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STRAIN

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INTRODUCTION

The consideration and measurement of strain are important aspects of engineering outside forces. In most engineering applications unit strain—change of length per unit length—has greater significance than total strain. The word "strain" then, when used alone, commonly refers to unit strain. Total strain is generally so designated.

Strain measurement is sometimes made for its own sake. It may be important to be able to estimate the probable amount of total strain to be expected in a structure or machine, because of space relationships between various components, or for some other reasons. More often, however, strain is of importance because of its relation to stress. "Stress" refers to internal forces of a body which resist external forces, or loads, on the body. Strain is a direct result of stress. Like strain, "stress" used alone generally refers to unit stress, force per unit area.

Strain is a fundamental physical phenomenon; stress is a derived property which cannot be directly measured. Yet, the ability of a material to support applied loads or forces is conventionally expressed in terms of stress, not strain. Engineering design depends in large measure on stress analysis. Stress analysis, particularly in complicated shapes, oftentimes depends on strain analysis, usually experimental. The measurement of strain, then, is a very basic and important phase of stress analysis.

Through knowledge of the properties of materials, or by direct calibration against known loads, strain measurement may also be used in transducer applications, for direct measurement of load, torque, pressure, and other such quantities.

PROPERTIES AND BEHAVIOR OF MATERIALS

To make successful strain readings, and to interpret these readings correctly in terms of stress-strain relationships, it is necessary to have an understanding of certain properties of materials, and of the behavior of materials under stress. Properties of materials of particular concern in strain measurement are Modulus of Elasticity, E, Temperature Coefficient of Expansion, α, and Poisson's Ratio, μ. The Modulus of Elasticity, E, is an elastic constant of the material and is related to stress σ and strain ϵ by Hooke's law namely $\sigma = E\epsilon$. When a bar of material is subjected to an axial tensile load, the ratio of the lateral linear strain to the longitudinal linear strain within the elastic behavior of the material is called Poisson's ratio. It is designated by the symbol μ. Values of these properties for some of the materials of importance to agricultural engineers are given in Table 1.

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Experimental stress analysis usually includes the process of making strain measurements, from which stresses may be calculated by considering the relationships existing between strains and stresses. This procedure pre-supposes that there is a definite relationship between stress and strain. This supposition restricts the condition in the material mainly to that of elastic behavior which is usually characterized by a single-valued linear relationship between strain and stress. If inelastic action occurs, the stress is dependent not on strain alone, but also on such factors as strain-rate, temperature, time, etc. Materials having single-valued but non-linear stress-strain relationships also cause increased difficulty in experimental stress analysis.

Figure 1 and Table 2 give stress-strain relationships at a point for ideal elastic members under conditions of one-, two-, and three-dimensional stress.

Figure 2 indicates the stress-strain relationships for the condition of pure torsion in a bar. This relationship, an example of a biaxial stress condition, is of considerable importance in both strain-measurement and in transducer applications.

In complicated shapes, it is generally not possible to predict the location and direction of principal stresses and strains at a point for two- or three-dimensional stress situations. By measuring a number of strains, however, it is possible to compute, utilizing the relationships of Table 3, the direction and magnitude of the principal stresses. The field of experimental stress involves the measurement of strain from which the state of stress in a body may be determined. The relationships between stress and strain constitute the subject matter of the theories of elasticity and plasticity, found in textbooks on mechanics of materials. This chapter outlines the basic relationships (equations) between stress and strain and provides an introduction to methods of strain measurement. In stress analysis

TABLE 1. Certain properties of common materials

Material	Thermal expansion coefficient, α ($\Delta L/L$ per °C $\times 10^6$)	Modulus of elasticity, E (GPa)	Poisson's ratio, μ
Aluminum	24.0 - 28.7	55 - 75	0.330 - 0.334
Brass	16.9 - 20.4	90	0.33 - 0.36
Brick	9.5	14	
Concrete	10 - 14	17 - 38	0.10 - 0.15
Copper	14.09 - 16.07	100 - 128	0.355
Iron			
Cast	8.5 - 10.6	83	0.21 - 0.30
Wrought	11.4	180 - 200	0.27
Masonry	4 - 7	21 - 55	
Steel	10.5 - 16.0	193 - 207	0.25 - 0.30
Wood			
Parallel to fiber	2.6 - 9.5	6 - 15	0.01 - 0.04
Across fiber	32 - 61	6 - 15	0.3 - 0.7

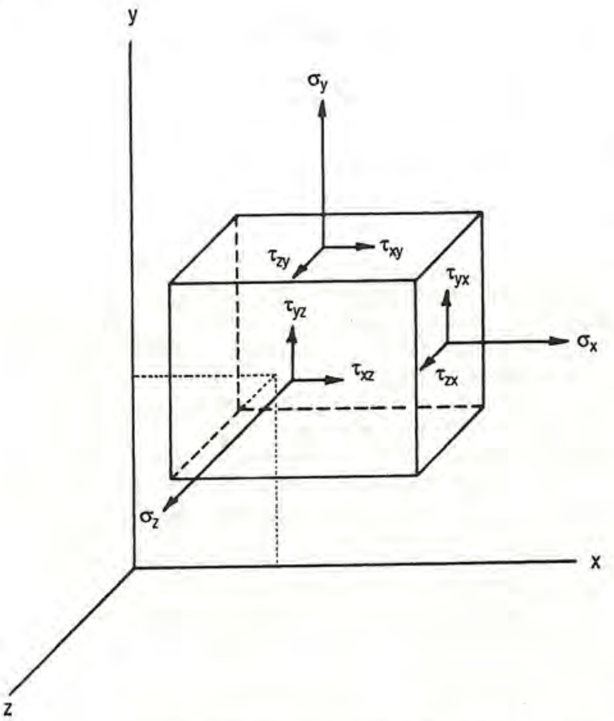


Figure 1–Stresses at a point represented by a differential volume.

TABLE 2. Stress-Strain relationships at a point

	Uniaxial stress $\sigma_y = \sigma_z = 0$	Biaxial stress $\sigma_z = 0$	Triaxial stress
ϵ_x	$\frac{\sigma_x}{E}$	$\frac{1}{E}(\sigma_x - \mu\sigma_y)$	$\frac{1}{E}(\sigma_x - \mu\sigma_y - \mu\sigma_z)$
ϵ_y	$-\mu\frac{\sigma_x}{E}$	$\frac{1}{E}(-\mu\sigma_x + \sigma_y)$	$\frac{1}{E}(-\mu\sigma_x + \sigma_y - \mu\sigma_z)$
ϵ_z	$-\mu\frac{\sigma_x}{E}$	$\frac{1}{E}(-\mu\sigma_x - \mu\sigma_y)$	$\frac{1}{E}(-\mu\sigma_x - \mu\sigma_y + \sigma_z)$
σ_x	$E\epsilon_x$	$\frac{E}{1-\mu^2}(\epsilon_x + \mu\epsilon_y)$	$E\left[\frac{\epsilon_x + \mu(-\epsilon_x + \epsilon_y + \epsilon_z)}{1 - \mu - 2\mu^2}\right]$
σ_y	0	$\frac{E}{1-\mu^2}(\mu\epsilon_x + \epsilon_y)$	$E\left[\frac{\epsilon_y + \mu(\epsilon_x - \epsilon_y + \epsilon_z)}{1 - \mu - \mu^2}\right]$
σ_z	0	0	$E\left[\frac{\epsilon_z + \mu(\epsilon_x + \epsilon_y - \epsilon_z)}{1 - \mu - \mu^2}\right]$

work, a situation approximating two-dimensional stress is most often of concern. For this situation, measurement of strain in three directions is sufficient to compute the principal stresses. Electrical resistance strain gage rosettes are used for the measurement of strains in three directions (at a point). Electrical resistance strain gages are described later in this chapter.

Strain Gage Rosettes

For the general case of plane stress (biaxial), it may be shown that it is necessary to measure strains in three directions in order to find the principal strains and their directions. Therefore, Strain gage rosettes generally consist of three gages. If the directions of the principal strains are known, a two-gage (or "tee") rosette with gages at 90° is sufficient for determination of principal strains and stresses. The gage axes are aligned to coincide with the principal stress axes. The principal stresses, σ_{max}, σ_{min}, and the maximum shearing stress, τ_{max}, may be calculated directly from the rosette readings by the equations given in Table 3. The derivation of these equations is given by Perry and Lissner (1962). Also shown in Table 3 is the expression for calculating the direction of the maximum normal stress, σ_{max}, with respect to gage 1 of the rosette. Although the delta rosette should be used when one has no idea of the principal stress directions, the rectangular rosette is in more common use.

A graphical solution for finding the magnitude and direction of the principal strains for the rectangular rosette is presented in figure 3. The principal stresses can then be calculated from the principal strains using the expression for biaxial stress in Table 2, with σ_{max} and σ_{min} being substituted for σ_x and σ_y, and ϵ_{max} and ϵ_{min} being substituted for ϵ_x and ϵ_y.

Strain Measurement Methods

Numerous methods of strain measurement have been used. At present, strain measurement techniques may be classified into the following groups in order of importance (or frequency of use):

- Electrical resistance strain gages
- Surface coating techniques (stress coat and photoelastic coating)
- Mechanical and mechanical/optical methods
- Photoelasticity
- Moire method
- Miscellaneous methods

The overwhelming majority of strain measurements are presently being made by the use of electrical resistance strain gages. Furthermore, transducers for the measurement of force, pressure, torque, displacement, and flow are most often of a strain-gage type. In many instances Agricultural Engineers must design and construct transducers to be used in experimental equipment or for field measurements. For these reasons, this chapter is devoted principally to the electrical resistance strain gage. Other strain measurement techniques listed above are therefore discussed briefly followed by a detailed treatment of electrical resistance strain gages.

