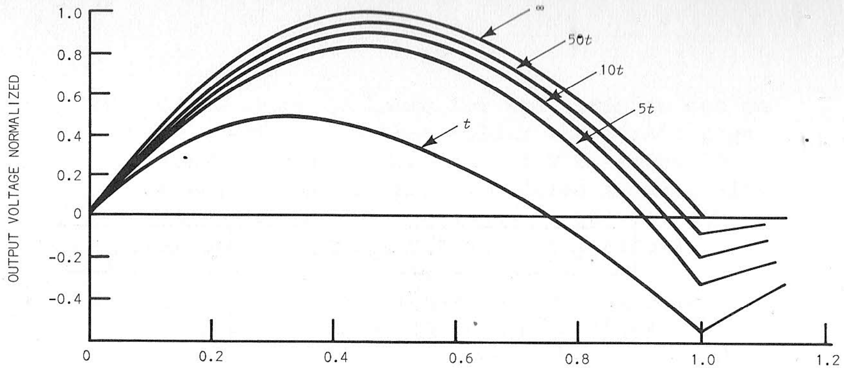



Fig. 6-12. Response of a piezoelectric accelerometer to a half-sine acceleration pulse.

| INDICATED UNDERSHOOT / INDICATED PEAK | ACTUAL PEAK / INDICATED PEAK | APPROX $RC/t$ |
|---|---|---|
| 5% | 1.04 | 9 |
| 10% | 1.06 | 6 |
| 15% | 1.08 | 4 |
| 20% | 1.11 | 3 |
| 25% | 1.15 | 2.1 |
| 30% | 1.19 | 1.7 |
| 35% | 1.21 | 1.5 |
| 40% | 1.25 | 1.3 |
| 45% | 1.28 | 1.2 |
| 50% | 1.32 | 1.0 |
| 100% | 1.90 | 0.4 |

Table 6-2. Undershoot or degree of error in driving a half-sine pulse through an $RC$ network.

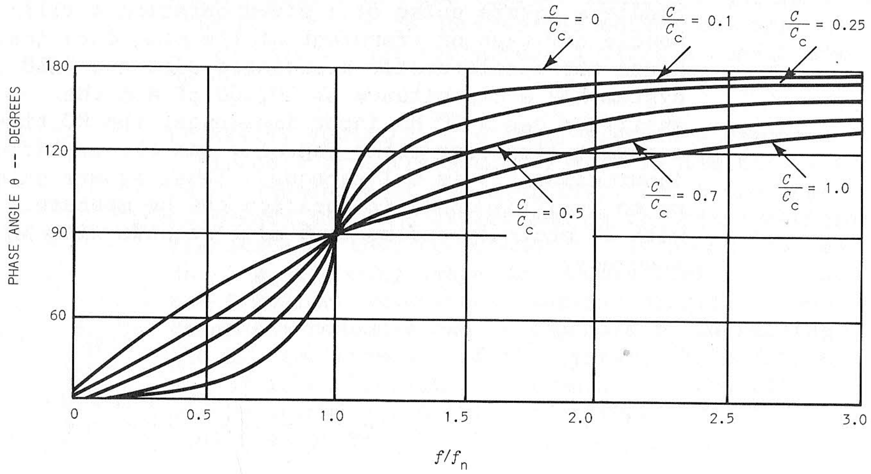



Fig. 6-13. Phase angles versus ratio of forcing to natural frequency.



Typical half-sine pulses react to inadequate $\frac{RC}{t}$ ratios by losing amplitude and exhibiting undershoot, as shown in Fig. 6-12. The five RC curves show that the accelerometer output decays with time and exhibits a negative overshoot before the pulse returns to zero. Table 6-2 lists the correction factors which should be applied when such a spurious undershoot is observed at the termination of the pulse. It should be noted that for small undershoots, the required correction for peak values is roughly one-half the undershoot.

The time-constant of the system may be increased by shunting the accelerometer with a capacitor. It should be noted, however, that the sensitivity of the transducer will be decreased by the same ratio as the capacitance is increased.

amplitude response

Due to the mechanical response characteristics of piezoelectric accelerometers, the amplitude and phase of the output varies with frequency. See Chapter 3, "Acceleration." Considering the transducer as a single-degree-of-freedom system without damping,

$$\frac{\text{actual peak}}{\text{indicated peak}} = \frac{1}{1 - (f/f_n)^2}$$

where $f$ = operating or forcing frequency and

$f_n$ = natural frequency

At the recommended $f/f_n$ ratio of 1/5, the sensitivity is 1.04 or about 4% high. This figure can be improved, however, with proper damping. The same is true of shifts in phase angle. Fig. 6-13 shows the effects of damping on phase angle of the output for various coefficients of critical damping.

It is customary for manufacturers to supply correction tables for sensitivity and phase angle with the transducer.

## APPLICATION: DIE-CASTING MACHINE

The purpose of this investigation was to monitor the operation of an aluminum die-casting machine to determine the nature and magnitude of various mechanical forces critical to its proper performance.

The die-casting machine (Fig. 6-14) is an apparatus which allows the casting of aluminum parts to precise dimensions, which cannot be achieved by older mold-casting methods. The die itself consists of two heavy blocks of special alloy steel, machined to form a mold for the molten aluminum. In operation, the two halves of the die are brought together under tremendous pressure to assure complete closure. Molten aluminum at about 1200°F is then injected into the die by a hydraulic ram, driving the molten metal into the small orfices and crevices in the die under very high pressure. Although the dies themselves are heated to about 500°F, the metal quickly solidifies. The casting or "biscuit" is then given a sharp "kick" to loosen it from the die. Then the halves of the die are separated and the casting is removed from the mold. After the die faces have been inspected and lubricated, the cycle is repeated. The entire cycle takes only a few seconds, so that one man can turn out large numbers of castings in a normal working day.

The force holding the dies in contact must be maintained at the proper level to assure absolute integrity of the mold. When this contact is not achieved, the molten aluminum may be ejected from the mold interface at very high velocities, sufficient to pit a concrete wall over 15 feet away. The operator is protected by a heavy sliding safety door. Closure of the door actuates a switch in the control circuit of the machine so that injection cannot be accomplished when the door is open.

Three measurements were made on this machine. To determine the closing force exerted on the dies, strain gages were mounted on one of the four 6" diameter tie bars as shown in Fig. 6-15. A heavy casting called the stationary platen carrying the die-closing mechanism is clamped to the tie bars. All the die-closing force is thus communicated to the tie bars by the platen, setting up tensional strains in the tie bars. By measuring these strains, the stress in the tie bars can be determined, and from these values the actual force applied to each shaft can be calculated.



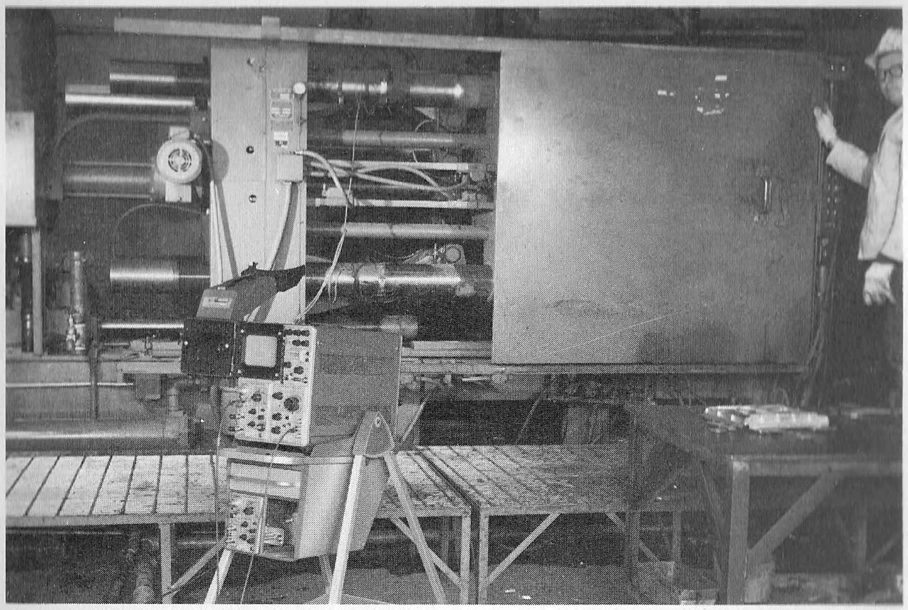


Fig. 6-14.

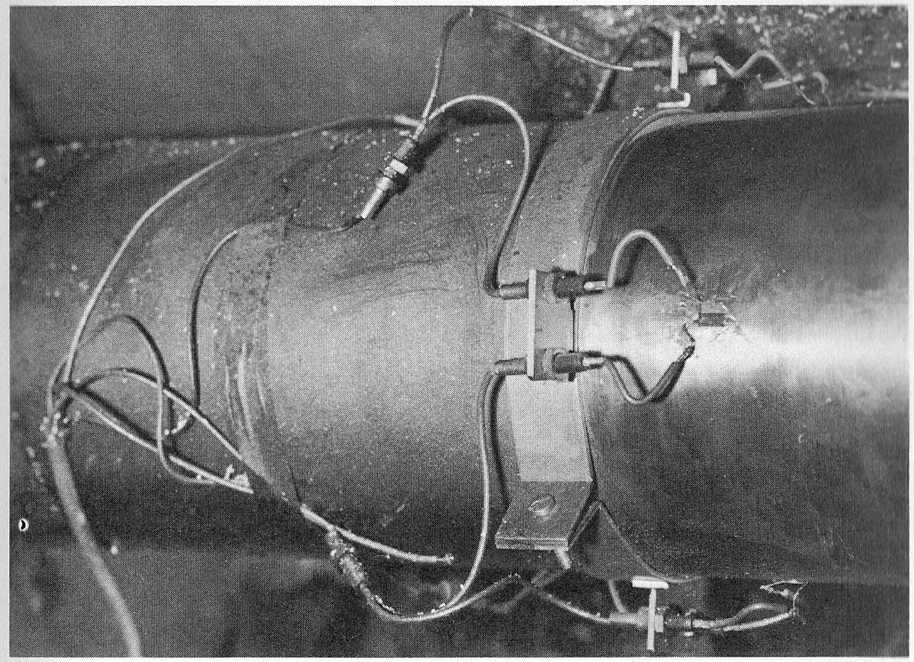


Fig. 6-15.

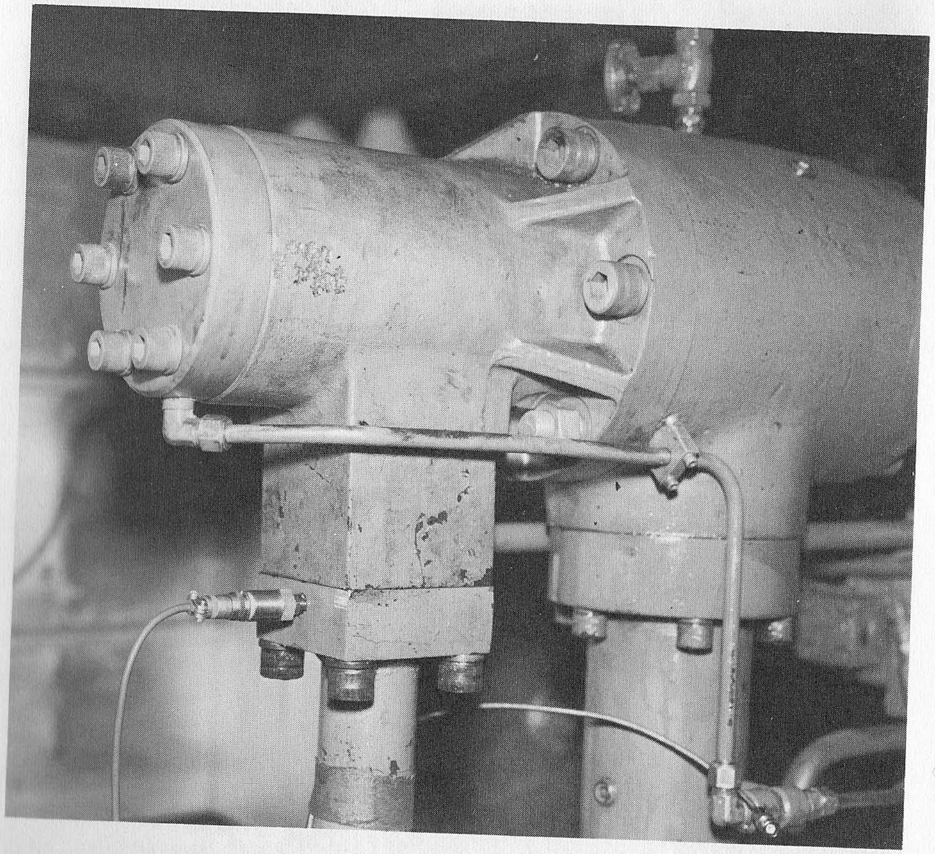


Fig. 6-16.



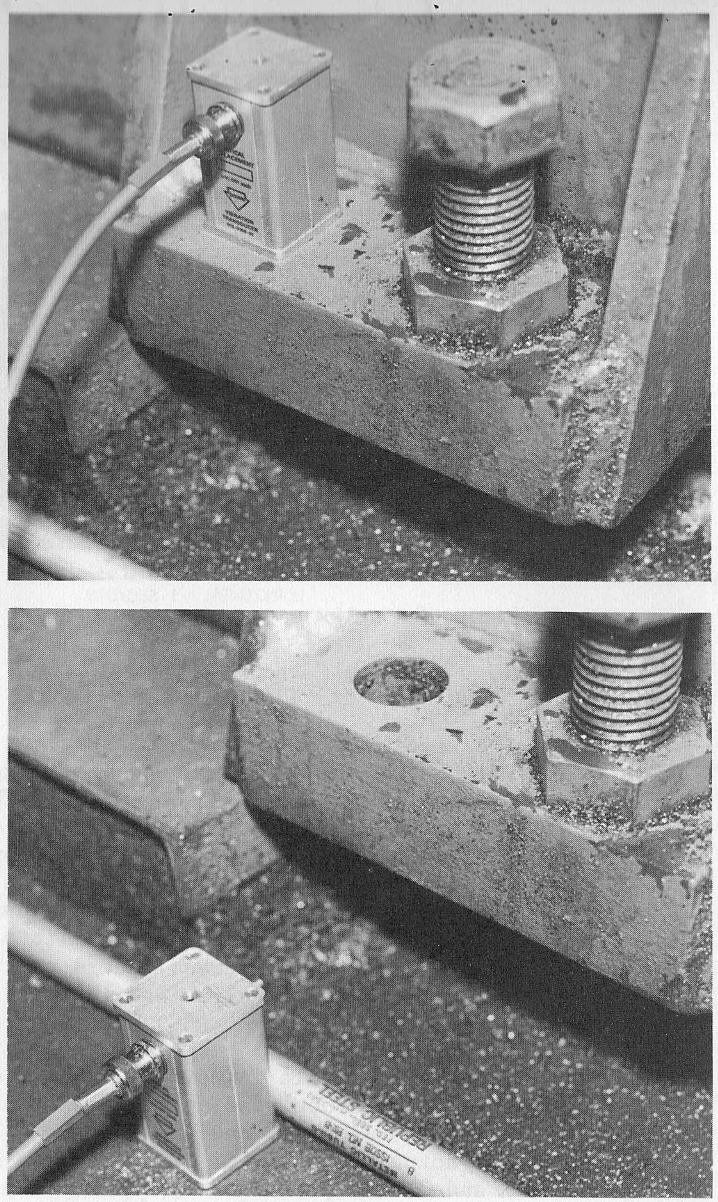


Fig. 6-17.

The hydraulic pressure exerted on the injection ram was measured by inserting a 3,000 pound pressure transducer in the hydraulic cylinder (Fig. 6-16). Vibration measurements were also taken at the base of the machine and from the floor closely adjacent, to determine the effectiveness of the shock mounting (Fig. 6-17).

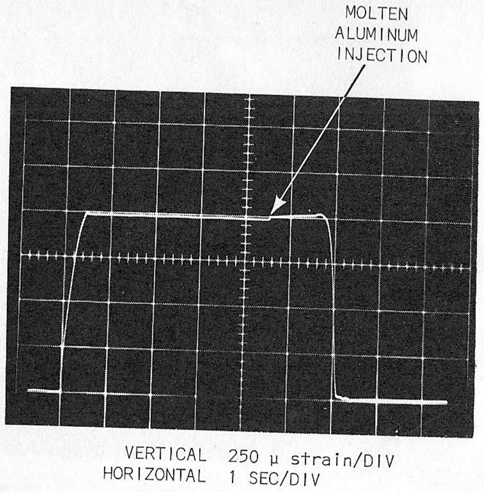



Fig. 6-18.