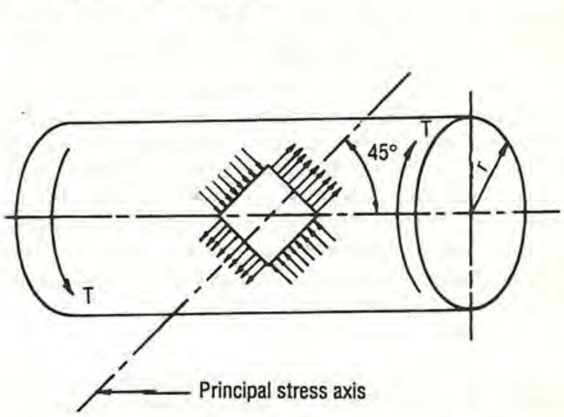
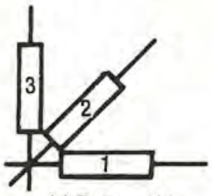
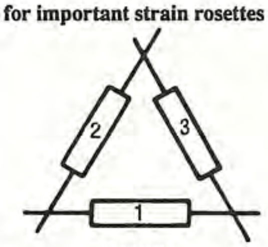


Figure 2–Stress-strain relationship for pure torsion. A special case of biaxial stress, in which the principal strains are of equal absolute value and of opposite sign.

TABLE 3. Stress-strain relationships for important strain rosettes



(a) Rectangular.



(b) Delta.

	(a) Rectangular	(b) Delta
Max. normal stress, $\sigma_{max.}$	$\frac{E}{2}\left[\frac{\epsilon_1+\epsilon_3}{1-\mu}+\frac{1}{1+\mu}\sqrt{(\epsilon_1-\epsilon_3)^2+[2\epsilon_2-(\epsilon_1+\epsilon_3)]^2}\right]$	$E\left[\frac{\epsilon_1+\epsilon_2+\epsilon_3}{3(1-\mu)}+\frac{1}{1+\mu}\sqrt{\left(\epsilon_1-\frac{\epsilon_1+\epsilon_2+\epsilon_3}{3}\right)^2+\left(\frac{\epsilon_2-\epsilon_3}{\sqrt{3}}\right)^2}\right]$
Min. normal stress, $\sigma_{min.}$	$\frac{E}{2}\left[\frac{\epsilon_1+\epsilon_3}{1-\mu}-\frac{1}{1+\mu}\sqrt{(\epsilon_1-\epsilon_3)^2+[2\epsilon_2-(\epsilon_1+\epsilon_3)]^2}\right]$	$E\left[\frac{\epsilon_1+\epsilon_2+\epsilon_3}{3(1-\mu)}-\frac{1}{1+\mu}\sqrt{\left(\epsilon_1-\frac{\epsilon_1+\epsilon_2+\epsilon_3}{3}\right)^2+\left(\frac{\epsilon_2-\epsilon_3}{\sqrt{3}}\right)^2}\right]$
Max. shearing stress, $\tau_{max.}$	$\frac{E}{2(1+\mu)}\sqrt{(\epsilon_1-\epsilon_3)^2+[2\epsilon_2-(\epsilon_1+\epsilon_3)]^2}$	$\frac{E}{1+\mu}\sqrt{\left(\epsilon_1-\frac{\epsilon_1+\epsilon_2+\epsilon_3}{3}\right)^2+\left(\frac{\epsilon_2-\epsilon_3}{\sqrt{3}}\right)^2}$
Angle from gauge 1 to $\sigma_{max.}$ axis, ϕ_p	$\frac{1}{2}\tan^{-1}\left[\frac{2\epsilon_2-(\epsilon_1+\epsilon_3)}{\epsilon_1-\epsilon_3}\right]$	$\frac{1}{2}\tan^{-1}\left[\frac{\frac{1}{\sqrt{3}}(\epsilon_2-\epsilon_3)}{\epsilon_1-\frac{\epsilon_1+\epsilon_2+\epsilon_3}{3}}\right]$

SURFACE COATING TECHNIQUES

Surface-coating techniques may be classified into two major types: brittle coatings and photoelastic coatings.

A brittle coating is a material which, when applied in a thin layer to a surface, will crack under load when a certain tensile strain is exceeded. A commercial brittle coating known as Stresscoat* is available in different sensitivities to provide various levels of threshold (initial cracking) strain. Typical threshold strain is 800 μ mm/mm. By the use of Stresscoat, the strain direction, magnitude, and gradient can be shown. Brittle coating technique is, therefore, an example of the "whole field" method of strain analysis. One of the main purposes of using the brittle coating technique is to determine where the maximum strains occur. A more accurate and detailed analysis is normally carried out at these locations by means of electrical-resistance strain-gage rosettes.

Considerable care and skill is necessary in successful application of Stresscoat. The initial (threshold) strain at which cracking of the coating commences, depends upon temperature, humidity, thickness of coating, loading rate, curing conditions, and sensitivity of the lacquer selected. The strain sensitivity of the coating is determined by use of a calibration bar supplied by the Stresscoat manufacturer. This bar is sprayed and dried under the same conditions as the part under test, then deflected as a cantilever beam. Coatings are available with strain sensitivities as low as 500 micro strain. After testing, Stresscoat can be easily removed from the part by scraping and by solvent cleaning. A major limitation of Stresscoat is its quantitative accuracy which is around ±10% under ideal conditions and may be only ±20% if adequate control of the many variables listed above is not maintained.

The photostress method consists of attaching sheets of photoelastic material to the member being investigated. Polarized light is then directed at the coating and reflected to be viewed through a polarizing instrument. The colored patterns can be interpreted quantitatively in terms of surface principal strains to within about 100 μ mm/mm.

Photoelastic strain gages have been marketed to indicate surface strain without the use of a polariscope. These units are made by covering photoelastic strips with a silver reflective film on one side and with a polarizing film on the other side. The photoelastic strips contain a frozen residual strain pattern that varies linearly along its length. The silvered side is bonded to the structure. In use, light above the gage is polarized, passes through the plastic, reflected, returned through the plastic and the polarizer film. Any strain will cause the residual fringes to shift. Photoelastic strain gages have not become popular probably because of their low sensitivity, poor resolution, and limited accuracy.

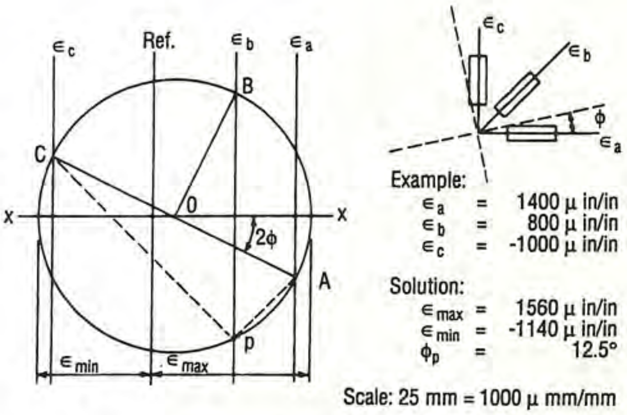


Figure 3–Murphy's circle for graphical determination of principal strain from a rectangular strain gage rosette.

*Magnaflux Corp.

MECHANICAL AND MECHANICAL/OPTICAL METHODS

Mechanical gages or extensometers have gone through various stages of development. Instruments for indicating strain and small motion by mechanical means generally consist of compound lever systems combined with dial indicators. An example of a mechanical strain gage is shown in figure 4. The total deformation divided by the distance between the knife edges (gage length) gives the average unit strain. Some mechanical gages have magnification ratios of 2000 to 3000 and are able to measure strains as low as 10 micro strain. One type of mechanical-optical gage employs a small mirror attached to a double knife edge. As the knife edge is rotated due to a change in length of the specimen, the light beam is rotated through twice the angle. The light beam is directed to a linear scale where the magnification depends upon relative distances between the mirror and the scale and between the scale and the short lever (double knife edge).

Disadvantages of mechanical strain measuring gages, such as weight, bulkiness, low frequency response and limited range of reading, have restricted their use. Their primary advantage is that they are completely self contained and therefore require no expensive electronic instrumentation.

Mechanical Strain and Motion Recorder. A unique type of mechanical strain gage, the mechanical strain and motion recorder (fig. 5), is a self-contained, measuring-recording instrument—perhaps the simplest of all strain-measuring systems. Basically this gage (originally called the Scratch Strain Gage), consists of a small arm carrying a sharp scriber point which sharply scratches the actual target. Subsequently, the target is viewed through a calibrated microscope and strain measurements read directly. The gage may be used for recording dynamic and static peak strains with a minimum of supervision.

In the original scratch gage, the scratch arm was deflected to one side and a scratch made on a target disc rotates with the application of strain cycles giving a strain trace on the circular target. This device is a self-activated, mechanical recording strain gage, which is actuated by length changes in the structural member to which the gage is attached. While being considerably larger than the electrical resistance strain gage, the mechanical strain and motion recorder has many unique advantages. It can be used in remote places where there is no power supply, on rotating machinery and under water. This instrument has been used in such diverse applications as measurement of strains in bridges, landing gear and helicopter rotor blades, and in measuring snow loads on structures in high, remote mountain regions.