The results of the strain measurement are shown in Fig. 6-18. The oscilloscope was triggered by the closing of the safety door switch. The leading edge of the pulse shows the sharp rise in strain communicated to one of the tie bars by the closing of the die. The slight "bump" at the end of the upper portion of the waveform is caused by the injection of the molten aluminum into the die. The trailing edge, of course, occurs as the mechanism separates the die halves and returns to the retract position.

Since four strain gages were mounted on the tie bar, the oscilloscope reading must be modified to reflect the true value of tensional strain. Fig. 6-19 shows the actual arrangement of the strain gages. Gages 1 and 3 were placed on opposite sides of the bar in line with the longitudinal axis to measure tensional strain. Gages 2 and 4 were placed at right angles to the longitudinal axis to measure Poisson strain. This arrangement provided an increased output, cancellation of any bending strain, and also temperature compensation.



Since the Poisson ratio of steel is about 0.3, the Poisson strains have a magnitude only 0.3 times that of the tensional strains. Thus the bridge will provide an output only 2.6 times that of a single gage measuring tensional strain. Also, since the total die-closing force is distributed between the four tie bars, the equation for the total force applied to the dies is:

$$F_t = 4\pi r^2 \sigma$$

$$= 4\pi r^2 E\varepsilon \quad \text{(from Equation 3-1)}$$

where $\varepsilon$ = oscilloscope strain reading

$r$ = radius of one tie bar

Therefore, taking the highest strain amplitude of 1100 μstrains shown by the waveform,

$$F_t = 4 \times 3.14 \times 3^2 \times (30 \times 10^6) \times \frac{(1100 \times 10^{-6})}{2.6}$$

$$= 14{,}500 \text{ lbs.}$$

$$= 7.25 \text{ tons}$$

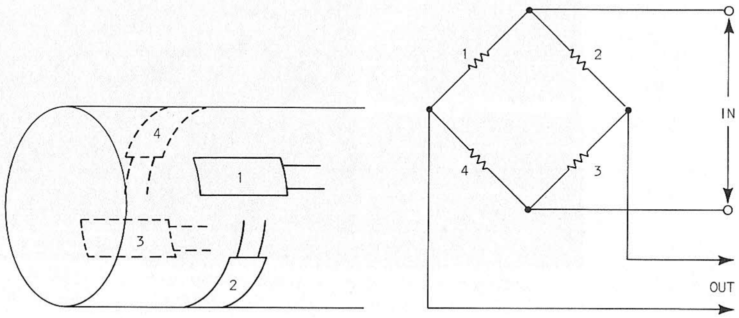



Fig. 6-19.

The pressure waveform (Fig. 6-20) is triggered by the switch which activates the injection ram. The hydraulic end of the ram has an area of 10 $in^2$, while the metal-injection end has an area of 2.5 $in^2$. Therefore, the metal-injection pressure exceeds the hydraulic pressure by a factor of 4. The waveform indicates that the hydraulic pressure initially peaked at 1380 $lbs/in^2$ and showed a steady-state pressure of about 840 $lbs/in^2$. Metal-injection pressure was therefore 5520 $lbs/in^2$ and 3360 $lbs/in^2$ respectively.

The vibration waveforms shown in Fig. 6-21 were also triggered by the injection initiation switch and cover a full cycle of machine operation. The peaks occur during the time of injection and later during the die closing operation. Since the displacement output of the vibration transducer was used, the peak vibration displacement at the machine base was about 0.0076". The floor vibration, however, peaked at a maximum of 0.00064", indicating that the shock mounting effectively damped out the machine vibration by a factor of about 10.

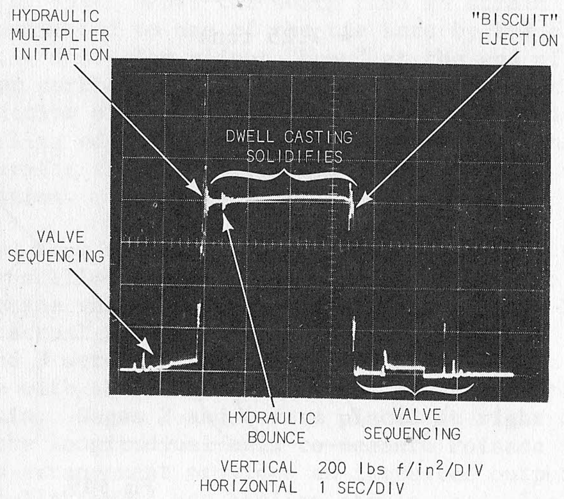



Fig. 6-20.



Waveforms such as those in Fig. 6-21 are highly useful in locating areas of malfunction when the die-casting machine fails to perform satisfactorily. In fact, in taking these photographs, the presence of air in the hydraulic system was immediately revealed when the "bump" on the strain waveform in Fig. 18 began to disappear. Normal operation was restored by bleeding off the trapped air.

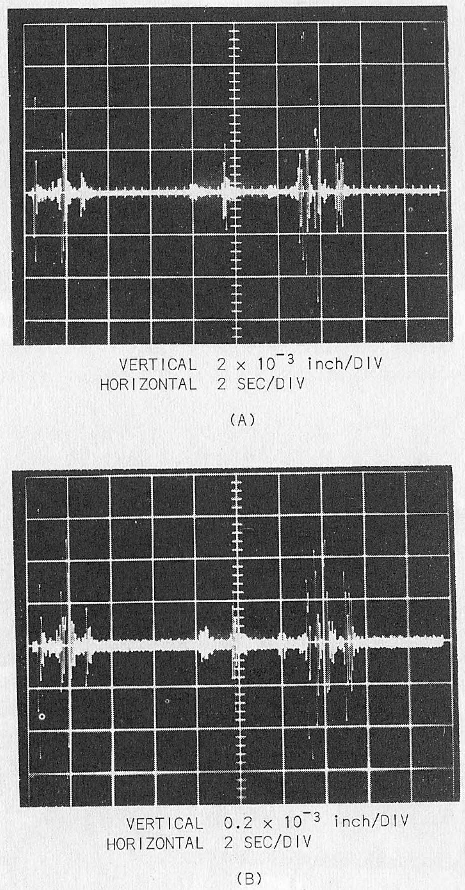



Fig. 6-21.

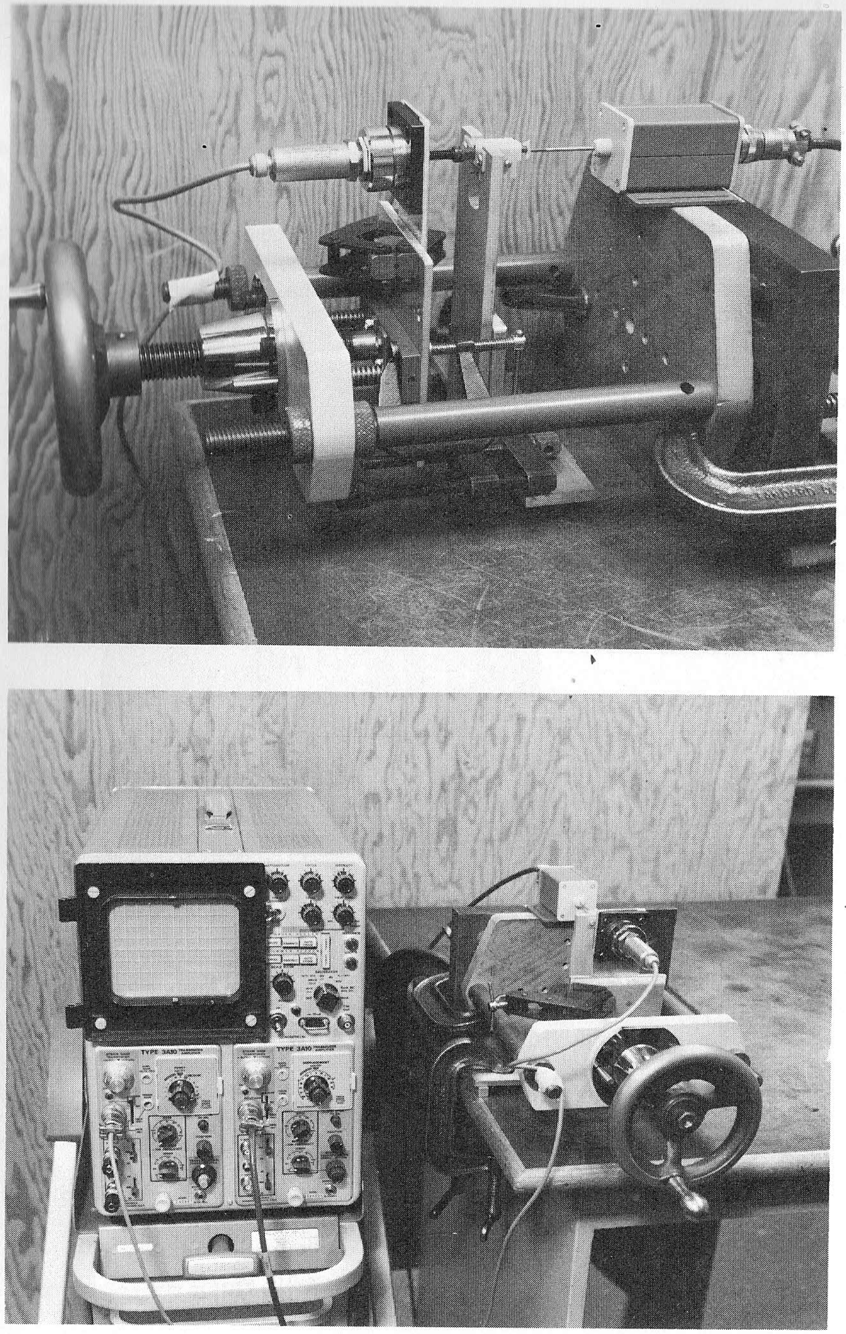


Fig. 6-22.



## APPLICATION: PUSHBUTTON SWITCH

It is highly important in designing an instrument to obtain a clear picture of the behavior of its mechanical components. In many cases it is not possible to rely on unaided sensory perceptions in obtaining this knowledge. Sensitive transducers can often give a clear picture of small events that would ordinarily go undetected. In this application the behaviour of a small plastic double-acting pushbutton switch was examined by making a plot of actuating force versus pushbutton displacement. A jig was improvised from a small press, using scraps of aluminum and several clamps (Fig. 6-22). The displacement transducer was bonded to the press frame with double adhesive tape. The 50 pound-force transducer was mounted in the same fashion on a metal strip clamped to the pressure plate. The switch itself was screwed to a third plate clamped to the bench. The press was also clamped to the bench. By turning the hand wheel of the press the force transducer was brought to bear on the switch-actuating pushbutton. Motion of the pushbutton was transmitted to the extension rod of the displacement transducer. Contact was maintained through another small piece of double adhesive tape.

Two 3A10 transducer amplifiers were used in a 564B oscilloscope, used in the storage mode. The displacement transducer output was applied to the right hand amplifier to provide horizontal displacement of the CRT electron beam. The force transducer was connected to the vertical amplifier.

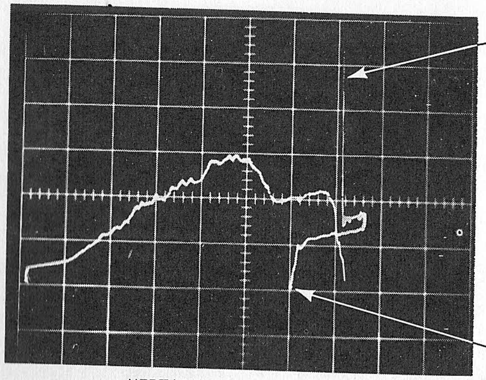



Fig. 6-23.

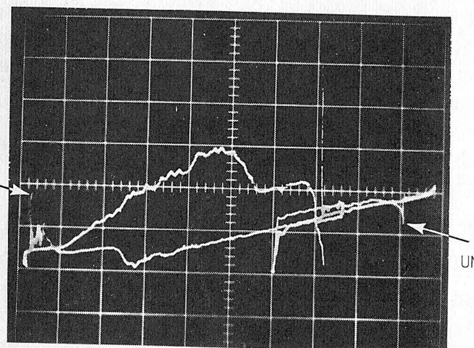



Fig. 6-24.



The recorded waveform reveals a number of interesting details of the switch's operation. In Fig. 6-23, as the hand wheel is rotated, the force applied to the switch rises abruptly until it overcomes the friction of the switch mechanism. Then for a period, the increase of force with displacement forms a fairly linear pattern, although small aberrations in the waveform indicate "stick-slip" operation. Where the force begins to drop off, the switch spring has reached the linear portion of the cam and is about ready to snap the contacts together. Just before the snap, force on the switch has dropped almost to zero. The actual contact closure administers a sharp impulse of force to the transducer and occurs so rapidly that only a faint trace appears on the CRT screen.

As the hand wheel is rotated in the opposite direction, the pushbutton retracts, eventually returning to its "cocked" or "on" position with the contacts closed. Fig. 6-24 shows the completed cycle waveform. To unlatch the switch, it is first pushed forward until the latching spring is forced off the cam. The small negative spike at the ninth horizontal division line reflects this event. The return to the "off" position of the switch is quite linear, falling almost to zero force until the opening action of the switch contact spring is initiated. Another sharp pulse near the origin of the waveform shows the actual opening of the contacts.

The switch used in this demonstration would be rejected due to the rough spring action noted above, probably caused by irregularities in the switch cam.

APPLICATION: DROP TEST

Drop tests are performed to administer shock pulses of known magnitude and duration to an object or instrument and usually are encountered as part of any comprehensive environmental testing program.

A typical drop test setup is shown in Fig. 6-25. An accelerometer is mounted on a drop table which supports the instrument under test. The drop table is raised by an electrically driven mechanism to the desired height, then allowed to drop in free fall. As it hits bottom, a shock pulse is applied to the test instrument. The pulse is communicated to the oscilloscope by the transducer. The amplitude, shape and duration of the pulse are controlled by varying the height of the drop and by using cushioning materials of various thicknesses and compositions to soften the table's fall. The instrument may be subjected to pulses of increasing amplitude or shorter duration, until something "gives," in order to establish the limits of abuse it will tolerate, or may be subjected to a specified program of shock events to prove its ability to tolerate rough handling. For example, the National Safe Transit Committee publishes a program designed to simulate actual truck shipment conditions over various trip mileages. Such tests are highly useful in designing adequate packaging and safe containers for fragile shipments.

In this application the drop table was raised to a height of 6 inches and its fall was cushioned by two layers of 3/4 inch rubber. A vertical vibration transducer was fixed to the floor to register the vibration induced by the action of the drop table.



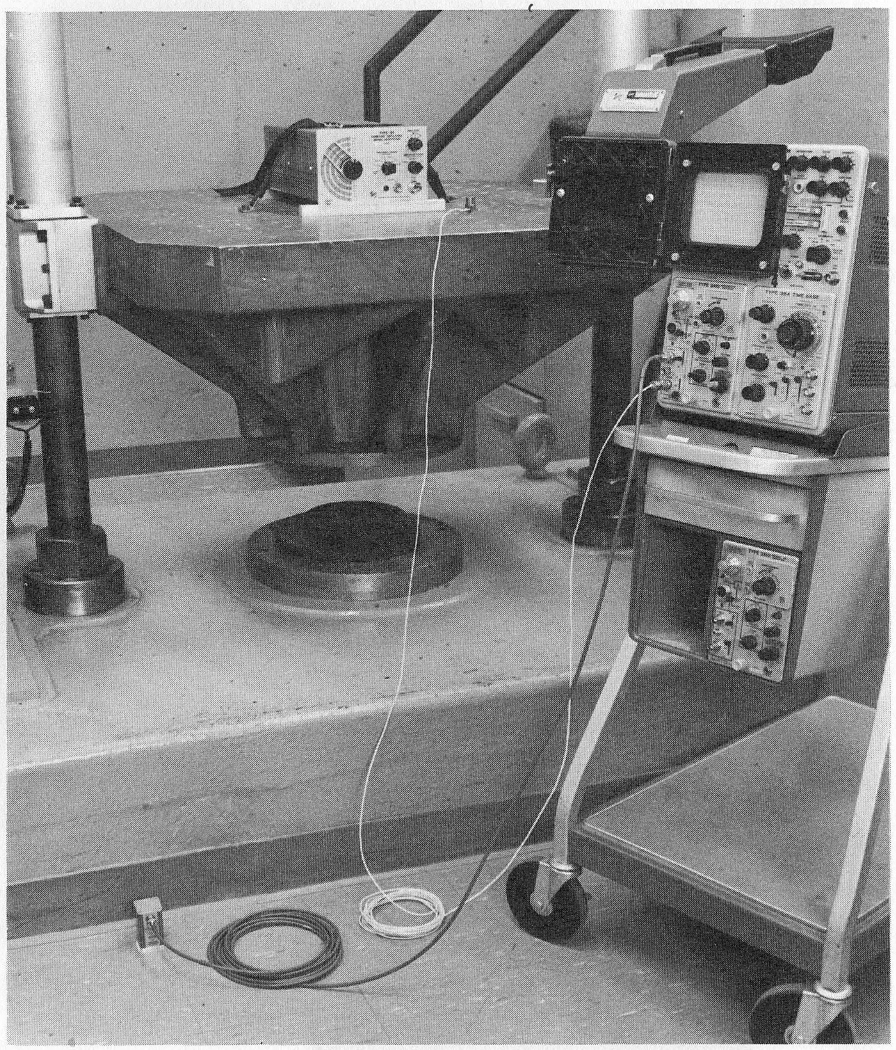


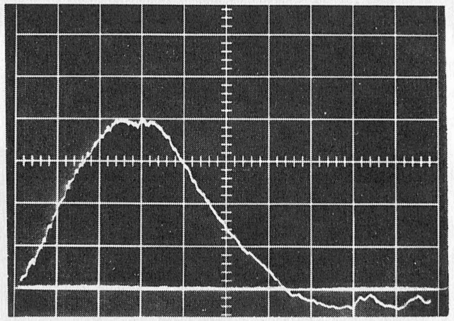
Fig. 6-25.

Fig. 6-26.



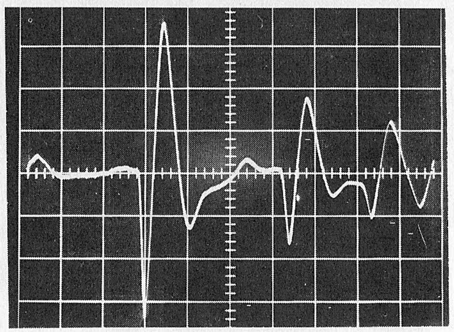
The instrument under test was mounted on metal bars (so that its rubber supporting feet could not cushion the administered shock) and strapped down firmly to the table. When the table was dropped (Fig. 6-26), the waveform shown in Fig. 6-27 was produced. After correcting the pulse amplitude by one-half the undershoot as explained earlier in this chapter, a peak acceleration of about 42.5 g's was attained by the 6 inch drop. Duration of the pulse, measured from origin to the first negative peak, was 16 milliseconds.

The vibration waveform (Fig. 6-28) was triggered by the unlatching mechanism of the drop table. It shows the vibration displacement caused by the first impact and two successive bounces of the table on the rubber cushioning. As shown by the low frequency (about 20 Hz) and extremely low amplitude (about 0.00035" max) of the vibration cycles, very little shock was communicated to the floor by the dropping of the table.



VERTICAL 10 g/DIV
HORIZONTAL 2 mSEC/DIV

Fig. 6-27.



VERTICAL $0.1 \times 10^{-3}$ inch/DIV
HORIZONTAL 50 mSEC/DIV

Fig. 6-28.

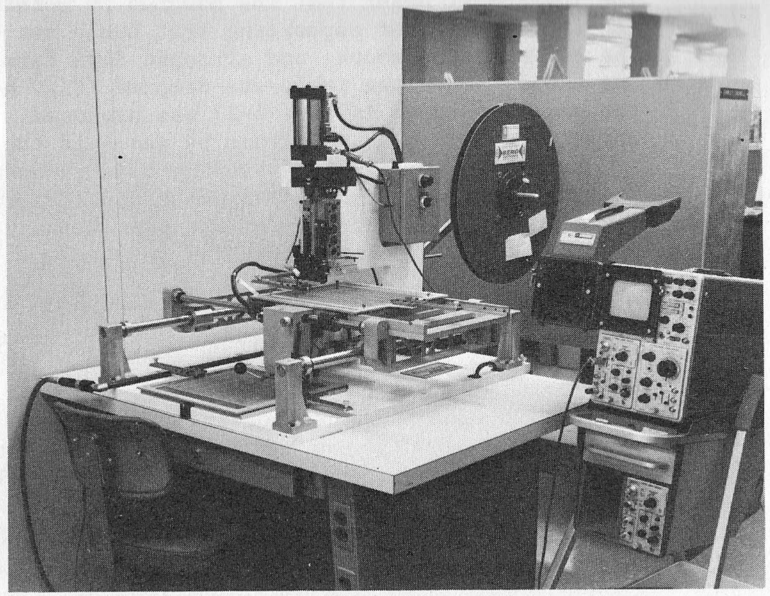


Fig. 6-29.

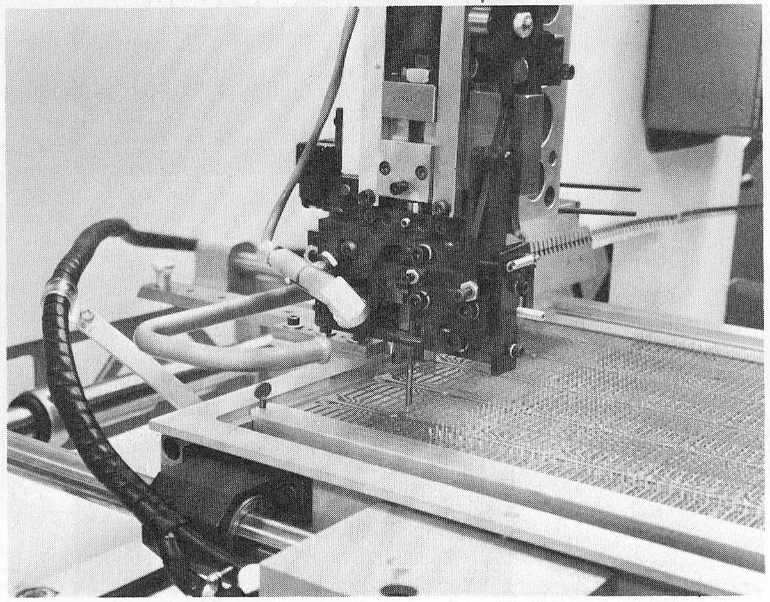


Fig. 6-30.



## APPLICATION: PNEUMATIC PRESSURE TEST

Many industrial processes are performed by machines which are both powered and controlled by pneumatic pressure. In this application the operation of a pneumatic pin-setting machine (Fig. 6-29), used to insert wiring-terminal pins in etched-circuit boards, was examined. The most convenient access point proved to be on the under side of the header piston. This piston drives the pin into the board when pressure is applied to the upper side of the piston and the lower side is vented to the atmosphere (Fig. 6-30). At the conclusion of its power stroke, the header is retracted by pressure applied to the under side of the piston and venting of the upper side.

The waveform shown in Fig. 6-31 reveals the sequence of events as the machine was put through one cycle of operation. When the control valve vents the lower side of the piston to the atmosphere(1), the pressure drops rapidly at first. Since the piston is being forced down by pressure on its upper half, however, the pressure in the lower half levels off at about 8 $lbs/in^2$(2) until the piston reaches the end of its stroke(3). Then the remaining pressure bleeds rapidly off until it is in equilibrium with the atmosphere(4). As the control valve reverses, pressure rises rapidly before the piston can move(5), then levels off(6) as the piston returns to its retracted position(7). Finally, the curve climbs slowly as cylinder and operating pressure come to equilibrium at about 76 $lbs/in^2$.

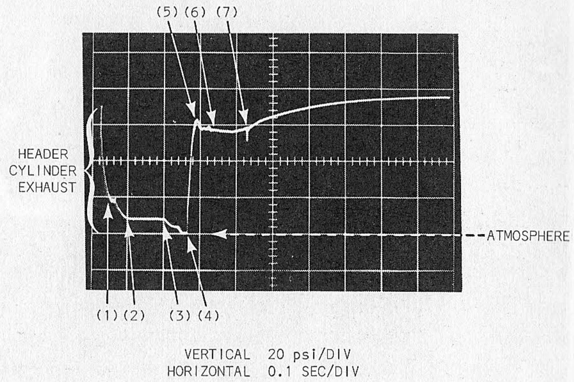



Fig. 6-31.

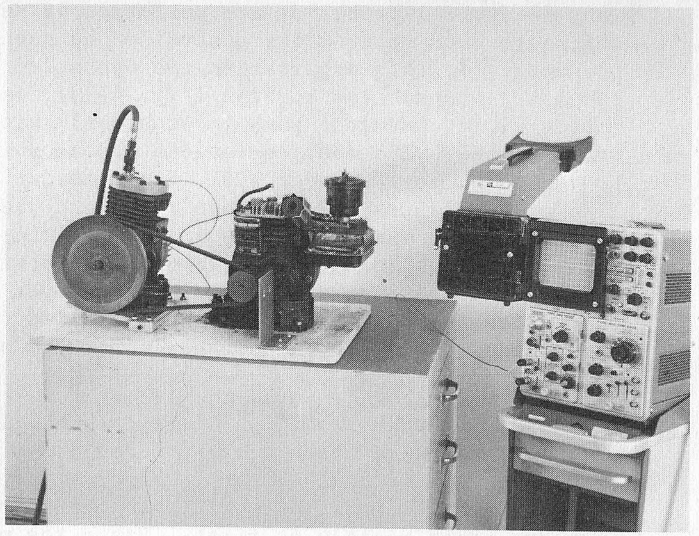


Fig. 6-32.

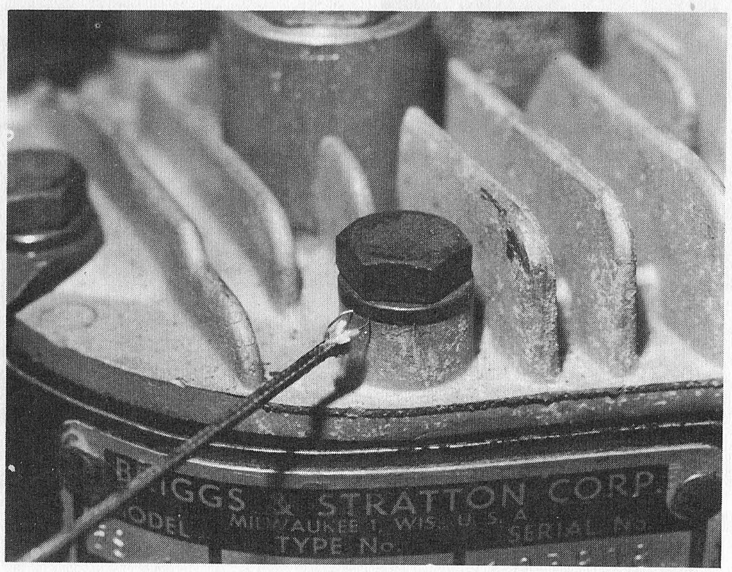



Fig. 6-33.



By comparing waveforms of this kind with the sequence of events normally performed in the operation of the machine, malfunctions may be quickly identified and located, with a consequent savings in time and labor.

APPLICATION: PRESSURE-TEMPERATURE VARIATIONS IN A COMPRESSOR

A small, home-assembled compressor, driven by a lawnmower-type gasoline engine (Fig. 6-32), provided some interesting data in this application. Interest was centered on temperature variations of the engine's cylinder head, as well as pressure and temperature variations in the compressor itself.

To measure cylinder-head temperature variations, the 20-foot glass-braid thermocouple was first inserted under one of the cylinder head bolts (Fig. 6-33). When the engine was started, the DC level of the resulting waveforms climbed rapidly, showing that the thermocouple was reacting properly to the changing temperature. However, at the 20-microvolt sensitivity setting necessary to show temperature variations of the cylinder head to the internal combustion, differences in the conductivity of the two thermocouple materials was sufficient to cause pickup of the ignition voltage even though the amplifier was used in the differential mode (see Fig. 6-34). Interpretation of the waveform as a temperature signal, therefore, could not be made.

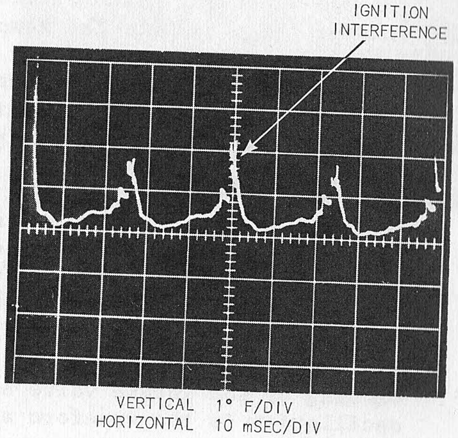



Fig. 6-34.

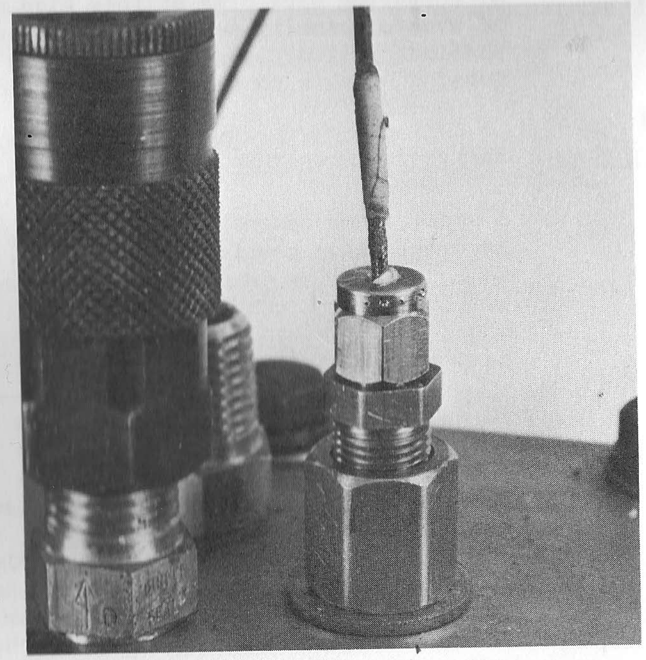
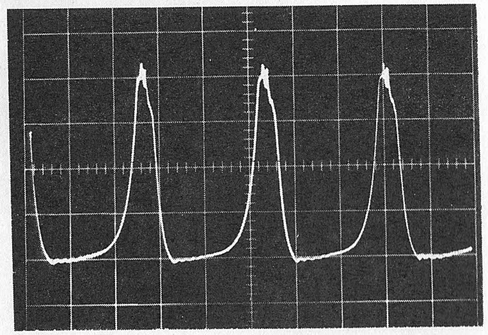


Fig. 6-35.

Much more satisfying results were obtained in measuring the temperature variations in the compressor. Here the thermocouple was inserted through a packing gland directly into the compression chamber (Fig. 6-35). The compressor was loaded by controlling the escape of air from the pressure outlet. Variations in air temperature within the compression chamber as cool air was drawn in then compressed by the compressor piston are clearly shown by the waveform in Fig. 6-36.

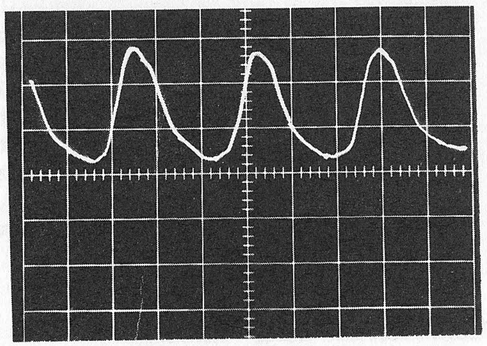
Pressure measurements were also made at the same location to show the relationship between the two quantities. Fig. 6-37 shows the waveform obtained. Note the slight aberrations at the waveform peaks, due to opening and closing of the pressure valve and subsequent opening of the intake check valve. Closing of the intake valve also produced a slight oscillation in the waveform at the beginning of the pressure stroke.