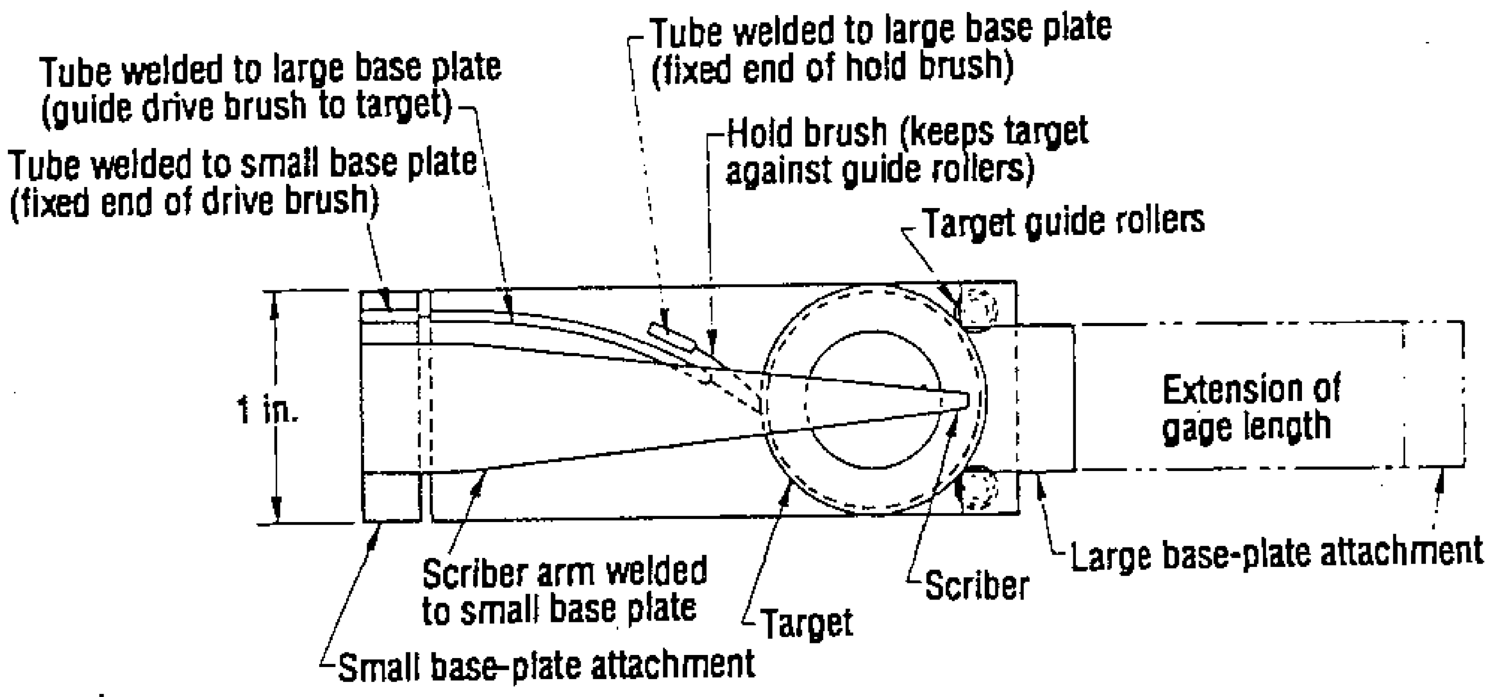


Figure 5–Components of mechanical strain and motion recorder (Tatnall).

Optical Strain Gage. The Tuckerman instrument (fig. 6) is an optical strain gage which measures the distance between a fixed knife-edge and a rotating lozenge. This distance is the gage length and it may be varied from 6 mm (1/4 in.) to 305 mm (12 in.), but usually a gage length of 50.8 mm (2 in.) is used. When the surface is strained, the lozenge rotates and this rotation is read on the scale of an autocollimator. The scale is calibrated to read in micro strain. An elongation as low as 50×10^{-6} mm is measurable.

PHOTOELASTICITY

Photoelasticity is an important method of experimental stress analysis of irregular shaped members which may be subjected to load conditions such that mathematical calculations of stress levels is difficult if not impossible. The technique has been successfully used for problems involving three-dimensional geometry. Photoelastic analysis provides quantitative values for highly stressed areas at the surface and interior parts of a member. It has been the most common method used to establish the stress concentration factors for machine members having a discontinuity such as a hole or a change in shape.

The principle of photoelasticity depends on the property of certain transparent plastics (or photoelastic materials) known as birefringence or double refraction. When a photoelastic model is stressed by an external load and monochromatic light enters the

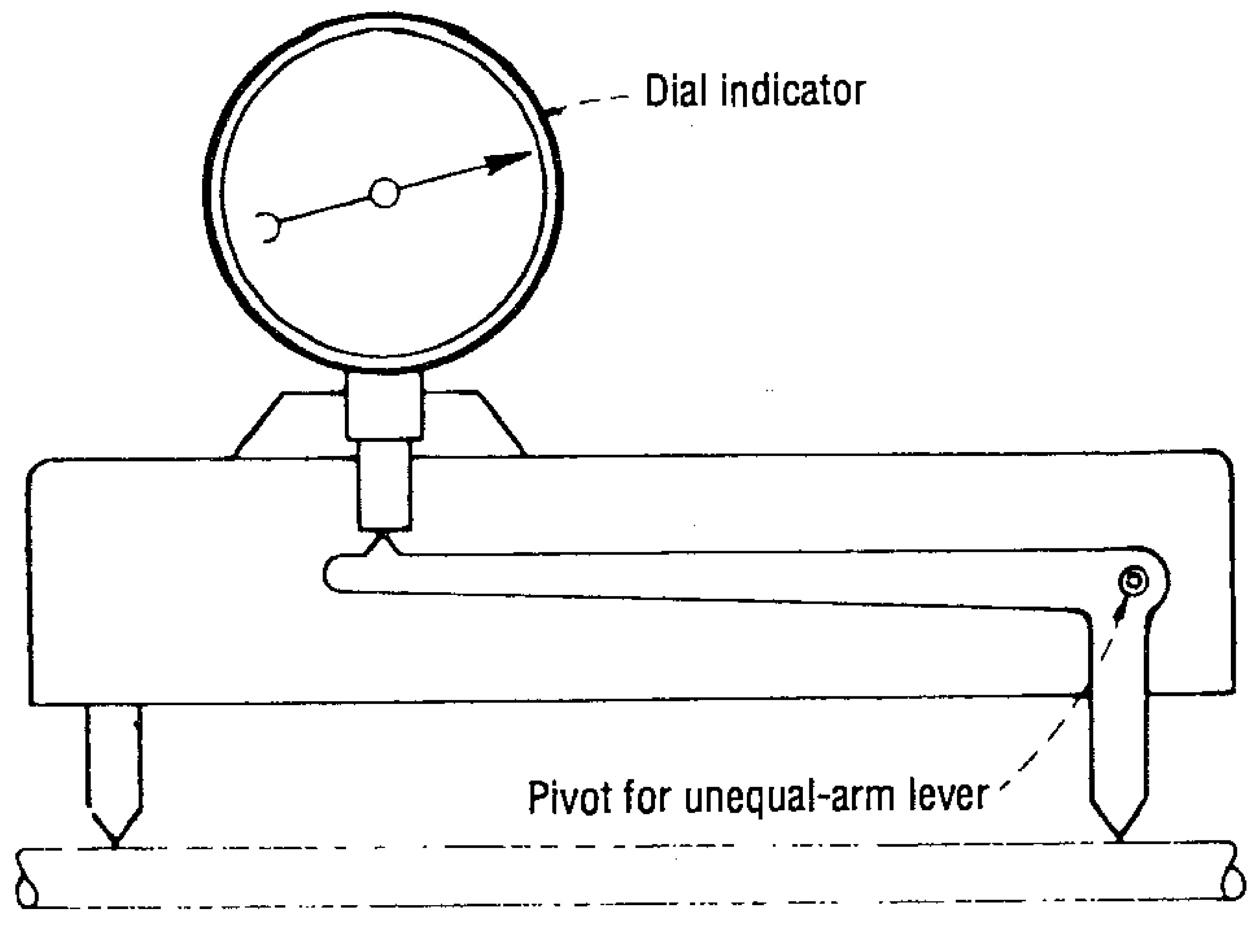


Figure 4–Mechanical strain gage (R. H. Prewitt from Kobayashi).

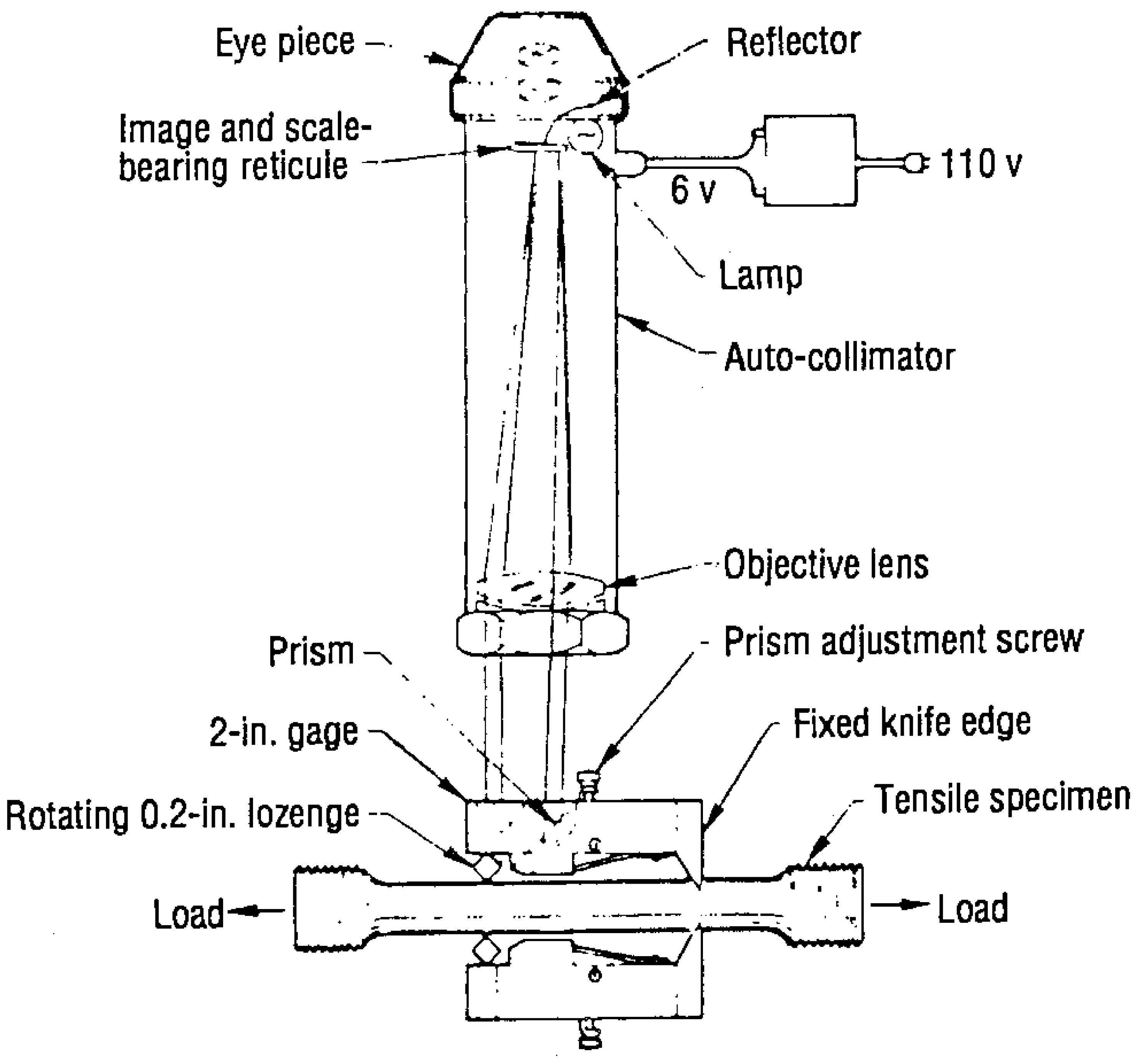


Figure 6–Tuckerman optical strain gage.

model along one of the directions of principal stress, the light is divided into two components. These two component waves of light travel through the model each with its plane of vibration (polorization) parallel to one of the two remaining principal planes. The light also travels along these two paths at different velocities. The relative magnitude of the velocities is proportional to the difference in the magnitudes of $\sigma 1$ and $\sigma 2$. This variation in velocity of the two waves causes them to emerge from the model with a new phase relationship or relative retardation. By means of a circular polariscope, a pattern of light and dark bands, called fringes, are formed on the model under load. The number of bands or fringe order, N, increases in proportion to the external forces. These patterns from which the value of N can be observed for the entire model, are called isochromatic patterns.

The isochromatic pattern is related to the difference in magnitude of the principal stresses by the stress-optic law:

$$\sigma_1 - \sigma_2 = \frac{fN}{t} \qquad (1)$$

where

- f = the stress-optical coefficient, a constant that depends upon the model material and the wavelength of the light used,
- t = the model thickness,
- N = the relative retardation of rays forming the pattern, i.e., the isochromatic fringe order.

Application or use of photoelasticity requires a comprehensive knowledge of the theory and techniques involved, especially when dealing with three-dimensional problems. The reader is referred to textbooks or other references such as Lee (1950), Dally and Riley (1965) and Kobayashi (1978), before considering this method of stress analysis.

Grid Techniques

Grid techniques of strain measurement consist of mounting a grid pattern on the surface and then measuring the deformation of the grid. This is another example of "whole field" strain measurement. The grids are usually formed on the surface by photographic printing or by cementing a grid network to the surface. For crude measurements, hand scribing may be used. After straining, the grid dimensional changes may be measured with a micrometer microscope.

A recent development related to the grid technique is the moire fringe method. This method of strain analysis is particularly useful for measurements of large elastic and plastic strains on thin films and low-modulus materials. A fine grid, often 100 lines (and spaces) /mm, is cemented to the surface to be strained. A master grid of the same line density is then placed over the mounted grid. Before loading, no fringes will occur, but with load a fringe pattern appears. The greater the number of interference fringes per unit length, the greater the strain level. An excellent treatise of the moire method is given by Chiang in the Manual of Experimental Stress Analysis, edited by Kobayashi (1978).

The principal advantage of the moire fringe technique over grid methods is that no instrument is required. It is only necessary to measure the distance between fringes, however, two sets of grids are required. Both the grid and the moire fringe method are best suited for strain measurement on materials which undergo large or plastic strains. Shear strain as well as normal strain may be measured, as shown by Dove and Adams (1964).

Miscellaneous Methods

PVDF. A new kind of piezoelectric material—high Poly-Vinylidene Film (PVDF)—has been developed by the Pennwalt Corporation. The KYNAR™ piezoelectric films are pliant, flexible, and light-weight. The film is easily fabricated to make transducers, as it can be cut and formed, and glued with common adhesives. The important advantages of the film include:

- High mechanical strength,
- Wide frequency range,
- High output voltage,
- Wide operation temperature and, especially,
- Low cost, make it suitable for many applications.
- The voltage output is 10 times higher than piezo ceramic for the same force input.

These films are being used as transducer elements for the measurement of particle impact (e.g., grain), displacement and pressure in agricultural, industrial, and medical applications. A number of applications have been given in the technical manual† by Pennwalt Corporation on KYNAR™ piezo film.

Holography. This method is a technique which involves a double exposure on film. Unstrained parts are photographed, then a second exposure on the same film is made with the specimen loaded. The resulting double-exposure hologram shows interference fringes similar to those formed in photoelasticity. Holography as an experimental stress analysis technique is presented by Taylor in the Manual of Experimental Stress Analysis, edited by Kobayashi (1978).

X-Ray Diffraction. When a beam of X-rays of known wave length is directed onto a member under load, the reflected rays can be recorded in a way that indicates the spacings between planes of atoms. The spacing is changed by the applied load or by residual stress. This method is valid only for crystalline materials and only to a depth of about 0.025 mm. The chief advantage of the method is that residual surface stresses can be measured without damaging the part.

Each method of strain measurement and, in fact, each particular piece of strain-measuring equipment has certain advantages, disadvantages and limits of accuracy as summarized in Table 4. The adaptabilities and limits of measurement of the various strain measuring methods are summarized in Table 5.

EXAMPLE 1. Two strain gages are mounted on a grain bin wall, one in the circumferential direction and the other in the longitudinal direction. The bin wall is made of galvanized steel with a modulus of elasticity of 200 GPa and a Poisson ratio of 0.3. The circumferential and longitudinal measured strains were 66 and 39 microstrains. What are the corresponding values of the stresses?

SOLUTION Stresses in grain bin walls will always be biaxial because of the friction load carried by the bin wall. If the bin were filled with water or any other liquid product, there would be no friction load on walls. For calculation of corresponding stresses, we have to use formulae for biaxial stresses.

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†KYNAR Piezo Film Technical Manual. 1987. Pennwalt Corporation, Valley Forge, PA.

TABLE 4. General advantages and disadvantages of major strain methods

Method	Advantages	Disadvantages
Mechanical	Completely self-contained. Relatively inexpensive. Direct and convenient reading.	Errors due to friction, inertia, flexibility, etc. Bulky.
Optical	Frictionless, inertialess. Good for remote and inaccessible readings if mirrors can be used.	Relatively expensive. Delicate. Lacks versatility. Difficult to keep adjusted.
Surface coating techniques		
(a) Brittle lacquer	A "whole field" technique shows relative magnitudes & directions of principal strain.	Accuracy only to within 10 to 20%. Temperature, humidity sensitive.
(b) Photostress	Stresses of a part under actual load can be determined. No model required as with photoelasticity.	Relatively expensive instruments are required for analysis.
Grid techniques	Moire fringe method requires no expensive instrumentation.	Suitable mainly for low modulus materials - plastics, rubber, wood.
Photoelasticity	Excellent method to establish stress concentration factors for machine members with discontinuity (hole, fillet, etc.).	Requires plastic model, expensive equipment.
Unbonded: wire resistance	Highly accurate and sensitive instrumentation and techniques readily available. "Zero gage length" possible. Temperature compensating.	Difficult to apply (compared to bonded-wire gage). Zero drift.
Bonded: electrical resistance	Highly accurate and sensitive instrumentation and techniques readily available. Very inexpensive. (Necessary instrumentation quite expensive.) Easy to apply. Many types and sizes available.	Temperature sensitive (quite easily corrected). Long-term installations tend to creep due to humidity and other factors.
Bonded: semi-conductor strain gages	High output because of high gage factor; less interference from "noise" signals. No amplification required.	Requires relatively complex compensating network to offset temperature and non-linearity problems.