VERTICAL 20 psi/DIV
HORIZONTAL 10 mSEC/DIV

Fig. 6-36.



VERTICAL 2.5° F/DIV
HORIZONTAL 50 mSEC/DIV

Fig. 6-37.

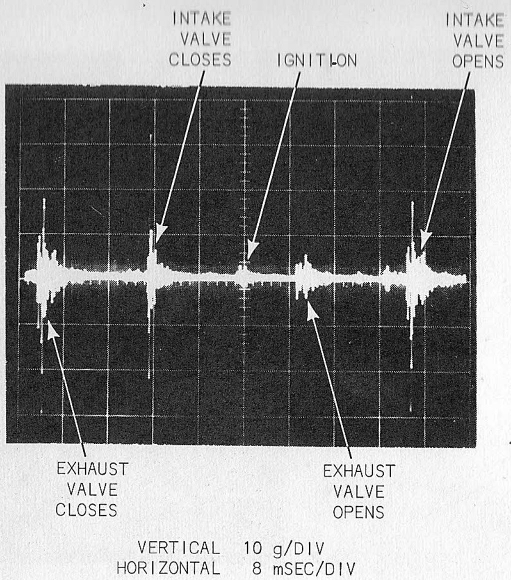



Fig. 6-38.

An accelerometer attached to the cylinder head of the 4-cycle engine provided the vibration waveform shown in Fig. 6-38. The lower bandwidth switch on the 3A10 was placed in the 10 kHz position to eliminate low-frequency vibrations. The high-frequency vibration remaining is due primarily to gas turbulence within the cylinder on intake and exhaust and valves hitting the seats. Note the relatively low amplitude of this vibration on the power stroke. This indicates that the valves and rings were in good condition, allowing very little leakage at the valve seats or "blow-by" (gas leakage past the piston rings during the power stroke).

APPLICATION: SHAKE-TABLE EXPERIMENT

This application demonstrates the versatility of a transducer system as a classroom training aid. The objective, in this instance, was to provide graphic evidence of the mathematical relationship between various dimensions of motion (see Chapter 3). The apparatus shown in Fig. 6-39 consists of a small shake table, upon which are mounted a vertical vibration transducer and an accelerometer. A 60-Hz squarewave voltage was applied to the shake table.



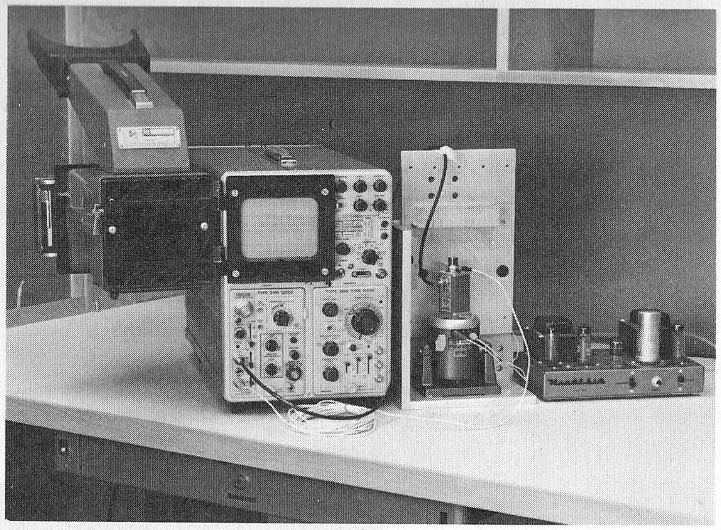


Fig. 6-39.

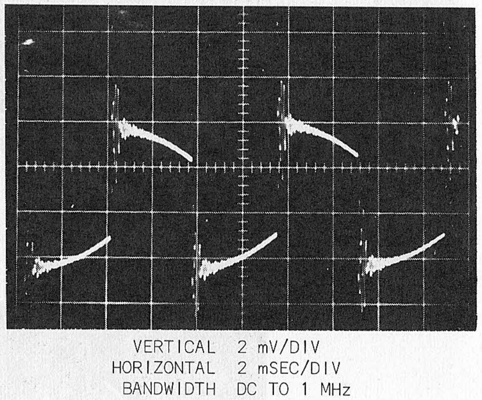
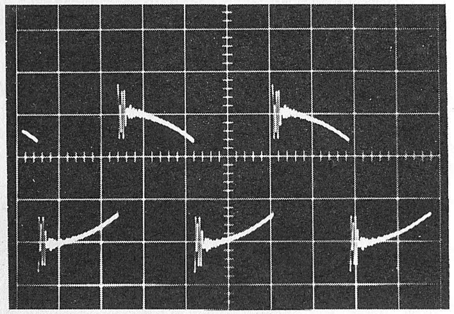



Fig. 6-40.

The first measurement taken was that of acceleration. The output of the accelerometer was applied to the 3A10 amplifier, adjusted for maximum bandwidth. The resulting waveform is shown in Fig. 6-40. This waveform should represent the first derivative of the vibration velocity, and the second derivative of the vibration displacement, both with respect to time.

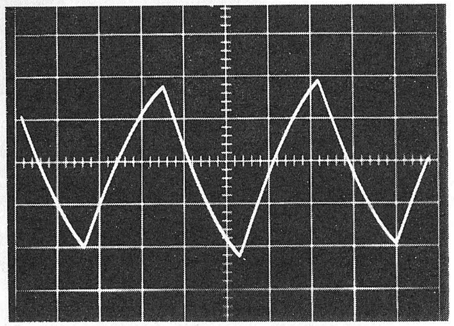
Fig. 6-41 shows the same waveform, but with the high-frequency components attenuated by reducing the upper bandwidth limit of the 3A10 to 3 kHz.

The next measurement taken was of vibration velocity (Fig. 6-42). For this measurement the bandwidth was again adjusted to maximum. It can be shown without much difficulty that the resulting waveform is a fairly accurate representation of the integration of the acceleration waveform in Fig. 6-41. To reinforce this contention, the velocity waveform was differentiated by raising the lower bandwidth limit to 10 kHz, yielding the curve shown in Fig. 6-43. Although considerable attenuation of the signal occurs in this procedure, the resemblance between Fig. 6-43 and Fig. 6-41 is unmistakable.



VERTICAL 2 mV/DIV
HORIZONTAL 2 mSEC/DIV
BANDWIDTH DC TO 3 kHz

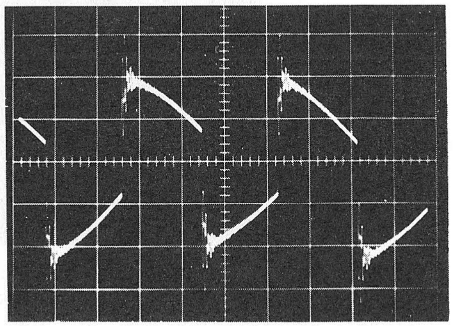
Fig. 6-41.



VERTICAL 0.1 mV/DIV
HORIZONTAL 2 mSEC/DIV
BANDWIDTH DC TO 1 MHz

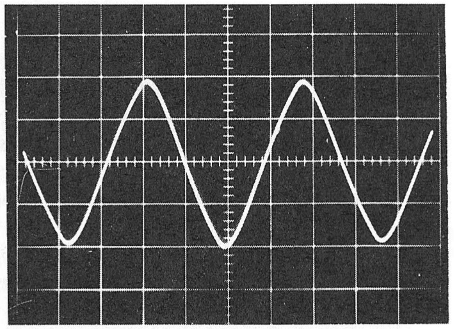
Fig. 6-42.





VERTICAL 0.5 mV/DIV
HORIZONTAL 2 mSEC/DIV
BANDWIDTH 10 kHz TO 1 MHz

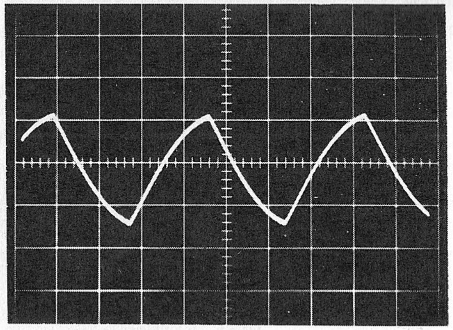
Fig. 6-43.



VERTICAL 50 mV/DIV
HORIZONTAL 2 mSEC/DIV
BANDWIDTH OPEN

Fig. 6-44.

The waveform in Fig. 6-44 shows the actual displacement of the shake table and its load being driven by the 60-Hz voltage squarewave. Being the integral of the velocity waveform of Fig. 6-42, it tends to be more sinusoidal because of the attenuation of higher frequency components.



VERTICAL 50 x $10^{-6}$ V/DIV
HORIZONTAL 2 mSEC/DIV
BANDWIDTH UPPER: 1 MHz
LOWER: 10 kHz

Fig. 6-45.

Differentiating the displacement waveform by raising the lower bandwidth limit to 10 kHz (Fig. 6-45) shows that although attenuated by the differentiation process, the waveform is a close replica of the velocity waveform shown in Fig. 6-42.

At the 60 Hz frequency used in this demonstration, integration cannot be performed with the bandwidth controls. At frequencies of 300 Hz and above, however, integration operations can be performed on waveforms in a manner similar to that described above to demonstrate important mathematical relationships between various quantities of motion.

Visual demonstration of fundamental physical laws and relationships has always been regarded as a basic educational tool. The 3A10 transducer measurement system should prove invaluable, therefore, in physical science departments of most modern educational institutions.



# APPENDIX A

## GLOSSARY OF TRANSDUCER TERMS

(The following is extracted from *Introduction to Transducers for Instrumentation*, by J. S. Hernandez; published by Statham Instruments, Inc., 2230 Statham Boulevard, Statham Industrial Park, Oxnard, California 93030. Used with permission.)

*absolute pressure* - A quantity of pressure which is referenced to a total vacuum.

*acceleration* - The time rate of change in velocity and/or direction.

*acceleration sensitivity* - The difference between the output at zero acceleration and the output measured at a given steady-state acceleration. In pressure transducers it is usually indicated as percentage of full-scale output per "g." May be expressed as output difference under acceleration at zero stimulus or at some other value of the stimulus. In accelerometers it is ordinarily shown in terms of millivolts per "g."

*accelerometer* - A transducer which measures acceleration and/or gravitational forces capable of imparting acceleration.

*accuracy* - See *inaccuracy*.

*ambient temperature* - The prevailing temperature in a given environment. Also temperature at which a transducer may be stored or transported but at which temperature the transducer performance is not necessarily expected to remain within its specified limits of error if said temperature falls outside the operating temperature range of the instrument.

*amplitude* - A measure of the departure of a phenomenon from its average or mean position. Applied to vibratory conditions it pertains generally to the peak magnitude of the acceleration or displacement applied.

*analog output* - Output in which the amplitude is continuously proportional to the stimulus or measurand, the proportionality being limited by the resolution of the device. Distinguished from *digital output*.

*angular acceleration* - The time rate of change in angular velocity.

*angular accelerometer* - A device capable of measuring the magnitude of, and/or variations in, angular acceleration.

*angular velocity* - The time rate of change of angular displacement.

*active leg* - An electrical element within a transducer which changes its electrical characteristics as a function of the applied stimulus.

*armature* - The member, in certain transducers, which is displaced by the collected forces in the force-summing element and which in turn changes the characteristics of the electrical elements as a function of the applied stimulus. Also the component which completes the magnetic path in "E" core inductive coils.

*attenuation* - The reduction in amplitude of a given stimulus or signal.

*balance* - A condition of symmetry in an electrical circuit, such as a Wheatstone bridge. Or the condition of zero output from a device when properly energized. Depending on the nature of the excitation, two general categories of balance (in the latter sense) may be encountered:
For DC excitation: resistive balance
For AC excitation: resistive and/or reactive balance.
Also see *unbalance*.



*bellows* - A force-summing member used in certain pressure transducers. It consists of a tube that alternates between two diameters and is terminated and sealed at one end.

*best fit straight line* - A line chosen to represent the sensitivity of a transducer and from which nonlinearity errors may be calculated. The line is chosen such that the response curve contains a minimum of three points of equal and maximum deviation from the line. The phrase "best fit straight line" is often used to mean nonlinearity error calculated from such a line. See *independent linearity*.

*best fit straight line with forced zero* - The line from which zero-based linearity is calculated.

*best fit straight line with "y" intercept* - A best fit straight line the position of which is fixed by a given output of the transducer at zero measurand. Nonlinearity errors may be expressed as deviation from such a line. The phrase "best fit straight line with 'Y' intercept" is often used to indicate nonlinearity error calculated from such a line. See *index-point linearity*.

*bidirectional transducer* - A device capable of measuring stimuli in both a positive and a negative direction from a reference zero or rest position.

*bonded pickup* - Same as *bonded transducer*.

*bonded strain gage* - Strain-sensitive elements arranged to facilitate bonding to a surface in order to measure applied stresses. Other forms of stimuli may also be measured with bonded strain gages by collecting the applied force in a column or other suitable force-summing member and measuring the resultant stresses.

*bonded transducer* - A transducer which employs the bonded strain gage principle of transduction.

*Bourdon tube* - A tubular configuration, which may be twisted, circular, helical, or spiral, employed in certain transducers as the force-summing member. The tube is sealed at one end. A pressure differential between the inside and outside tends to straighten the tube, thus producing a displacement for transduction.

*bridge* - Used to signify the general electrical configuration of certain transduction elements. The term is an abbreviation of "Wheatstone bridge."

*bridge resistance* - The resistance of each element of a transducer whose configuration is that of a Wheatstone bridge. Also the output resistance of such a device.

*burst pressure* - The pressure at which the housing or force-summing member of a pressure transducer fails to support the associated stresses, so that a rupture or leak results.

*calibration* - Known values of the measurand are applied while the transducer output is observed or recorded. The calibration data provides information pertaining to the nonlinearity, combined nonlinearity and hysteresis, and/or hysteresis characteristics of the transducer. See *primary and secondary calibrations.*

*calibration curve* - The plot of the data obtained during calibration.

*case pressure* - The total differential pressure between the pressure in the internal cavity of a transducer and the ambient pressure. The term is commonly used to summarize the limiting combined differential and/or line pressure capabilities of differential transducers.

*center of seismic mass* - The point in the seismic mass where acceleration and/or gravitational forces are summed. The center of seismic mass provides the reference from which the radius is determined when calculating, or applying, linear acceleration levels generated by a centrifuge. The center of seismic mass is often determined empirically by spinning the accelerometer in the center of a centrifuge and observing the position of the instrument when its output is equivalent to zero acceleration.

*centrifuge* - A rotating circular table in which steady states of acceleration are easily developed and controlled. This device has gained universal acceptance for the purpose of primary calibration of linear accelerometers.



*chord sensitivity* - The slope of a chord from a reference point to the point measured. See *end point sensitivity.*

*combined error* - A term used to specify the largest possible error of an instrument in the presence of adding or interacting parameters. Generally applied to the largest error due to the combined effect of nonlinearity and hysteresis.

*compensation* - A method employed to reduce or eliminate the thermal effects on one or more of the performance parameters of a transducer. See *span compensation* and *zero compensation.*

*conformity* - The measure of deviation between the indicated and the real value of the stimulus in nonlinear devices. The term *nonlinear linearity* is often used as equivalent to *conformity.*

*continuous calibration* - A calibration in which the stimulus is continuously varied over the entire range while the output is observed or recorded. Usually the output is continuously referenced to the output of a standard device the error of which is accurately known.

*creep* - A slow, continuous and unidirectional translation of a transducer parameter which is attributable to any cause.

*critical damping* - The value of damping which provides the most rapid transient response *without overshoot.*

*cross-acceleration* - Same as *transverse acceleration.*

*cross-sensitivity* - The ratio of change in output to an incremental change in a given stimulus along any axis perpendicular to the sensitive axis. In accelerometers it refers to the change in the transducer output at zero acceleration and at some other acceleration value applied along a plane perpendicular to the sensitive axis.

*crosstalk* - Interference in a given transmitting or recording channel which has its origin in another channel. Often used as equivalent to *transverse sensitivity.*

*crystal transducer* - A transducer in which the transduction is accomplished by means of the piezoelectric properties of certain crystals or salts. Often abbreviated to "crystal."

*DC transducer* - A transducer which is capable of proper operation when excited with direct current, and the output of which is also given in terms of direct current unless otherwise modified by the function of the stimulus.