$$\sigma_x = \frac{E}{1-\mu^2}(\epsilon_x + \mu\epsilon_y)$$

$$\sigma_y = \frac{E}{1-\mu^2}(\mu\epsilon_x + \epsilon_y)$$

$$\sigma_x = \frac{200 \times 10^9 \frac{N}{m^2} \times (66 + 0.3 \times 39) \times 10^{-6}}{1 - (0.3)^2}$$

$$= 17.1 \times 10^6 \frac{N}{m^2} = 17.1 \text{ MPa}$$

$$\sigma_y = \frac{200 \times 10^9 \frac{N}{m^2} \times (0.3 \times 66 + 39) \times 10^{-6}}{1 - (0.3)^2}$$

$$= 12.9 \times 10^6 \frac{N}{m^2} = 12.9 \text{ MPa}$$

Electrical Resistance Strain Gages

Since its appearance about 1940, the electrical resistance strain gage has become the most important method of measuring strain. This strain gage is relatively inexpensive, accurate, small in size and mass, with excellent frequency response. Of all strain measuring techniques available, the electrical resistance strain gage best approaches the ''ideal'' strain gage for stress analysis work as listed by Perry and Lissner (1962):

1. Extremely small in size.
2. Of insignificant mass.
3. Easy to attach to the member being analyzed.
4. Highly sensitive to strain.
5. Unaffected by temperature, vibration, humidity or other ambient conditions likely to be encountered in testing machine parts under service loads.
6. Capable of indicating both static and dynamic strains.
7. Capable of remote indication and recording.
8. Inexpensive.
9. Characterized by an infinitesimal gage length.

These factors would all be of importance for an ''ideal'' general purpose gage. In practice, compromise is necessary. The factors on which to compromise depend on the particular application.

Principle of Operation

Two basic forms of the resistance strain gage are the bonded and unbonded types. The bonded electrical resistance strain gage consists of a grid of fine wire or metallic foil bonded to a suitable backing which in turn is cemented to the specimen under test (or to the elastic member in the case of a transducer). Strain in the specimen is transmitted to the gage. Tension in the part under the gage causes an increase in gage resistance due to a decrease in cross-section of the strain gage grid. Likewise, compression in the member causes a decrease in gage resistance. The unbonded strain gage is used principally in transducers. It usually consists of wires connected to an armature and frame assembly. The armature is moved in proportion to the variable (force, pressure)

TABLE 5. Special adaptabilities of major strain measuring methods

Method	Suitable Application	Measurement Limit
Mechanical	Laboratory work on properties of materials. Long-term measurements in large structures, such as bridges. Static strain measurements.	10×10^{-6} mm/mm.
Optical	Dynamic strains to 150 Hz. Static strains. Laboratory.	2×10^{-6} mm/mm.
Surface coating techniques		
(a) Brittle lacquer	Most suitable in atmosphere of controlled temperature and humidity but can be used in field. Metallic, irregular-shaped parts where strain level cannot be calculated.	400×10^{-6} mm/mm to 100×10^{-6} mm/mm with special techniques.
(b) Photostress	For study of surface stresses on actual parts (static & dynamic).	Approximately 100×10^{-6} mm/mm.
Grid techniques	Low modulus materials.	Varies with grid pitch.
Photoelasticity	Two and three dimensional stress analysis.	Depends greatly on plastic used in model.
Unbonded: wire resistance	Displacement. Where short gage length is needed.	1×10^{-6} mm/mm.
Bonded: electric resistance	Most widely used in all strain gages. Range of application seemingly endless.	1×10^{-6} mm/mm.
Bonded: semi-conductor	Small transducers.	10×10^{-6} mm/mm.

being measured. The resistance change is accomplished by pinning the wires to the armature and frame so that two wires (or sets or wires) are shortened and two wires (or sets of wires) are lengthened. These wires are connected electrically into a Wheatstone bridge circuit. The following discussion will apply to the more common bonded strain gage.

The gage factor, F, is an index of the strain sensitivity of the gage, and is defined as:

$$F = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\epsilon} \qquad (2)$$

where

ΔR = change in gage resistance (ohms),
R = initial gage resistance (ohms),
ΔL = change in gage length (mm),
L = initial length of the strain gage filament (gage length) (mm),
ε = strain (mm/mm).

Strain gages can be bonded to almost any solid material if the surface of the material is properly prepared. Cleanliness in gage mounting is of utmost importance. All open surfaces must be thoroughly and freshly cleaned prior to gage installation, otherwise the surfaces must be considered contaminated. Five basic steps are generally necessary for proper surface preparation. These are solvent degreasing, abrading, application of gage layout lines, conditioning, and neutralizing. This preparation will produce a chemically clean surface having a roughness appropriate to the gage installation requirements with a surface alkalinity of at least 7 and visible gage layout lines for locating and orienting the strain gage. Detailed instructions for surface preparation and gage mounting are provided by manufacturers.

BONDED GAGE TYPES

Original electrical resistance strain gages were made of a fine wire in a wrap-around construction (fig. 7). These gages were then replaced by the flat grid construction. Grid wires are

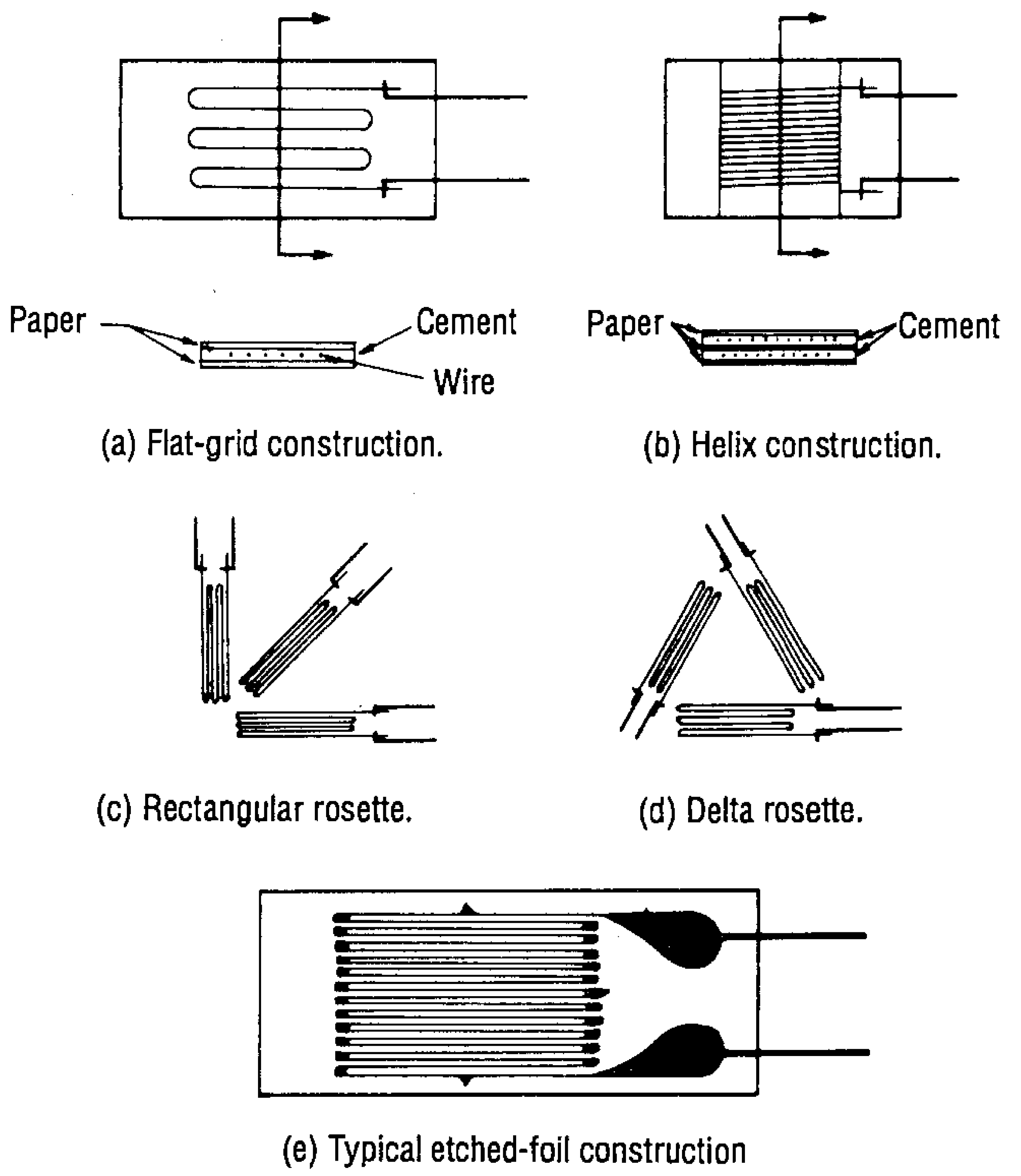

Figure 7–Early wire gages, rosettes, and foil gages.

DISPLACEMENT, VELOCITY, ACCELERATION, AND SOUND

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INTRODUCTION

The measurement and evaluation of displacement, velocity, acceleration, and sound are frequent problems faced by engineers and scientists. The need for displacement measuring equipment can be cited for most areas of agricultural engineering. Evaluations of displacement are used in all phases of engineering; research, development, design, and quality control. Some examples are: dimensions of machine parts, deflection of structural components, vibratory motion of a machine parts; such as an internal combustion engines or tractor operator's seats; and dimensions of agricultural products, such as fruits and vegetables for size determination. In other measurement situations, transducers convert a parameter, such as force or pressure to displacement. As a result, displacement measurement is an intermediate step in evaluating these parameters.

Measurement of displacement involves either linear or angular measurement. The former is the most commonly measured, although angular displacement is needed in determining shaft rotational position and speed. Special design considerations must be made for each type of measurement and will be discussed later.

Static and dynamic displacement is another method of categorizing this parameter. In the static measurement, the parameter is relatively constant with time and can be evaluated directly with a scale or micrometer. In the dynamic case, velocity or acceleration is often the measured parameter which is integrated electronically to obtain displacement. A transducing device sensing time varying displacement and velocity is referred to as a vibrations pickup or vibrometer. The term accelerometer is used for a transducer having an output proportional to acceleration.

In the dynamic case, motion is often harmonic; as a result it can be represented by a single harmonic wave or the sum of several harmonic component waves. The single integration of velocity and double integration of acceleration provide a signal which is proportional to displacement. For an example of a simple harmonic motion:

$$x(t) = A \sin(2\pi ft)$$

where
- $x(t)$ = time dependent displacement,
- A = amplitude of vibration, and
- f = frequency of vibration.

Differentiating the above equation with respect to time results in:

$$v(t) = \frac{dx(t)}{dt} = A(2\pi f)\cos(2\pi ft)$$

where
- $v(t)$ = time dependent velocity.

To obtain acceleration, differentiation of time dependent velocity is performed, resulting in:

$$a(t) = \frac{d^2x(t)}{dt^2} = -A(2\pi f)^2 \sin(2\pi ft).$$

Since many transducers convert acceleration and velocity to an electric signal, electronic circuitry is readily available to carry out the necessary integration to obtain a signal proportional to displacement. In the majority of the dynamic cases, acceleration is sensed and integrated twice to obtain displacement. In some cases, velocity is the desired parameter but only a displacement transducer is available. The signal from the displacement transducer can be differentiated using electronic circuitry, but the accuracy using this approach is limited.

Velocity measurement is important when the linear or rotational speed of some machine or machine component is desired. In mechanical power studies, the speed is necessary to determine the power transmitted. Many modern tractors and combines have speed sensor systems which provided the operator with information regarding equipment operation.

Acceleration measurement is also important in machine testing because it is an indication of the vibratory force exerted on the machine components. High levels of acceleration will indicate high forces.

An awareness of the sound effect on the health of people, both hearing loss and work stress has increased the availability of sound level meters. Farm equipment manufacturers have designed operator's positions with reduced noise levels. Federal laws specify maximum noise exposure levels for employees, therefore, agricultural engineers must be aware of sound measurement with respect to their production designs and to the environment of the employees within their organization.

DISPLACEMENT MEASUREMENT

Many displacement transducers convert a mechanical displacement signal to another form of signal which can be transmitted to an amplifying and recording system. This leads to grouping displacement transducers by the type of output. The most prevalent displacement tranducers have an electric output, but many of the earlier devices have a mechanical output.

Displacement transducers can be quite varied, from complex units costing from several hundred dollars to a simple strain gage unit constructed in any laboratory. Also, the range of displacement may vary from 0.002 mm for tool or machine part measurement to distances in excess of a hundred meters. As a result, displacement tranducers are specialized from the standpoint of range and accuracy.

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Mechanical Displacement Transducers

The most common displacement measuring device used for static measurement is a scale or ruler, utilizing direct comparisons. Increased accuracy can be obtained through mechanical amplification such as a dial indicator. This device is used extensively in machine shop work to determine dimensions. Also used quite extensively in the shop are verniers and micrometers for obtaining dimensions of machine parts. The dial indicator can be utilized in dynamic measurement when only the amplitude of vibration is the parameter of interest and not frequency and wave form. In comparison with other dynamic displacement transducers, the frequency range for satisfactory operation of a dial indicator is relatively low and dependent on indicator characteristics, such as mass of the moving parts and its spring constant. The dial indicator consists of a rack and pinion gear system or some other system of gears to obtain mechanical amplication as shown in figure 1. In other transducers, a series of other mechanical linkages may be used to obtain mechanical amplification. In many pressure gages, the linear displacement of the bourdon tube is amplified and converted to a rotatory motion for observation. Often dial indicators are used in force sensing such as proving rings to sense the deflection of the ring under load. The resultant displacement is directly related to the force (Beckwith and Buck, 1969).

Measurements with dial indicators, verniers and micrometers can usually be made to the 0.01 mm. If greater accuracy is required, measuring equipment should be calibrated with respect to gage blocks. These are dimensionally stable and made of hard steel or other materials. Blocks having accuracies of 0.2 µm are readily available. More accurate blocks can be obtained. In any case, gage blocks can be sent to the National Bureau of Standards for highly accurate calibration (beyond 0.01 µm).

Electrical Displacement Transducers

A major portion of the dynamic displacement transducers on the market today convert a change in displacement to some change in an electrical parameter, such as resistance, inductance, or capacitance. This change can be converted to a voltage or current change which is relatively easy to transmit long distances to amplifying and recording systems.

Variable Resistance Transducers. One of the earlier and more simple resistance displacement transducers was the slide wire potentiometer, shown in figure 2. These transducers may be designed for linear or angular displacement.

This transducer has three terminals, one at each end of the resistance coil and a third one attached to a wiper. Electrical contact is maintained between the wiper and resistance element. The wiper is mechanically linked to the system under investigation for displacement. The resistance between the wiper and one terminal is directly proportional to the position of the wiper.

In most cases, the resistance element is formed by wrapping the resistance wire around a form made of some nonconducting material. The turns are spaced to prevent shorting. A constant voltage is applied across the extreme terminals of the resistance element and the output voltage is obtained from one of the element terminals and the wiper. The relationship for the output voltage is:

$$E_{out} = \frac{R_w E_{in}}{R_t}$$

where

E_{out} = output voltage,
R_w = resistance between the wiper and one terminal,
R_t = total resistance of the resistive element, and
E_{in} = input voltage.

The resistance (R_w) will be directly proportional to the displacement of the wiper.

A slide wire potentiometer was utilized in studies by Ashcroft and Kjelgaard (1972) to sense the displacement of the loading device used to evaluate creep properties of forages. The wiper of the potentiometer was mechanically linked to the movable crosshead of the loading device. The resistance element was fixed to the base of the machine.

The linear potentiometer is particularly adaptable to the range from 0.25 cm to several centimeters with resolution down to 0.0025 cm. The magnitude of the resolution is equal to the reciprocal of the number of windings per centimeter. For example, if there are 100 windings or turns per centimeter, the resolution is 0.01 cm. Therefore no matter how well refined the remainder of the measuring system, it is impossible to improve the precision of the measurement beyond this level. The system may be somewhat nonlinear as the wiper is moved across the windings. This non-linearity is dependent on the number of windings per centimeter and size of the wiper.

For angular displacement, the wire is wound on a form having a circular shape. Many rotary rheostats used as variable resistors are quite similar in construction. Again, the accuracy is dependent on the number of turns and the diameter of the form. Nonwire wound resistance elements are available which provide improved resolution and life but are temperature sensitive and can tolerate only moderate wiper currents. Materials in these devices include plastic and a mixture of ceramic and metallic materials. No matter which type of transducer, the voltage must be limited to the manufacturer's specifications. Often excessive