*damped natural frequency* - The frequency at which a system with a single degree of freedom will oscillate, *in the presence of damping*, upon momentary displacement from the rest position by a transient force. In accelerometers the damped natural frequency is generally determined by means of the 90° phase shift method. That is, by vibrating the instrument at a constant amplitude and observing the lowest frequency where there is a 90° phase shift between the accelerometer output and the applied vibration monitored with a velocity coil or some other suitable reference signal.

*damping* - The resistance, friction or other cause that diminishes the amplitude of an oscillation with each successive cycle.

*damping factor* - The ratio of any one amplitude and the next succeeding it in the same sense or direction, when energy is not supplied on each cycle. In second-order systems with single degree of freedom the decrement is constant. The amplitude decays as $e^{-at}$
where:
$t$ = time
$a$ = logarithmic decrement
$e$ = base of natural logarithms

*damping ratio* - The ratio of actual damping to critical damping. May be expressed as the ratio of output under static conditions to twice the output at the lowest frequency where a 90° phase shift is observed.

*data* - Any record or display of information about physical phenomena. In the field of instrumentation the word *data* is generally used to signify quantitative information, ultimately intelligible to humans.



*dead volume* - The total volume of the pressure port cavity of a pressure transducer at the rest position, i.e., with no stimulus applied.

*dependent linearity* - Nonlinearity errors expressed as deviation from a desired straight line of fixed slope and/or position.

*diaphragm* - A dividing membrane. Widely used as the force-summing member in pressure transducers.

*differential pressure transducer* - A transducer which is designed to accept simultaneously two independent pressure sources and the output of which is proportional to the pressure difference between the sources.

*differential transducer* - A device which is capable of measuring simultaneously two separate stimulus sources and which provides an output proportional to the difference between the stimuli.

*digital output* - Transducer output that represents the magnitude of the stimulus in the form of a series of discrete quantities coded to represent digits in a system of notation. Distinguished from *analog output*.

*digitizer* - A device which converts analog data into numbers expressed in digits in a system of notation.

*double amplitude* - In the field of vibratory acceleration the term *double amplitude* is employed to indicate the total, or peak-to-peak, dimensional displacement of a vibrating structure.

*drift* - A slow and continuous change of a given parameter, attributable to any internal cause.

*dynamic response* - Same as *frequency response*.

*dynamic run* - A test performed on accelerometers by means of which information is gathered pertaining to the over-all behavior, frequency response, and/or damping and natural frequency of the device.

*dynamic test* - Same as *dynamic run*.

*"E" core* - The configuration of laminations used in certain inductive transducers which resembles the form of the capital Roman letter "E."

*effective area* - In a pressure transducer force summing member, the fraction of the total area which may be used for the calculation of transmitted force.

*electrical calibration* - Same as *secondary calibration.*

*electromagnetic damping* - Same as *magnetic damping.*

*end points* - The output values, in a calibration curve, at the points where the magnitudes of the stimulus equal the limits of the rated range of the instrument. Also the output at the limits of values of the measurand applied during a given calibration. In nonbiased unidirectional devices the points are given by the output at zero and at maximum applied stimulus. In bidirectional instruments the points are fixed by the output measured at maximum minus and maximum plus applied measurand.

*end-point linearity* - Nonlinearity errors expressed as deviations from a straight line drawn between the end points.

*end-point sensitivity* - The algebraic difference in electrical output between the maximum and minimum value of the measurand over which the instrument is calibrated.

*error* - The difference between the indicated value and the true value of the measurand.

*error band* - An error value, usually expressed in percentage of full scale, which defines the maximum allowable error permitted for a specified combination of parameters.

*error curve* - A plot of the difference between the indicated and true values of the measurand versus the true value of the measurand for a particular calibration.

*excitation* - The external electrical energy required for the proper operation of a transducer.



*excursion* - The application of measurand in a controlled manner in one direction only, whether it be increasing or decreasing. Ordinarily the term implies application of stimulus over the entire range of the transducer, although in bidirectional devices it is often used to indicate positive or negative excursion, in one direction only, away from zero (or rest position).

*"f" factor* - The slope of the straight line from which nonlinearity is calculated. Given as microvolts output per volt excitation per unit stimulus.

*flat frequency response* - See *frequency response.*

*fluid damping* - Damping obtained through the displacement of a viscous fluid and the accompanying dissipation of heat.

*force balance transducer* - A transducer in which the output from the sensing member is amplified and fed back to an element which causes the force-summing member to return to its rest position. The magnitude of the signal fed back determines the output of the device.

*force-summing device* - The element in a transducer which is directly displaced by the applied stimulus.

*frequency-modulated output* - A transducer output which is obtained in the form of a deviation from a center frequency, where the deviation is proportional to the applied stimulus.

*frequency response* - The portion of the frequency spectrum which can be sensed by a device within specified limits of amplitude error.

*friction effects* - The difference in resistance or output between readings obtained prior to and immediately after tapping an instrument while applying a constant stimulus. Particularly applicable to potentiometric transducers.

*full excursion* - The application of measurand, in a controlled manner, over the entire range of a transducer.

*full range* - See *full scale.*

*full scale* - The total stimulus interval over which the instrument is intended to operate. Also, the output of the device over said interval.

*full-scale output* - The algebraic difference in electrical output between the maximum and minimum values of measurand over which the instrument is calibrated. When the sensitivity slope is given by any other line than the end-point sensitivity, the term *full-scale output* expresses the algebraic difference, for the span of the instrument, which is calculated from the slope of the straight line from which nonlinearity is determined. (Note that in this case full-scale output is calculated rather than real.)

*full-scale sensitivity* - Same as *full-scale output.*

*gage* - Literally, an instrument or means for measuring or testing. By extension the term is often used as synonymous with *transducer.* Also a pressure transducer in which the output represents the value of the applied stimulus with reference to the ambient pressure.

*gage factor* - A measure of the transfer function of strain-sensitive resistive materials. Numerically expressed as:

$$GF = \frac{\Delta R/R}{\Delta l/l}$$

Where
$\Delta R/R$ = unit change in resistance
$\Delta l/l$ = unit change in length
The term is often used as synonymous with *gage sensitivity.*

*gage pressure* - A differential pressure measurement in which the ambient pressure provides the reference. Also a pressure in excess of a standard atmosphere at sea level, i.e., 14.7 PSIa.

*generated noise* - The noise in potentiometric transducers which is attributable to causes such as the generation of EMF when dissimilar metals are rubbed against each other, or the EMF resulting from the thermocouple effects at points where dissimilar metals are joined.



*high-velocity noise* - The noise in wire-wound potentiometric transducers which appears as a series of momentary open circuits when the slider bounces along the coil when moved too quickly.

*hysteresis* - The summation of all effects, under constant and static environmental conditions, which cause the output of a transducer to assume different values at a given stimulus point when the point is approached first with increasing stimulus and then with decreasing stimulus. It is customary to express the maximum hysteresis value in per cent of full scale output. Generally the hysteresis is taken over a total increasing and decreasing excursion for the entire range of the instrument. Special cases of hysteresis may be encountered in which a given starting point, other than rest position, is specified. The extent of the excursion may also be specifically limited to a value which is less than the entire range of the device.

*inaccuracy* - A term sometimes used to indicate deviations from a specific reference in which "all causes" of error attributable to the instrument are lumped. It is too broad a concept to be applied properly, due to the multitude of parameters that must be specified as inclusions or exceptions. Furthermore, corresponding magnitude for each environmental condition would also be required.

*inactive leg* - An electrical element within a transducer which *does not* change its electrical characteristics as a function of the applied stimulus. Specifically applied to elements which are employed to complete a Wheatstone bridge in certain transducers.

*independent linearity* - A manner of expressing nonlinearity errors as deviations from the *best fit straight line.*

*index-point linearity* - A manner of expressing nonlinearity errors as deviations from the *best fit straight line with "Y" intercept.* A special case of *point-based linearity.*

*inductive transducer* - A transducer in which the stimulus information is conveyed by means of changes in inductance.

*infinite resolution* - The capability of providing a stepless, continuous output over the entire range of a device.

*input* - Same as *excitation*. Sometimes employed to indicate the applied stimulus.

*instability* - The measure of the fluctuations or irregularities in the performance of a device, system or parameter which are induced by any cause. *Instability* implies the variations of a transducer parameter, or set of parameters, in reference to time.

*insulation resistance* - An electrical measure of the insulation, at a specified voltage, between given components. Usually expressed in megohms.

*integrating accelerometer* - A transducer designed to measure and capable of measuring, velocity by means of a time integration of acceleration.

*internal pressure* - Same as *case pressure*.

*interval calibration* - A calibration in which the stimulus is applied in discrete increments and/or decrements. The number of calibration points may vary depending on the nature and quality of the device being calibrated. Same as *step calibration*.

*ionization transducer* - A transducer in which the displacement of the force-summing member is sensed by means of induced changes in differential ion conductivity.

*least average deviation* - A method of calculating the best fit straight line for which the average residuals are minimized.

*least maximum deviation* - A manner of expressing nonlinearity as deviation from a straight line for which the deviations for proportional or normal linearity are minimized.

*least-squares deviation* - A manner of expressing nonlinearity as deviation from a straight line for which the sum of the squares of the residuals is minimized.



*life* - The expected number of full excursions over which a transducer would operate within the limits of the applicable specifications.

*linear acceleration* - The time rate of change in linear velocity.

*linear accelerometer* - A transducer designed to measure, and capable of measuring, linear accelerations.

*linearity* - Uniformity in ratio of stimulus increment to output change; that is, a condition where equal increments in the measurand result in equal changes in the output. Ordinarily, the term *linearity* is used to refer to the nonlinearity error.

*line pressure* - The reference pressure from which differential measurements are taken. Often used to specify the smaller of two pressures, absolute or gage, from which a differential measurement is derived.

*loading error* - The error introduced when more than negligible current is drawn from the output of a device. In potentiometric transducers the loading error varies with the position of the slider and the current drawn.

*loading noise* - A noise which occurs in potentiometric transducers when current is drawn from the instrument. It is caused by fluctuating contact resistance between the slider and the wire or film and by the surface of contact between the slip ring and the slip ring contact.

*magnetic damping* - Damping accomplished through the generation and dissipation of electromagnetic energy.

*mass* - Mass is that which has inertia. When applied to accelerometers the term *mass* is frequently used as an abbreviation of *seismic mass*.

*measurand* - A physical quantity, force, property or condition which the instrument is intended to measure. Same as *stimulus*.

*most favorable straight line* - A line from which nonlinearity deviations are minimized for the largest number of points. Often used as synonymous with *best fit straight line*.

*multiplexing* - The simultaneous transmission of two or more signals within a single channel. The three basic methods of multiplexing involve the separation of signals by time division, frequency division and phase division.

*natural frequency* - The frequency at which a system with a single degree of freedom will oscillate upon momentary displacement from the rest position by a transient force. Often used as synonymous with *damped natural frequency*.

*negative acceleration* - A relative term often used to indicate that, referenced to zero acceleration, a negative electrical output will be obtained from a linear accelerometer when its sensitive axis is oriented normal to the surface of the earth, and a given minus reference point, along the sensitive axis, is located upwards from the center of seismic mass.

*noise* - Any unwanted electrical disturbance or spurious signal which modifies the transmission, indicating or recording of desired data.

*nominal range* - Same as *rated range*.

*nonlinearity* - The difference between the actual instrument output and the expected output as defined by a reference straight line. It may be calculated as deviation from the straight line of the ascending cycle of calibration or on both the ascending and descending applications of stimulus. There are many interpretations of nonlinearity. For specific definitions see:

1. *best fit straight line*
2. *best fit straight line with forced zero*
3. *best fit straight line with "Y" intercept*
4. *conformity*
5. *dependent linearity*
6. *end-point linearity*
7. *independent linearity*
8. *index-point linearity*
9. *least average deviation*
10. *least maximum deviation*
11. *least-squares deviation*
12. *linearity*
13. *most favorable straight line*
14. *normal linearity*
15. *point-based linearity*
16. *proportional linearity*
17. *slope-based linearity*
18. *terminal-based linearity*
19. *weighted error distribution*
20. *zero-based linearity*



*normal linearity* - A manner of expressing linearity as deviation from a straight line in terms of a given percentage of the output at a certain stimulus value, usually the full-scale value.

*null* - (Adjective) Pertaining to a condition of balance in a device or system which results in zero output.
(Verb) To oppose an output which differs from zero by a counteraction which returns the output to zero.

*null detector* - An apparatus employed to sense the complete balance, or zero output condition, of a system or device.

*operating temperature* - The temperature, or range of temperatures, over which a transducer is expected to operate within specified limits of error.

*optimal damping* - Damping ratio slightly less than unity in which the overshoot is less than the specified uncertainty of the instrument.

*oscillating transducer* - A transducer in which information pertaining to the stimulus is provided in the form of deviation from the center frequency of an oscillator.

*output* - The electrical signal which emanates from the transducer and which is a function of the applied stimulus. The quantity represented by the signal may be given in terms of electrical units, frequency or time.

*overload* - A stimulus applied in excess of the rated range of a transducer.

*overpressure* - Pressure applied in excess of the rated range of a pressure transducer.

*peak amplitude* - The maximum deviation of a phenomenon from its average or mean position. When applied to vibration, same as single amplitude.

*peak-to-peak* - The algebraic difference between maximum relative plus and maximum relative minus of a varying stimulus, signal, or condition.

*pickup* - Same as *transducer*.

*point-based linearity* - Nonlinearity expressed as deviation from a straight line which passes through a given point or points.

*positive acceleration* - A relative term often used to indicate that, referenced to zero acceleration, positive electrical output will be obtained from a linear accelerometer when its sensitive axis is oriented normal to the surface of the earth and a given plus reference point, along the sensitive axis, is located upwards from the center of seismic mass.

*pot* - In general usage, a contraction of *potentiometer*. When applied to instrumentation, often a contraction of *potentiometric transducer*.

*potentiometric transducer* - A transducer in which the displacement of the force-summing member is transmitted to the slider in a potentiometer, thus changing the ratio of output resistance to total resistance. Transduction is accomplished in this manner by means of the changing ratios of a voltage divider.

*pressure cell* - Same as *pressure transducer*.

*pressure sensitivity* - Same as *sensitivity* but specifically applied to pressure transducers.

*primary calibration* - Calibration in which the transducer output is observed, or recorded, while direct stimulus is applied under controlled conditions.



*proportional linearity* - A manner of expressing nonlinearity as deviation from a straight line in terms of a given percentage of the transducer output at the stimulus point under consideration, i.e., as a given percentage of the reading.

*random vibration* - Continuous nonuniform vibratory accelerations.

*range* - See *full scale*. The range is generally given by expressing the quantitative limits of the stimulus between which the instrument is intended to perform measurements.

*rated range* - The nominal operating range within which a device should be operated in order to maintain the performance characteristics specified by its manufacturer.

*ratio calibration* - A method by which potentiometric transducers may be calibrated, in which the value of the measurand is expressed in terms of decimal fractions representing the ratio of output resistance to total resistance.

*reactive balance* - The capacitive or inductive balance which is often required to null the output of certain transducers or systems when the excitation and/or the output is given in terms of alternating currents.

*readability* - The legibility of a visual display. Normally expressed in terms of resolution.

*readout equipment* - The electronic apparatus which is employed to provide indications and/or recordings of a transducer output.

*reliability* - A measure of the probability that an instrument will continue to perform within specified limits of error for a specified length of time under specified conditions.

*repeatability* - The maximum deviation from the average of corresponding data points taken from repeated tests under static and identical conditions for any one stimulus value. Often the number of repeated tests is specifically limited to a convenient number of runs. The number of stimulus points may include the full range of the instrument or may be limited to a measurand interval within the range of the device. The term is often extended to mean the difference in output for any given identically repeated stimulus with no change in the remaining test conditions.

*residual* - (Adjective) Pertaining to a measure of the output of a transducer under static conditions and with no stimulus applied.
(Noun) Used to mean *residual unbalance*.

*resolution* - The degree to which small increments of the measurand can be discriminated in terms of instrument output. Also the smallest change in applied stimulus that will produce a detectable change in the instrument output. Often the notation "in the absence of friction" is made after the latter definition in order to differentiate resolution from "threshold sensitivity."

*resolution noise* - The noise due to the stepped character of the resistance element in wire-wound potentiometric transducers.