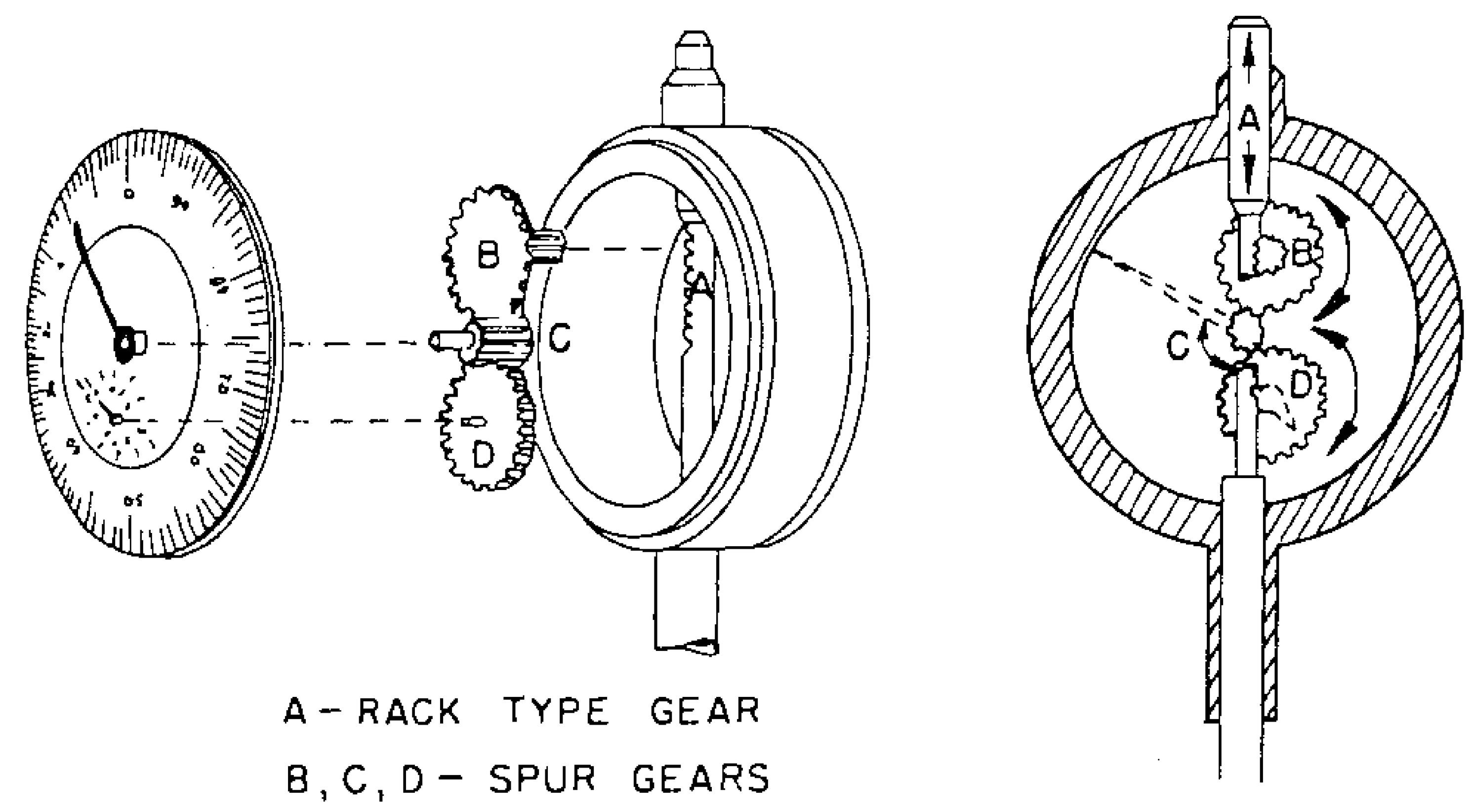

Figure 1–Dial indicator.

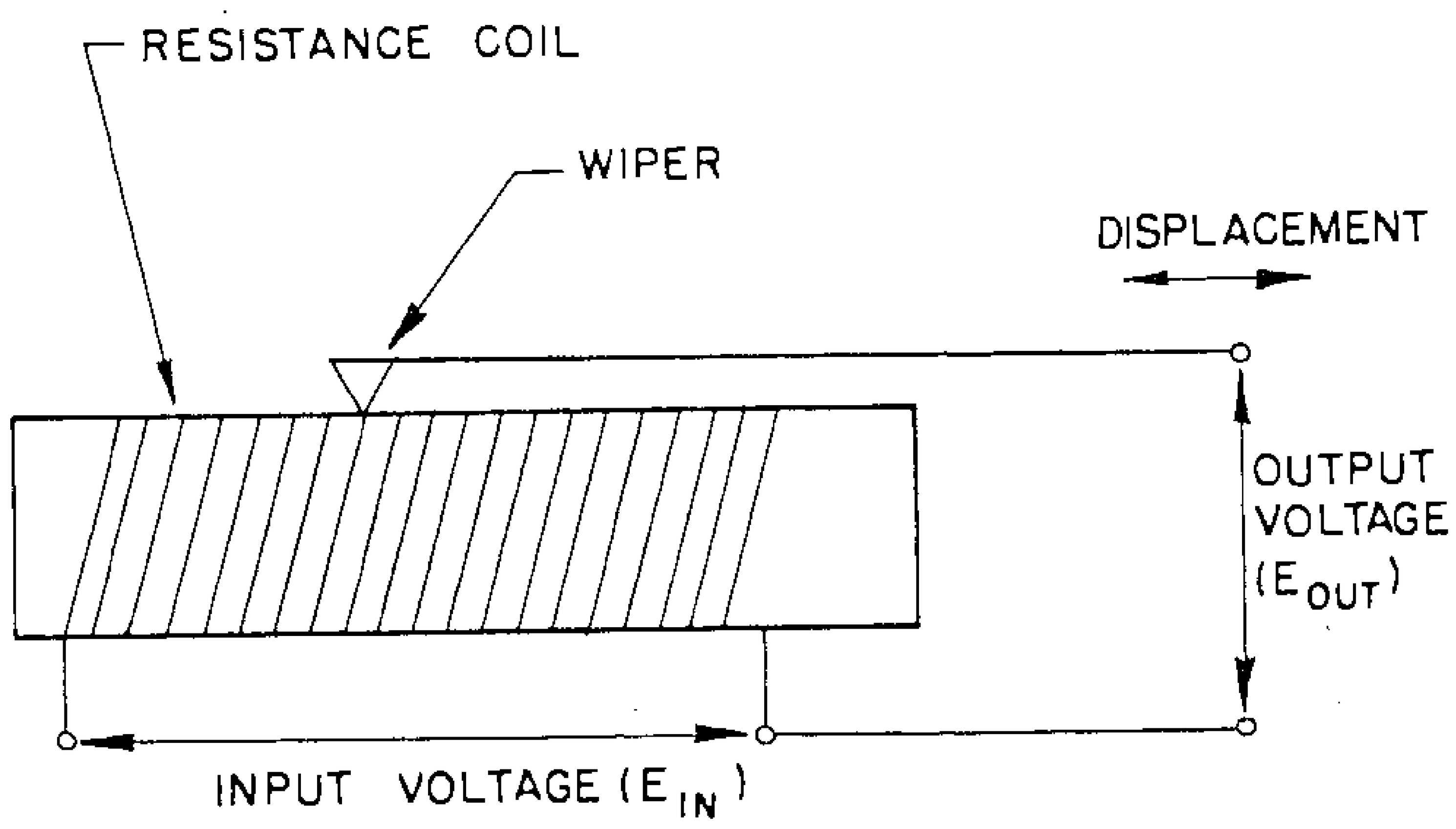

Figure 2–Potentiometric displacement transducer.

voltage is used to increase transducers output, but the result may be a damaged transducer.

Another variable resistance displacement transducer consists of a flexible cantilever beam with strain gage elements, either wire or foil, mounted near the base. The free end of the beam is mechanically linked to the object being studied for displacement. As the free end of the beam is displaced the resistance of the gage will change proportionately (Perry and Lissner, 1962). This transducer, as shown in figure 3, is easily designed and fabricated in any laboratory. Thompson et al. (1972) while studying the dynamic response of agricultural tires, used this design for a transducer to sense the displacement of a wheel hub. Other elastic elements, such as diaphragms, can be used for displacement measurement, and are used commercially in force and pressure transducers. In the case of pressure transducers, one side of the diaphragm is exposed to the fluid pressure, and strain gages are mounted on the opposite side. A detailed discussion of pressure transducers is considered in another section of this text. The range and accuracy may be controlled by the physical dimension of the elastic element and the number of active strain gages.

Strain gages may also be used to sense very small displacements directly in the form of strain which is discussed in Chapter 2. A device commercially available utilizes unbonded strain gages to measure small displacements of a pressure sensitive diaphragm and elastic force sensitive device.

In cases where extreme accuracy is needed, piezoresistive strain gage elements can be used. They are constructed of semiconductor material which has a large gage factor relative to the wire or foil gages previously discussed (Lommatsch, 1971).

Variable Inductance Transducers. A number of different forms of variable inductance transducers are available commercially, but only the more common units will be discussed. The most common is the linear variable differential transformer (LVDT). The inductive impedance of a coil is expressed by:

$$X_L = 2\pi fL,$$

where

X_L = inductive impedance, and
L = inductance.

An example of a simple self inductance displacement transducer is shown in figure 4. The coil is wrapped around the base of a magnetic U-shaped core. The armature, as shown in figure 4 is separated by an air gap from the core. The armature position with respect to the core is proportional to the displacement being studied. As the distance between the core and armature is changed, the permeability of the flux path is also changed, which results in a proportional change of the inductance of the coil. Based on the above relationship for an inductor, the inductive impedance is also changed. With an AC

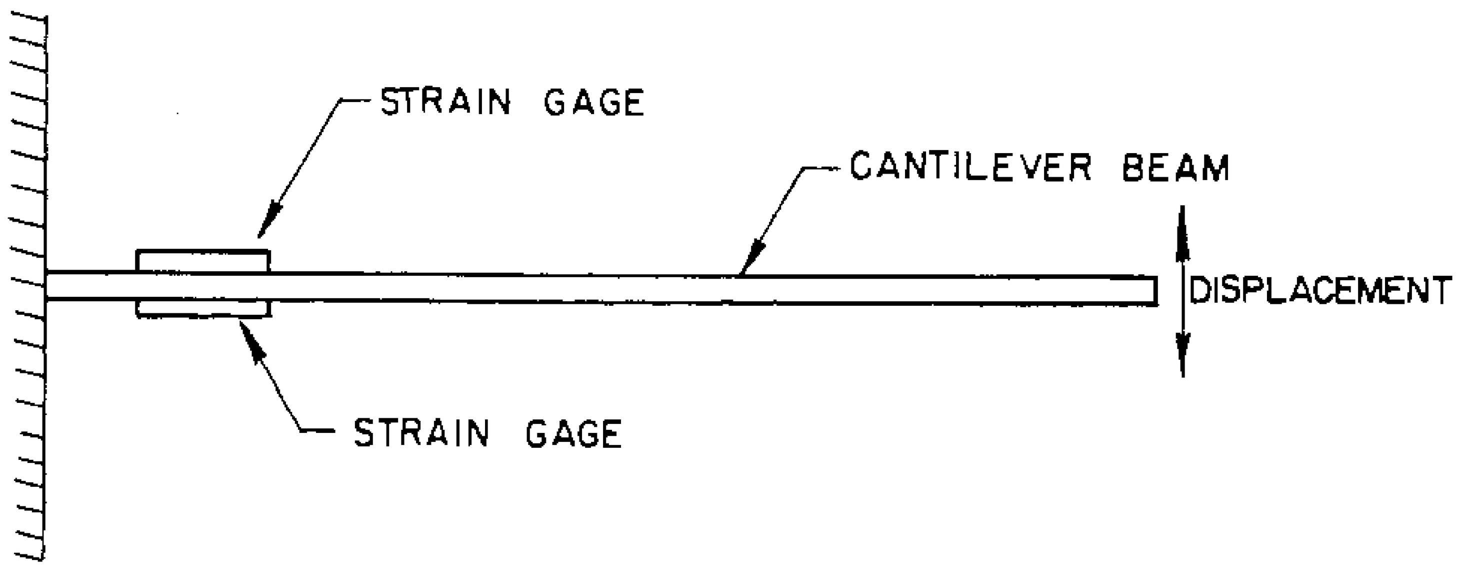

Figure 3–Cantilever beam, strain gage displacement transducer.