*resonant frequency* - The frequency at which a given system, or object, will respond with maximum amplitude when driven by an external sinusoidal force of constant amplitude.

*response curve* - A plot of output versus frequency for a specific device. Also a plot of stimulus versus output.

*scale factor* - The ratio of full-scale output to the value of the measurand at full range.

*secondary calibration* - Calibration of accessory equipment in which the transducer is deliberately unbalanced electrically to change the output voltage, current, or impedance. Generally performed by means of a calibration resistor which is placed across one leg of the bridge.

*seismic mass* - The element in an accelerometer which is intended to serve as the force-summing member for applied accelerations and/or gravitational forces.



*self-generating transducer* - A transducer which does not require external electrical excitation to provide specified output signals.

*sense step* - Same as *secondary calibration*.

*sensing* - The algebraic transduction of the magnitude of a stimulus into an electrical output.

*sensitivity* - The slope determined, at constant excitation, by the change in output signal as a function of the applied stimulus. The slope of the line from which nonlinearity is calculated. Also the ratio of full scale output to the excitation level. This latter interpretation is usually expressed in terms of millivolt output per volt input. The term *sensitivity* is also used as synonymous with *full-scale output*.

*sensitivity adjustment* - The control of the ratio of output signal to excitation voltage per unit measurand. Generally accomplished in a system by changing the gain of one or more amplifiers. The practice of placing excitation control components (such as potentiometers or rheostats) in series with the excitation to a transducer is a sensitivity adjustment *for the system*. However, in the latter case no significant change is introduced in the output-to-input ratio *of the transducer*.

*sensitivity drift* - A slow and continuous change in sensitivity, due to any internal cause.

*sensitivity set* - A permanent change in sensitivity attributable to any cause, such as over-ranging, shock, aging, etc.

*sensitivity shift* - A change in sensitivity from a reference value. That is, change due to any cause from a response slope previously obtained. Often used as synonymous with *thermal coefficient of sensitivity*.

*sensitivity shift with temperature* - The change in sensitivity which is a function of temperature only.

*sensor* - Same as *transducer*.

*servo transducer* - Same as *force balance transducer*.

*set* - A permanent change of a given parameter, attributable to any cause.

*shaker* - An electromagnetic device capable of imparting known and/or controlled vibratory acceleration to a given object. Also called shake table.

*shock* - A force impulse of short duration.

*shorting noise* - A noise which occurs in wire-wound potentiometric transducers even when no current is drawn from the device. It is due to the shorting out of adjacent turns of the wire as the slider traverses the winding. The portion of the interturn current which flows through the slider appears as noise.

*shunt calibration* - A form of secondary calibration in which a resistor is placed in parallel across one element of the bridge in order to obtain a known and deliberate electrical unbalance.

*signal* - The output, or intelligence, emanating from a device.

*single amplitude* - With reference to vibratory conditions, the peak displacement of an oscillating structure from its average or mean position.

*slope-based linearity* - A manner of expressing nonlinearity as deviation from a straight line for which only the slope is specified.

*span* - Same as *full scale*.

*span adjustment* - Same as *sensitivity adjustment*.

*span compensation* - Same as *thermal coefficient of sensitivity*. Also a method by which the effects of temperature on the sensitivity of certain transducers may be minimized and maintained within known limits.

*spin table* - Same as *centrifuge*.

*stability* - The degree of freedom from changes in performance of a device or system as a function of any internal cause, over a period of time. As a rule "stability" ratings actually indicate the instability characteristics of a transducer.



*standardization* - The act or process of reducing something to, or comparing it with, a standard. A measure of uniformity. The term is also used to denote a special case of calibration whereby a known input is applied to a device or system for the purpose of verifying the output or adjusting the output to a desired level or scale factor. Applied to transducers, the term indicates control of the full-scale output (referenced to a standard value) within specified limits of error.

*static acceleration* - A sustained angular or linear acceleration which does not change in magnitude.

*static acceleration sensitivity* - Same as *acceleration sensitivity*. Often used to emphasize the difference from vibration sensitivity.

*static conditions* - An environment which closely resembles ideal laboratory circumstances, and in which a device or system is located.

*static measurement* - A measurement taken under conditions where neither the stimulus nor the environmental conditions fluctuate.

*step calibration* - Same as *interval calibration*. Often confused with *sense step*, that is, the application of a calibration resistor to produce a deliberate electrical unbalance.

*stimulus* - Same as *measurand*.

*storing temperature* - The temperature, or range of temperatures, at which a transducer may be stored or transported but at which temperature the transducer is not necessarily expected to remain within its specified limits of error, if said temperature falls outside the operating temperature range of the instrument.

*strain* - Elastic deformation produced in a solid as a result of stress.

*strain gage* - An element, or group of elements, which change their resistivity as a function of applied stresses. When used with a force-summing member it is termed a "strain gage transducer." Also used to indicate that the operation of a transducer is based on the strain gage principle.

*strain wire* - Wire having a composition such that it exhibits favorable strain gage performance. Also the strain-sensitive filaments which constitute the transfer electrical elements in certain transducers.

*stress* - The force acting on a unit area of a solid.

*subcarrier oscillator* - In a telemetry system, the oscillator which is directly modulated by the measurand, or by the equivalent of the measurand in terms of changes in the transfer elements of a transducer.

*swept resistance* - The portion of the total resistance of a potentiometric transducer over which the slider travels when the device is operated throughout its total range.

*tangent sensitivity* - The slope of the line tangent to the response curve at the point being measured.

*telemetering* - A measurement accomplished with the aid of intermediate means which allows perception, recording or interpretation of data at a distance from a primary sensor. The most widely employed interpretation of telemetering restricts its significance to data transmitted by means of electromagnetic propagation.

*temperature compensation* - Same as *compensation.*

*temperature effect* - The difference between the output at room temperature and at any other specified temperature at any one value of the stimulus within the range of the instrument. It is generally specified in percentage of full-scale output per 100 degrees change, or per any other discrete interval of temperature.

*terminal-based linearity* - Same as *end-point linearity.*

*terminal linearity* - Same as *end-point linearity.*

*thermal coefficient of resistivity* - The changes in the resistivity of a substance due to the effects of temperature only. Usually expressed in ohms per ohm per degree change in temperature.



*thermal coefficient of sensitivity* - The change in full-scale output due to the effects of temperature only. Usually expressed in percentage of the full-scale output at room temperature per unit, or interval, change in temperature.

*thermal sensitivity set* - A permanent change in sensitivity due to temperature effects only. Usually expressed as the difference in sensitivity at room temperature before and after a temperature cycle over the operating temperature range of the transducer.

*thermal zero set* - A permanent change in the residual, due to temperature effects only. Usually expressed as the difference in output at room temperature and zero measurand before and after a temperature cycle over the operating temperature range of the transducer.

*thermal zero shift* - The change in output, at zero measurand, due to the effects of temperature only. Usually expressed in percentage of full scale output at room temperature per unit, or interval, change in temperature.

*threshold of sensitivity* - The smallest change in stimulus that will result in a detectable change in output.

*tilt table* - A device used to calibrate linear accelerometers with rated ranges of, or below, plus or minus 1.0 g. It allows the accelerometer to be positioned at different angles, in reference to a surface perpendicular to the direction of the earth's gravity, so that the applied values of acceleration are equal to the cosine of the angle between the reference surface and the direction of the earth's gravity.

*time base* - A reference time signal recorded at given intervals, or continuously with the information signal.

*total excursion* - The application of stimulus, in a controlled manner, over the span of an instrument.

*total range* - Same as *full scale.*

*total resistance* - The resistance measured across the input terminals of a potentiometric transducer.

*transducer* - Broadly defined, a device by means of which energy may flow from one or more transmission systems to one or more other transmission systems. The energy may be of any form, such as electrical, mechanical or acoustical. The term *transducer* is often restricted to signify a device in which the magnitude of an applied stimulus is converted into an electrical signal which is proportional to the quantity of the stimulus. Variations of the phenomenon being measured may, in most cases be referenced to time.

*transverse acceleration* - In accelerometers, the acceleration which is applied in any direction perpendicular to the axis of sensitivity.

*transverse sensitivity* - Same as *cross-sensitivity*.

*unbalance* - A measure of the difference between the real output and the desired output at zero measurand from an instrument or system which is properly energized. The term *balance* is often employed to indicate the condition or quantity of unbalance.

*undamped natural frequency* - The frequency at which a system with a single degree of freedom will oscillate, *in the absence of damping,* upon momentary displacement from the rest position by a transient force.

*unidirectional transducer* - A transducer which measures stimulus in one direction only from a reference zero or rest position.

*velocity transducer* - A transducer which generates an output proportional to imparted velocities.

*vibration effect* - See *vibration sensitivity*.

*vibration sensitivity* - The peak instantaneous change in output at a given sinusoidal vibration level for any one stimulus value within the range of the instrument. Usually expressed in percentage of full scale output per vibratory "g" over a given frequency range. It may also be specified as a total error in percentage of full-scale output for a given vibratory acceleration level.



*vibration survey* - A method of determining the natural frequency of a transducer by observation of the output waveform upon the application of a shock, or tapping, of sufficient magnitude to initiate oscillation of the instrument.

*viscous damping* - Same as *fluid damping*.

*voltage breakdown test* - A test whereby a specified voltage is applied between given points in a transducer, to ascertain that no breakdown occurs at said voltage.

*volumetric displacement* - The change in volume required to displace the diaphragm of a pressure transducer from its rest position to a position corresponding to the application of a stimulus equal to the rated range of the transducer.

*weighted error distribution* - A manner of expressing nonlinearity errors as deviations from a straight line selected to permit a given portion of the response curve to be more linear than the rest of the curve.

*zero adjustment* - The act of nulling out the output from a system or device. Also the circuit or means by which a "no output" condition is obtained from an instrument when properly energized.

*zero balance* - Same as *residual balance*. Also see *zero adjustment*.

*zero-based linearity* - Nonlinearity errors expressed as deviations from the most favorable straight line which crosses the instrument output at zero measurand value. The line from which zero-based linearity is calculated is also termed *best fit straight line with forced zero*. The reference line is chosen so that the response curve contains a minimum of two points of equal and maximum deviation from the line.

*zero compensation* - Same as *thermal zero shift*. Also a method by which, in certain transducers, effects of temperature on the output at zero measurand may be minimized and maintained within known limits.

*zero drift* - Same as *zero shift*. Also a slow and continuous change in output at zero measurand attributable to any internal cause.

*zeroing* - Same as *zero adjustment*. Also a deliberate translation of recorded data, or data reduction equipment output, to a position selected as zero reference.

*zero set* - A permanent change in the output at zero measurand due to any cause.

*zero shift* - A temporary change in the output of a device, at zero measurand, due to any cause. *Zero shift* is often used synonymously with *thermal zero shift*.



## APPENDIX B

# MATERIAL CHARACTERISTICS

TYPICAL MECHANICAL PROPERTIES OF METALS AT ROOM TEMPERATURE
(Based on ordinary stress-strain values)

| METAL | Tensile strength, kpsi | Yield strength, kpsi | Ultimate elongation, percent | Reduction of area, percent | Brinell No. |
|---|---|---|---|---|---|
| Cast iron | 18-60 | 8-40 | 0 | 0 | 100-300 |
| Wrought iron | 45-55 | 25-35 | 35-25 | 55-30 | 100 |
| Commercially pure iron, annealed | 42 | 19 | 48 | 85 | 70 |
| Hot rolled | 48 | 30 | 30 | 75 | 90 |
| Cold rolled | 100 | 95 | ..... | ..... | 200 |
| Structural steel, ordinary | 50-65 | 30-40 | 40-30 | ..... | 120 |
| Low alloy, high strength | 65-90 | 40-80 | 30-15 | 70-40 | 150 |
| Steel, SAE 1300, annealed | 70 | 40 | 26 | 70 | 150 |
| Quenched, drawn 1300 F | 100 | 80 | 24 | 65 | 200 |
| Drawn 1000 F | 130 | 110 | 20 | 60 | 260 |
| Drawn 700 F | 200 | 180 | 14 | 45 | 400 |
| Drawn 400 F | 240 | 210 | 10 | 30 | 480 |
| Steel, SAE 4340, annealed | 80 | 45 | 25 | 70 | 170 |
| Quenched, drawn 1300 F | 130 | 110 | 20 | 60 | 270 |
| Drawn 1000 F | 190 | 170 | 14 | 50 | 395 |
| Drawn 700 F | 240 | 215 | 12 | 48 | 480 |
| Drawn 400 F | 290 | 260 | 10 | 44 | 580 |
| Cold-rolled steel, SAE 1112 | 84 | 76 | 18 | 45 | 160 |
| Stainless steel, 18-8 | 85-95 | 30-35 | 60-55 | 75-65 | 145-160 |
| Steel castings, heat-treated | 60-125 | 30-90 | 33-14 | 65-20 | 120-250 |
| Aluminum, pure, rolled | 13-24 | 5-21 | 35-5 | ..... | 23-44 |
| Aluminum-copper alloys, cast | 19-23 | 12-16 | 4-0 | ..... | 50-80 |
| Wrought, heat-treated | 30-60 | 10-50 | 33-15 | ..... | 50-120 |
| Aluminum die castings | 30 | ..... | 2 | | |
| Aluminum alloy 17ST | 56 | 34 | 26 | 39 | 100 |
| Aluminum alloy 51ST | 48 | 40 | 20 | 35 | 105 |
| Copper, annealed | 32 | 5 | 58 | 73 | 45 |
| Copper, hard drawn | 68 | 60 | 4 | 55 | 100 |
| Brasses, various | 40-120 | 8-80 | 60-3 | ..... | 50-170 |
| Phosphor bronze | 40-130 | ..... | 55-5 | ..... | 50-200 |
| Tobin bronze, rolled | 63 | 41 | 40 | 52 | 120 |
| Magnesium alloys, various | 21-45 | 11-30 | 17-0.5 | ..... | 47-78 |
| Monel metal, 70Ni, 30Cu | 100 | 50 | 35 | ..... | 170 |
| Molybdenum, arc-cast | 97 | 91 | 28 | 40 | 260 |
| Zirconium, crystal bar | 24-43 | 8-26 | 24-54 | 25-75 | 70-130 |
| Titanium (99.0Ti), annealed bar | 95 | 80 | 47 | 27 | |
| Ductile iron, Grade 90-65-02, as cast | 95-105 | 70-75 | 2.5-5.5 | ..... | 225-265 |

Compressive strength of cast iron, 80,000 to 150,000 psi.
Compressive yield strength of all metals, except those cold-worked, = tensile yield strength.

| ELASTIC CONSTANTS OF METALS | | | | |
|---|---|---|---|---|
| | *E* | *G* | *K* | μ |
| METAL | Modulus of elasticity (Young's modulus 1,000,000 psi | Modulus of rigidity (shearing modulus) 1,000,000 psi | Bulk modulus 1,000,000 psi | Poisson's ratio |
| Cast steel | 28.5 | 11.3 | 20.2 | 0.265 |
| Cold-rolled steel | 29.5 | 11.5 | 23.1 | 0.287 |
| Stainless steel 18-8 | 27.6 | 10.6 | 23.6 | 0.305 |
| All other steels, including high-carbon, heat-treated | 28.6-30.0 | 11.0-11.9 | 22.6-24.0 | 0.283-0.292 |
| Cast iron | 13.5-21.0 | 5.2-8.2 | 8.4-15.5 | 0.211-0.299 |
| Malleable iron | 23.6 | 9.3 | 17.2 | 0.271 |
| Copper | 15.6 | 5.8 | 17.9 | 0.355 |
| Brass, 70-30 | 15.9 | 6.0 | 15.7 | 0.331 |
| Cast brass | 14.5 | 5.3 | 16.8 | 0.357 |
| Tobin bronze | 13.8 | 5.1 | 16.3 | 0.359 |
| Phosphor bronze | 15.9 | 5.9 | 17.8 | 0.350 |
| Aluminum alloys, various | 9.9-10.3 | 3.7-3.9 | 9.9-10.2 | 0.330-0.334 |
| Monel metal | 25.0 | 9.5 | 22.5 | 0.315 |
| Inconel | 31 | 11 | | |
| Z-nickel | 30 | 11 | | |
| Beryllium copper | 17 | 7 | | |
| Elektron (magnesium alloy) | 6.3 | 2.5 | 4.8 | 0.281 |
| Titanium (99.0 Ti), annealed bar | 15-16 | | | |
| Zirconium, crystal bar | 11-14 | | | |
| Molybdenum, arc-cast | 48-52 | | | |



# APPENDIX C

## POWER DENSITY GRAPHS

On the following pages are power density graphs for strain gages of three different resistance values. To use these graphs, first determine the power density range for the type of measurement and the material on which the strain gage is to be mounted (see table below). Next, determine the grid area for the strain gage to be used. Enter the graph with these figures to find the maximum safe bridge voltage (not the voltage across the strain gage) for the measurement.

EXAMPLE:

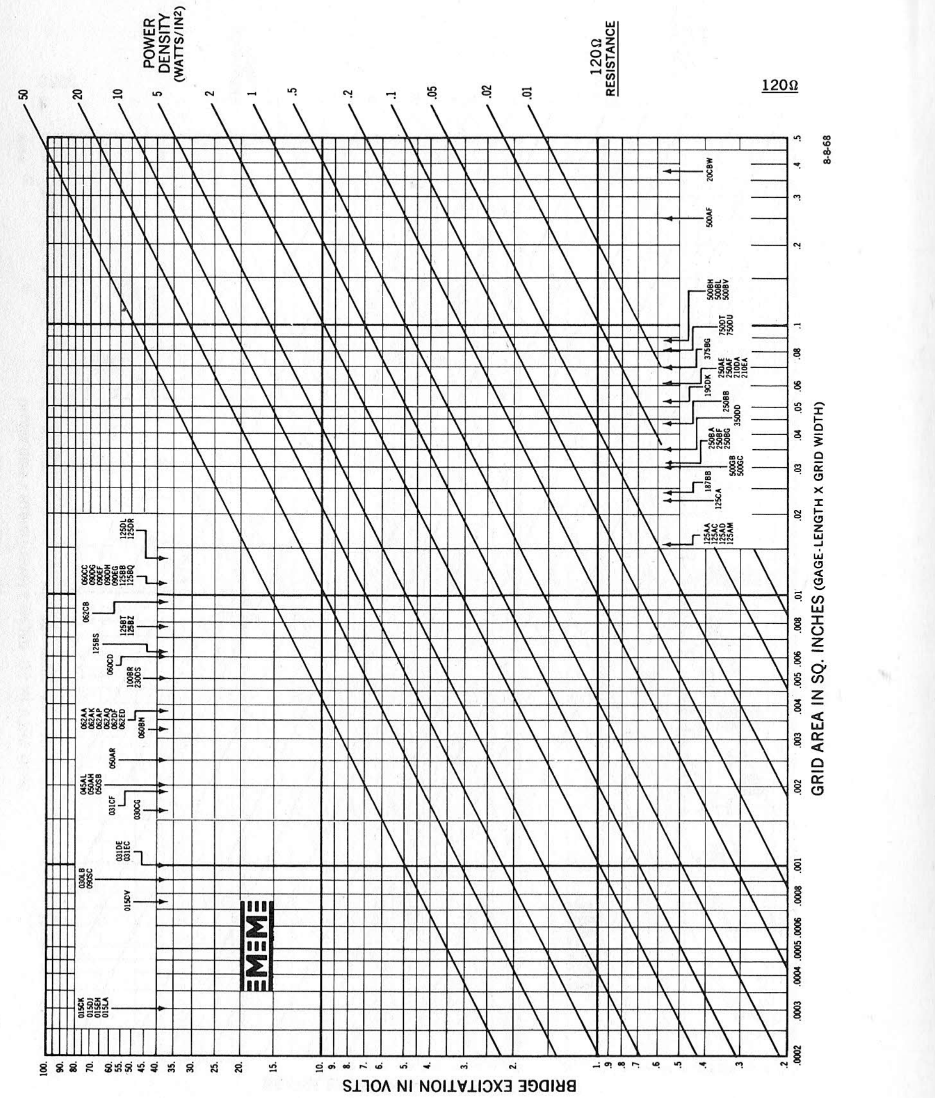
A highly accurate measurement is desired, using a 120-Ω M-M strain gage Type 125BT, whose grid area is about 0.075 in$^2$. The material under measurement is thin stainless steel. Dynamic conditions (frequency) are expected to be encountered. From the table it is seen that under these conditions the power density range is 2 to 10 watts/in$^2$. The intersections of the vertical line representing the grid area and the slanted lines representing these power density levels, when extended to the vertical scale, show the range of safe bridge voltages that can be used under the conditions of the measurement. In this example, the safe bridge voltage range is seen to be about 3 to 6 volts, with 6 volts as a maximum safe level.

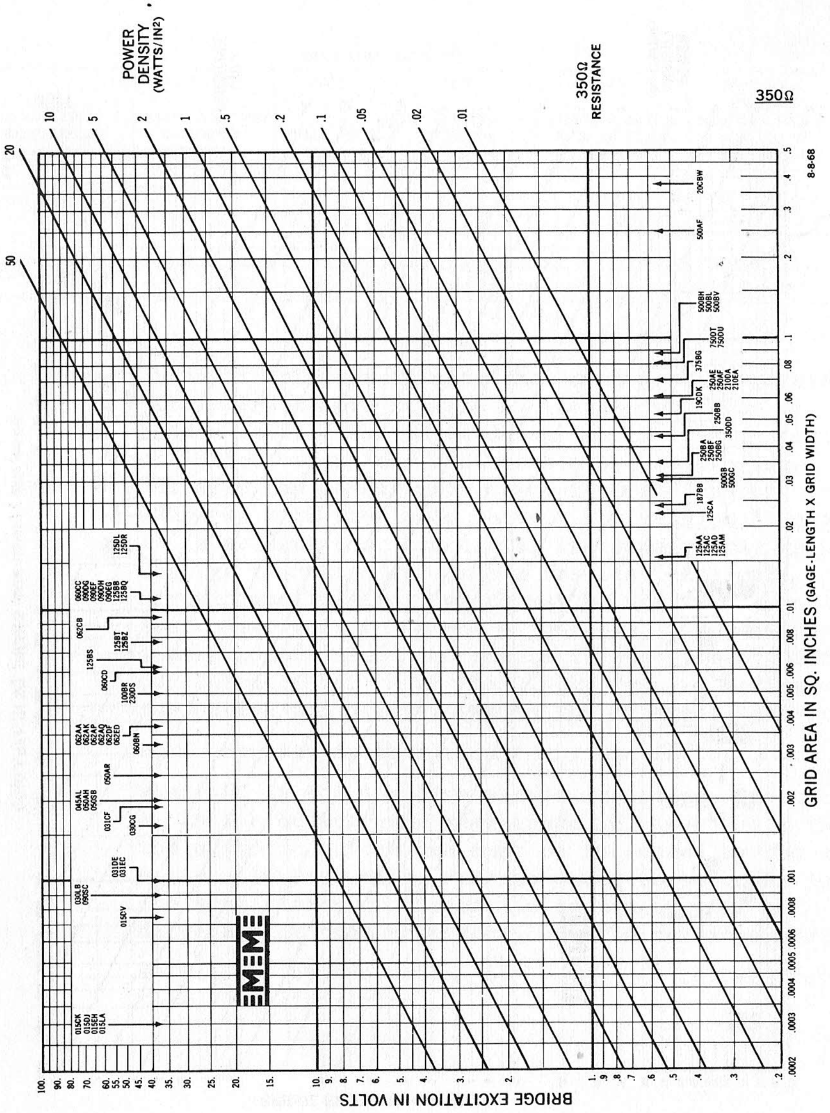
HEAT-SINK CONDITIONS

| ACCURACY REQUIREMENTS | | *EXCELLENT* HEAVY ALUMINUM OR COPPER SPECIMENS | *GOOD* THICK STEEL SPECIMENS | *FAIR* THIN STAINLESS-STEEL/OR TITANIUM | *POOR* FILLED PLASTICS SUCH AS FIBER-GLASS/EPOXY | *VERY POOR* UNFILLED PLASTICS SUCH AS ACRYLIC OR POLYSTRENE |
|---|---|---|---|---|---|---|
| *STATIC* | HIGH | 2.-5. | 1.-2. | .5-1. | .1-.2 | .01-.02 |
| | MODERATE | 5.-10. | 2.-5. | 1.-2. | .2-.5 | .02-.05 |
| | LOW | 10.-20. | 5.-10. | 2.-5. | .5-1. | .05-.2 |
| *DYNAMIC* | HIGH | 5.-20. | 5.-10. | 2.-10. | .5-1. | .01-.05 |
| | MODERATE | 10.-20. | 10.-20. | 5.-10. | 1.-2. | .02-.1 |
| | LOW | 20.-50. | 20.-50 | 10.-20. | 1.-5. | .2-.5 |

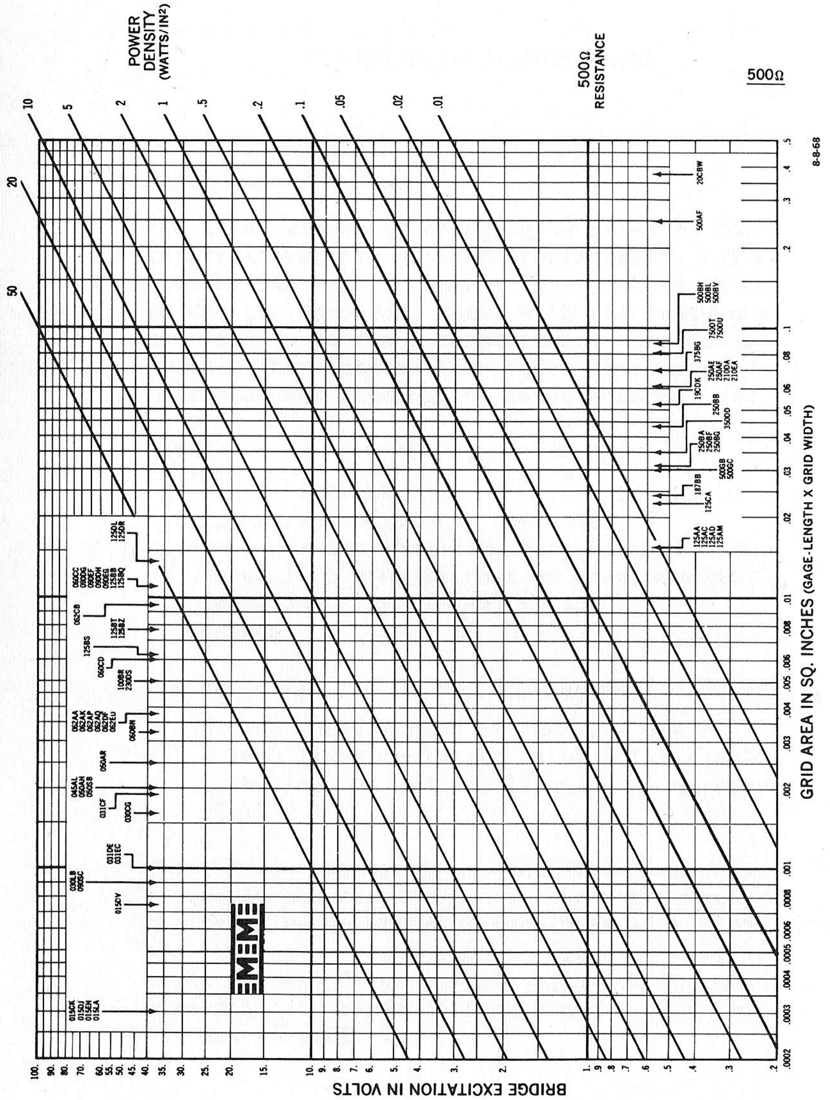
It is of interest to note that most good commercial strain indicators utilize excitation voltages of 3 to 5 volts. The power densities created in gages of various sizes and resistances by these bridge voltages can be directly taken from the charts, and compared with the table above. For very small gages, it is evident that commercial instruments may require voltage reduction for proper results. A simple circuit modification, which may be utilized when the instrument voltage is not adjustable, involves the insertion of 'dead' resistance in the form of high-precision resistors of the Vishay type in series with the active and dummy gages in the external half-bridge. Power density is then reduced by the factor $\left(\frac{R_D + R_G}{R_G}\right)^2$, where $R_D$ is the inactive series resistance in ohms, and $R_G$ is the active gage resistance in ohms. Note that the adjacent bridge arm must be increased by the same $R_D$ to maintain bridge balance under these conditions. The sensitivity of the strain indicator will be decreased by this procedure, and the readings must be multiplied by the ration of $\frac{R_D + R_G}{R_G}$ to correct for this desensitization.






POWER DENSITY (WATTS/IN²)
350Ω RESISTANCE
350Ω
GRID AREA IN SQ. INCHES (GAGE-LENGTH X GRID WIDTH)
BRIDGE EXCITATION IN VOLTS
8-8-68




POWER DENSITY (WATTS/IN²)
500Ω RESISTANCE
500Ω
GRID AREA IN SQ. INCHES (GAGE-LENGTH X GRID WIDTH)
BRIDGE EXCITATION IN VOLTS
8-8-68

APPENDIX D

# VIBRATION NOMOGRAMS

The first vibration nomogram is based on the interrelationship between displacement, velocity, acceleration and frequency as explained in Chapter 3. To use the nomogram, enter with the frequency value and read up to its intersection to the other known value. This intersection point becomes the reference for finding the third unknown.

Example 1: $f$ = 10 Hz, $v$ = 10 in/s

At the intersection of the 10 Hz and 10 inches/second lines, the value of acceleration (negative slope lines) is about 1.75 $g$ while that of displacement (positive slope lines) is about 0.175 inches.

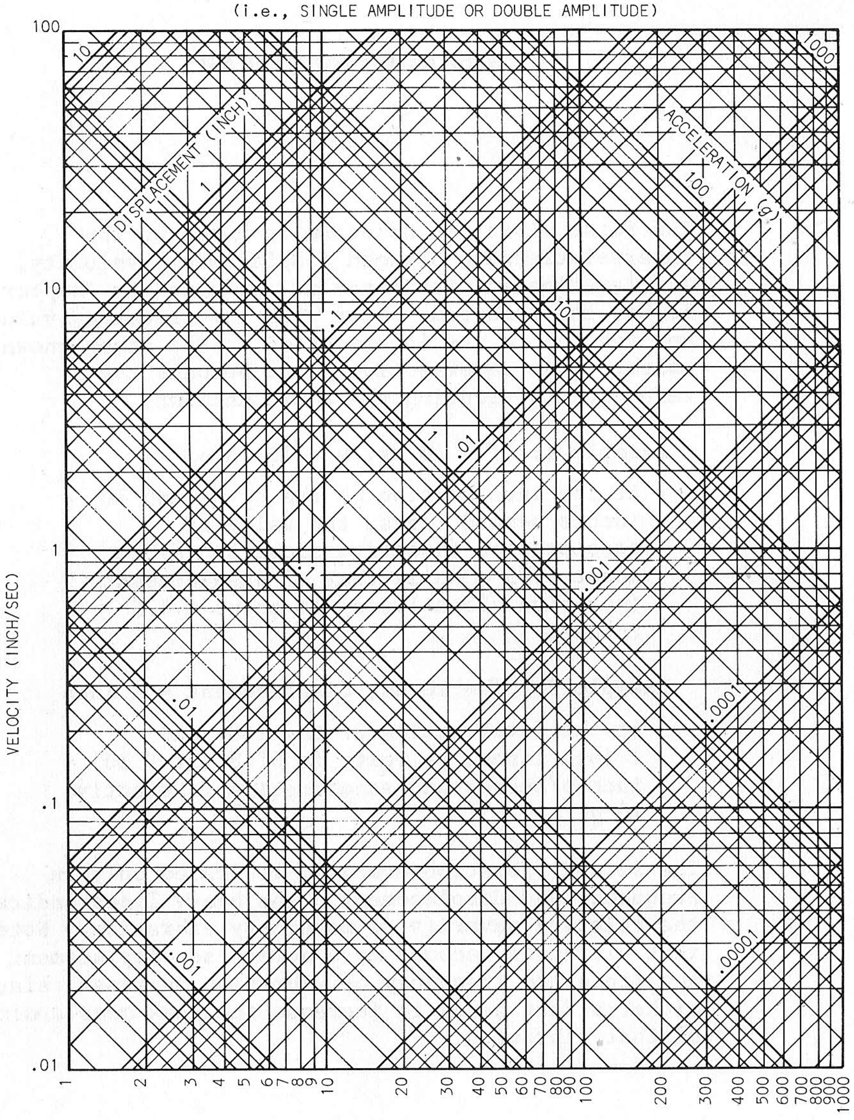
Example 2: $f$ = 10 Hz, displacement = 1 inch

At the intersection of the 10Hz and 1 inch lines, velocity is 62.8 ($2\pi$ X 10) inches/second and acceleration is exactly 10 $g$.

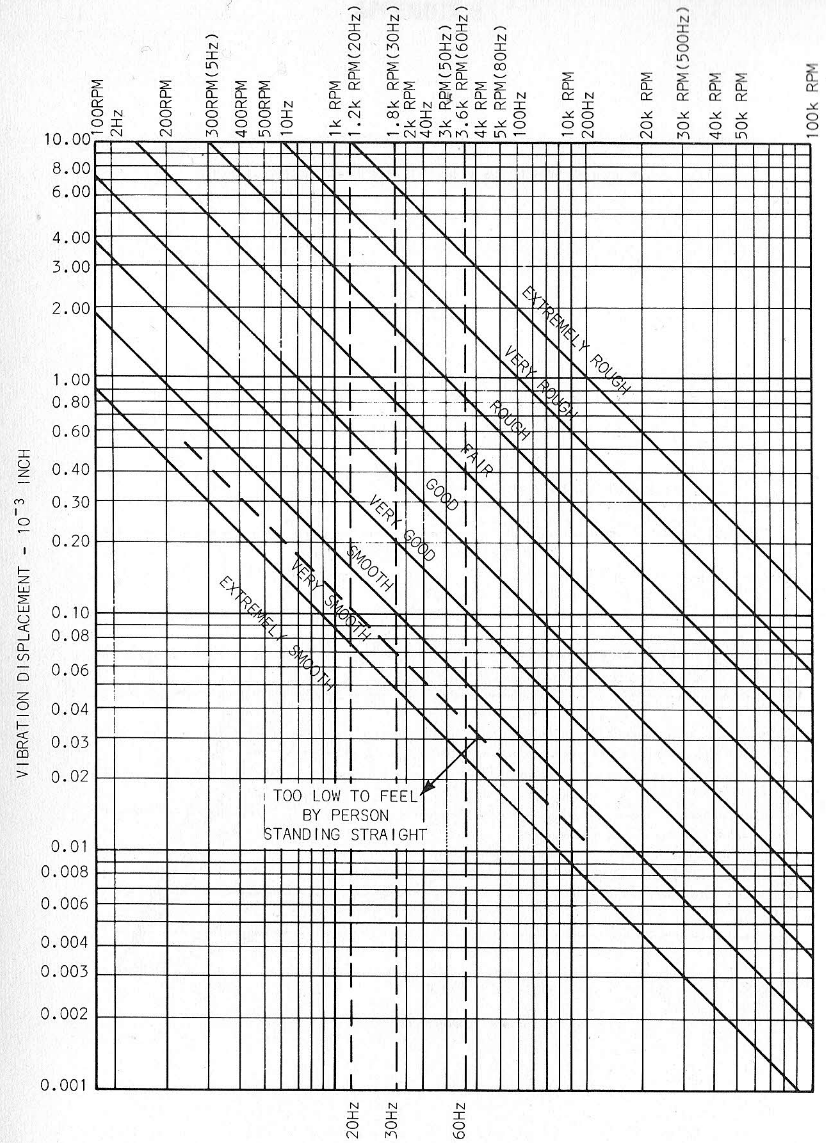
The second vibration nomogram is scaled only in frequency and displacement. The heavy lines indicate the relative severity of machinery vibration. Note that vibration becomes more severe as displacement amplitude and frequency of vibration increase, since either affect tends to increase the *peak acceleration* of that vibration.

VIBRATION NOMOGRAM

RELATION OF DISPLACEMENT, VELOCITY, AND ACCELERATION IN PURE SINUSOIDAL VIBRATION
ALL QUANTITIES MUST BE READ IN THE SAME RELATIVE AMPLITUDE
(i.e., SINGLE AMPLITUDE OR DOUBLE AMPLITUDE)

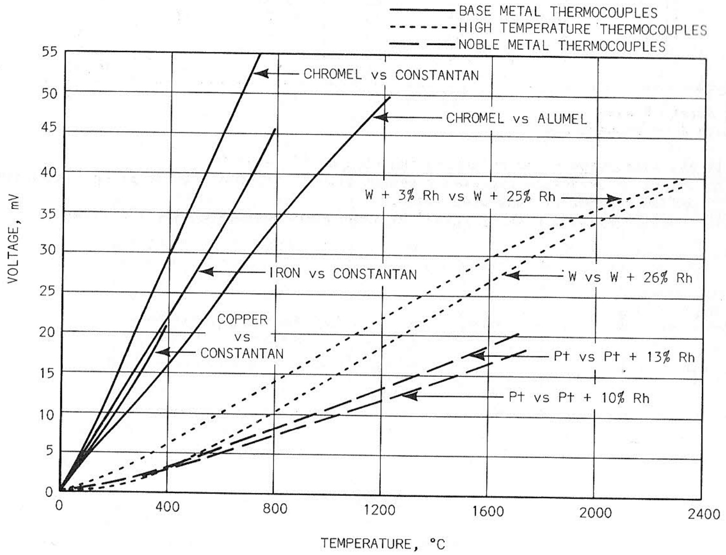




## APPENDIX E

# THERMOCOUPLE CHARACTERISTICS



THERMOCOUPLE OUTPUT VOLTAGES

| JUNCTION TEMPERATURE | IRON-CONSTANTAN (TYPE J) | | CHROMEL-ALUMEL (TYPE K) | | COPPER-CONSTANTAN (TYPE T) | | Pt + 10% Rh -- PLATINUM (TYPE S) | |
|---|---|---|---|---|---|---|---|---|
| °CELSIUS | ABSOLUTE OUTPUT(mV) | OUTPUT μV/degree | ABSOLUTE OUTPUT(mV) | OUTPUT μV/degree | ABSOLUTE OUTPUT(mV) | OUTPUT μV/degree | ABSOLUTE OUTPUT(mV) | OUTPUT μV/degree |
| -150 | -6.50 | 33 | -- | -- | -4.60 | 22 | -- | -- |
| -100 | -4.63 | 41 | -- | -- | -3.35 | 28 | -- | -- |
| -50 | -2.43 | 46 | -- | -- | -1.80 | 34 | -- | -- |
| * 0 | 0.00 | 50 | 0.00 | 40 | 0.00 | 38 | 0.00 | 5.6 |
| † +25 | +1.28 | 52 | +1.00 | 40 | +0.99 | 41 | 0.14 | 6.0 |
| +50 | 2.58 | 53 | 2.02 | 41 | 2.04 | 43 | 0.30 | 6.5 |
| +100 | 5.27 | 54 | 4.10 | 42 | 4.28 | 47 | .64 | 7.3 |
| +200 | 10.78 | 56 | 8.13 | 40 | 9.29 | 53 | 1.44 | 8.5 |
| +300 | 16.33 | 55 | 12.21 | 41 | 14.86 | 58 | 2.32 | 9.1 |
| +400 | 21.85 | 55 | 16.40 | 42 | -- | -- | 3.25 | 9.5 |
| +500 | 27.39 | 56 | 20.65 | 42 | -- | -- | 4.22 | 9.9 |
| +1000 | -- | -- | 41.13 | 39 | -- | -- | 9.57 | 11.5 |
| °FAHRENHEIT | | | | | | | | |
| -300 | -7.52 | 14 | -- | -- | -5.28 | 10 | -- | -- |
| -200 | -5.76 | 21 | -- | -- | -4.11 | 13 | -- | -- |
| -100 | -3.49 | 25 | -- | -- | -2.56 | 17 | -- | -- |
| * +32 | 0.00 | 28 | 0.00 | 21 | 0.00 | 21 | 0.00 | 3.0 |
| † +75 | +1.22 | 29 | 0.95 | 22 | 0.94 | 23 | 0.14 | 3.3 |
| +200 | +4.91 | 30 | 3.82 | 23 | 3.97 | 26 | 0.60 | 4.0 |
| +400 | 11.03 | 31 | 8.31 | 23 | 9.53 | 30 | 1.47 | 4.7 |
| +600 | 17.18 | 31 | 12.86 | 23 | 15.77 | 33 | 2.46 | 5.1 |
| +800 | 23.32 | 30 | 17.53 | 23 | -- | -- | 3.51 | 5.4 |
| +1000 | 29.52 | 31 | 22.26 | 24 | -- | -- | 4.60 | 5.6 |
| +2000 | -- | -- | 44.91 | 21 | -- | -- | 10.66 | 6.6 |

*Freezing Point of Water.
†Approximate Room Temperature.

NOTES: (1) Absolute outputs for reference junction at 0°C = 32°F.
(2) Output in μV/degree represents sensitivity of thermocouple at given temperature, and in degrees of indicated scale.
(3) Junction types are as specified by Instrument Society of America (ISA).



# APPENDIX F

## CONVERSION TABLES

TO CONVERT A QUANTITY IN A COLUMN (↓) TO A QUANTITY IN A ROW (→), MULTIPLY BY THE FACTOR APPEARING AT THE COLUMN/ROW INTERSECTION.

LENGTH

| | millimeter | centimeter | meter | inch | foot | yard |
|---|---|---|---|---|---|---|
| millimeter | 1 | 0.1 | 0.001 | $3.937 \times 10^{-2}$ | $3.281 \times 10^{-3}$ | $1.093 \times 10^{-3}$ |
| centimeter | 10 | 1 | 0.01 | 0.3987 | $3.281 \times 10^{-2}$ | $1.093 \times 10^{-2}$ |
| meter | 1000 | 100 | 1 | 39.37 | 3.281 | 1.093 |
| inch | 25.4 | 2.54 | 0.0254 | 1 | $8.333 \times 10^{-2}$ | $2.777 \times 10^{-2}$ |
| foot | 300.48 | 30.48 | 0.3048 | 12 | 1 | 0.333 |
| yard | 901.44 | 90.144 | 0.9014 | 36 | 3 | 1 |

ANGLE

| | DEGREES | MINUTES | SECONDS | RADIANS |
|---|---|---|---|---|
| DEGREES | 1 | 60 | 3600 | $1745 \times 10^{-5}$ |
| MINUTES | $1667 \times 10^{-4}$ | 1 | 60 | $29 \times 10^{-5}$ |
| SECONDS | 0.000278 | $1667 \times 10^{-4}$ | 1 | $48 \times 10^{-7}$ |
| RADIANS | 57.295 | 3437.75 | 206265.8 | 1.000 |

MASS

| | gram | kilogram | slug | ounce | pound | metric ton | U.S. (short) ton |
|---|---|---|---|---|---|---|---|
| gram | 1 | 0.001 | 6.852 X $10^{-5}$ | 3.527 X $10^{-2}$ | 2.205 X $10^{-3}$ | 1 X $10^{-6}$ | 1.02 X $10^{-6}$ |
| kilogram | 1000 | 1 | 6.852 X $10^{-2}$ | 35.27 | 2.205 | | 1.102 X $10^{-3}$ |
| slug | 1.459 X $10^{4}$ | 14.59 | 1 | 514.8 | 32.17 | 1.459 X $10^{-2}$ | 1.609 X $10^{-2}$ |
| ounce | 28.35 | 2.835 X $10^{-2}$ | 1.943 X $10^{-3}$ | 1 | 6.250 X $10^{-2}$ | 2.835 X $10^{-5}$ | 3.125 X $10^{-5}$ |
| pound | 453.6 | 0.4536 | 3.108 X $10^{-2}$ | 16 | 1 | 4.536 X $10^{-4}$ | 0.0005 |
| metric ton | 1 X $10^{6}$ | 1000 | | 35273.96 | 2204.6 | 1 | 1.102 |
| U.S. (short) ton | 9.072 | 907.2 | 62.16 | 3.2 X $10^{4}$ | 2000 | 0.907 | 1 |

VOLUME

| |
|---|
| 1 U.S. fluid gallon = 4 U.S. quarts = 8 U.S. pints = 128 fluid ounces = 231 $in^3$. |
| 1 British imperial gallon = volume of 10 lbs of water at 62°F = 277.42 $in^3$. |
| 1 liter = volume of 1 kilogram of water at maximum density = 1000.028 $cm^3$ = 61 $in^3$. |

PRESSURE

| | atmosphere | dyne/$cm^2$ | in $H_2O$ | cm Hg | newton/$meter^2$ | pound/$inch^2$ |
|---|---|---|---|---|---|---|
| atmosphere | 1 | 1.013 X $10^{6}$ | 406.8 | 0.76 | 1.013 X $10^{5}$ | 14.7 |
| dyne/$cm^2$ | 9.869 X $10^{-7}$ | 1 | 4.015 X $10^{-4}$ | 7.501 X $10^{-5}$ | 0.1 | 1.450 X $10^{-5}$ |
| * in $H_2O$ | 2.458 X $10^{-3}$ | 2491 | 1 | 0.1868 | 249.1 | 3.613 X $10^{-2}$ |
| † cm Hg | 1.316 X $10^{-2}$ | 1.333 X $10^{4}$ | 5.353 | 1 | 1333 | 0.1934 |
| newton/$meter^2$ | 9.869 X $10^{-6}$ | 10 | 4.015 X $10^{-3}$ | 7.501 X $10^{-4}$ | 1 | 1.450 X $10^{-4}$ |
| pound/$inch^2$ | 6.805 X $10^{-2}$ | 6.895 X $10^{4}$ | 27.68 | 5.171 | 6.895 X $10^{3}$ | 1 |

*at 4°C and where g = 9.80665 meters/$second^2$
†at 0°C and where g = 9.80665 meters/$second^2$



FORCE

| | newton | dyne | ounce (f) | pound (f) | gram (f) | kg (f) | metric ton | U.S. (short) ton |
|---|---|---|---|---|---|---|---|---|
| newton | 1 | 1 X $10^{5}$ | 3.597 | 0.2248 | 102.0 | 0.1020 | 1.02 X $10^{-4}$ | 1.124 X $10^{-4}$ |
| dyne | 1 X $10^{-5}$ | 1 | 3.597 X $10^{-5}$ | 2.248 X $10^{-6}$ | 1.019 X $10^{-3}$ | 1.019 X $10^{-6}$ | 1.02 X $10^{-9}$ | 1.124 X $10^{-9}$ |
| ounce (f) | 0.0278 | 2780 | 1 | 0.0167 | 28.35 | 2.835 X $10^{-2}$ | 2.835 X $10^{-5}$ | 3.124 X $10^{-5}$ |
| pound (f) | 4.448 | 4.448 | 16 | 1 | 453.6 | 0.4536 | 4.535 X $10^{-4}$ | 5 X $10^{-4}$ |
| gram (f) | 9.807 X $10^{3}$ | 980.7 | 3.527 X $10^{-2}$ | 2.205 X $10^{-3}$ | 1 | 0.001 | 1 X $10^{-6}$ | 1.102 X $10^{-6}$ |
| kg (f) | 9.807 | 9.807 X $10^{5}$ | 35.27 | 2.205 | 1000 | 1 | 1 X $10^{-3}$ | 1.102 X $10^{-3}$ |
| metric ton | 9.807 | 9.807 X $10^{8}$ | 35273.96 | 2205 | 1 X $10^{6}$ | 1000 | 1 | 1.102 |
| U.S. (short) ton | 10.807 | 8.896 X $10^{8}$ | 32000 | 2000 | 907.185 X $10^{3}$ | 907.185 | 0.907 | 1 |

TEMPERATURE

| To convert | To | Use this equation |
|---|---|---|
| $T_F$ | $T_C$ | $T_C = 5/9(T_F - 32°)$ |
| $T_F$ | $T_K$ | $T_K = 5/9(T_F - 32°) + 273.16°$ |
| $T_C$ | $T_F$ | $T_F = 32° + 9/5\ T_C$ |
| $T_C$ | $T_K$ | $T_K = T_C - 273.16°$ |
| $T_K$ | $T_C$ | $T_C = T_K + 273.16°$ |
| $T_K$ | $T_F$ | $T_F = 9/5(T_K - 273.16°) + 32°$ |

$T_F$ = Degrees Fahrenheit
$T_C$ = Degrees Celcius (centigrade)
$T_K$ = Degrees Kelvin (absolute)

## APPENDIX G

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# INDEX

NOTES