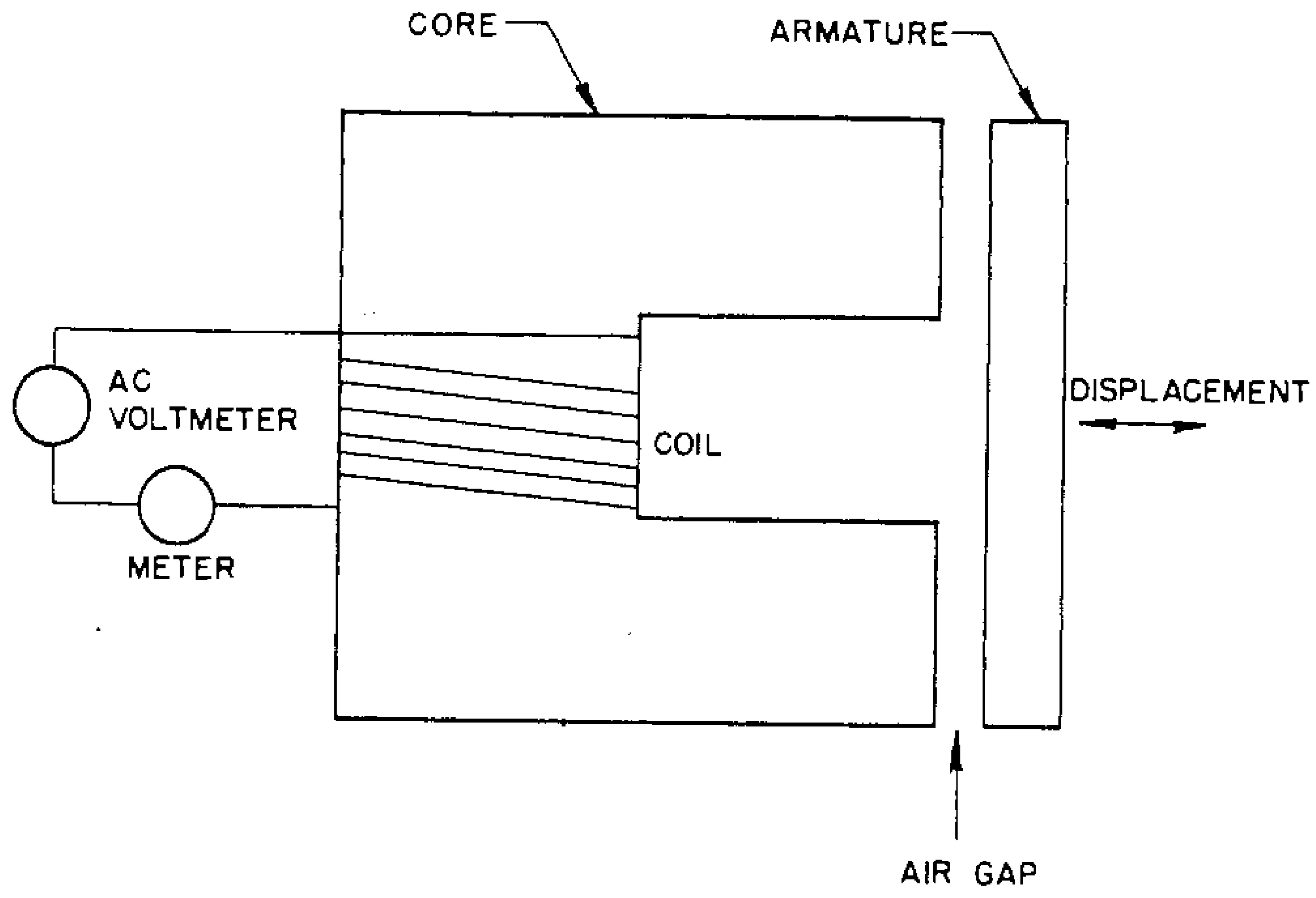

Figure 4–Simple self-inductance displacement transducer.

voltage applied to the inductive coil, the resultant current through the coil will be directly related to the displacement of the armature. In some cases, the armature may be a component of the system being tested, but may be some ferrous object attached to the system (Neubert, 1963). The commercially available inductive device utilizes a single coil which has a AC current. The position of a metal target within a magnetic field will affect the coil's inductive characteristics (Kaman, 1979). Another type of self inductance displacement transducer, as shown in figure 5, has two coils or a center tapped single coil. A iron core is located in the center of the coils and is moved parallel to the central axis of the coils. The position of the core relative to the coils is determined by the displacement being investigated. The movement of the core changes the inductance in the coils such that, movement of the core in one direction will reduce the inductive impedance of one coil and increase the inductive impedance in the other coil. Movement of the core in the opposite direction results in a converse change of the inductive impedances of the coils. A center position exists where the inductive impedances of the coils are equal. These two coils often form half of a four arm inductive bridge of the measuring system. The output of this AC bridge is proportional to the inductive impedance ratio of the two coils. This ratio is proportional to the displacement of the core (Beckwith and Buck, 1969).

Mutual inductance transducers consist of two or more coils and two electrical circuits. The input voltage is applied to one coil and an output voltage is induced into the remaining coil or coils. A common example of a mutual inductance transducer is the linear variable differential transformer (LVDT), shown in figure 6. The LVDT has a center primary winding with an applied input voltage and two similar secondary windings. The magnetic coupling between the primary and secondary coils can

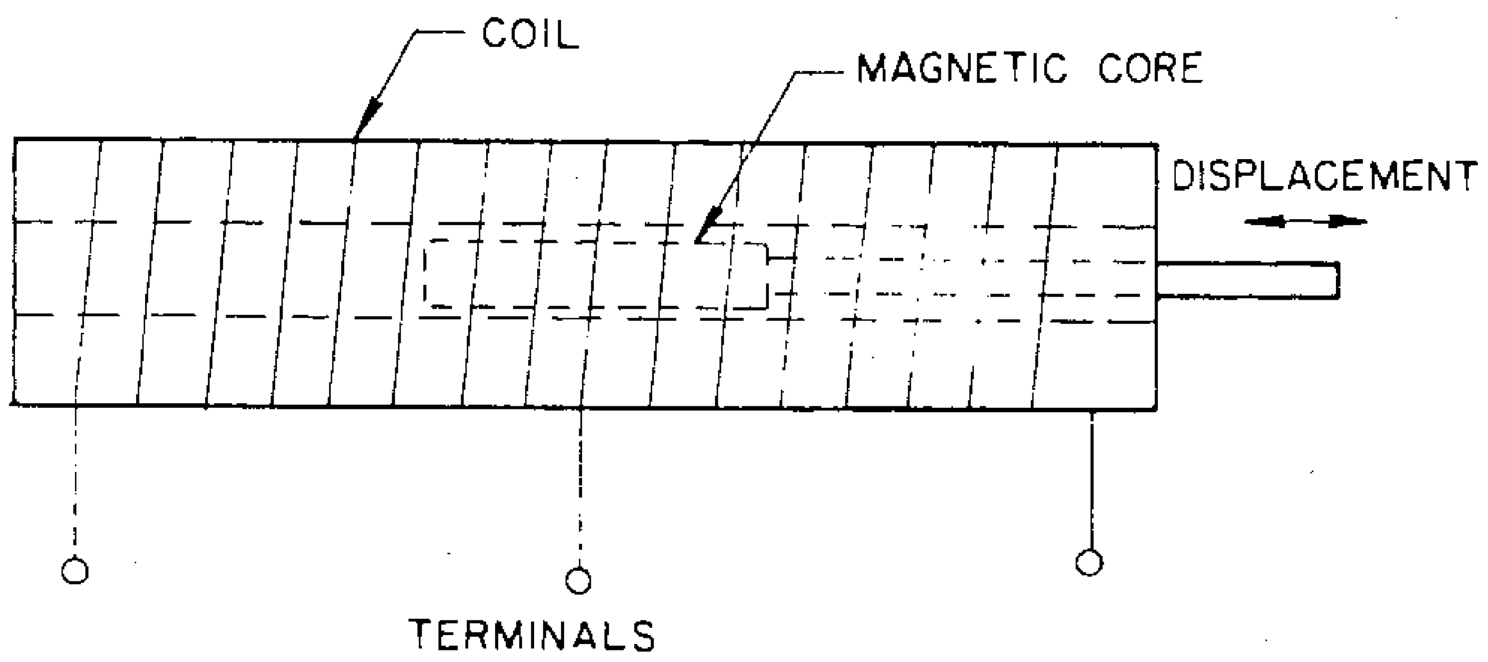

Figure 5–Center tapped, self-inductance displacement transducer.

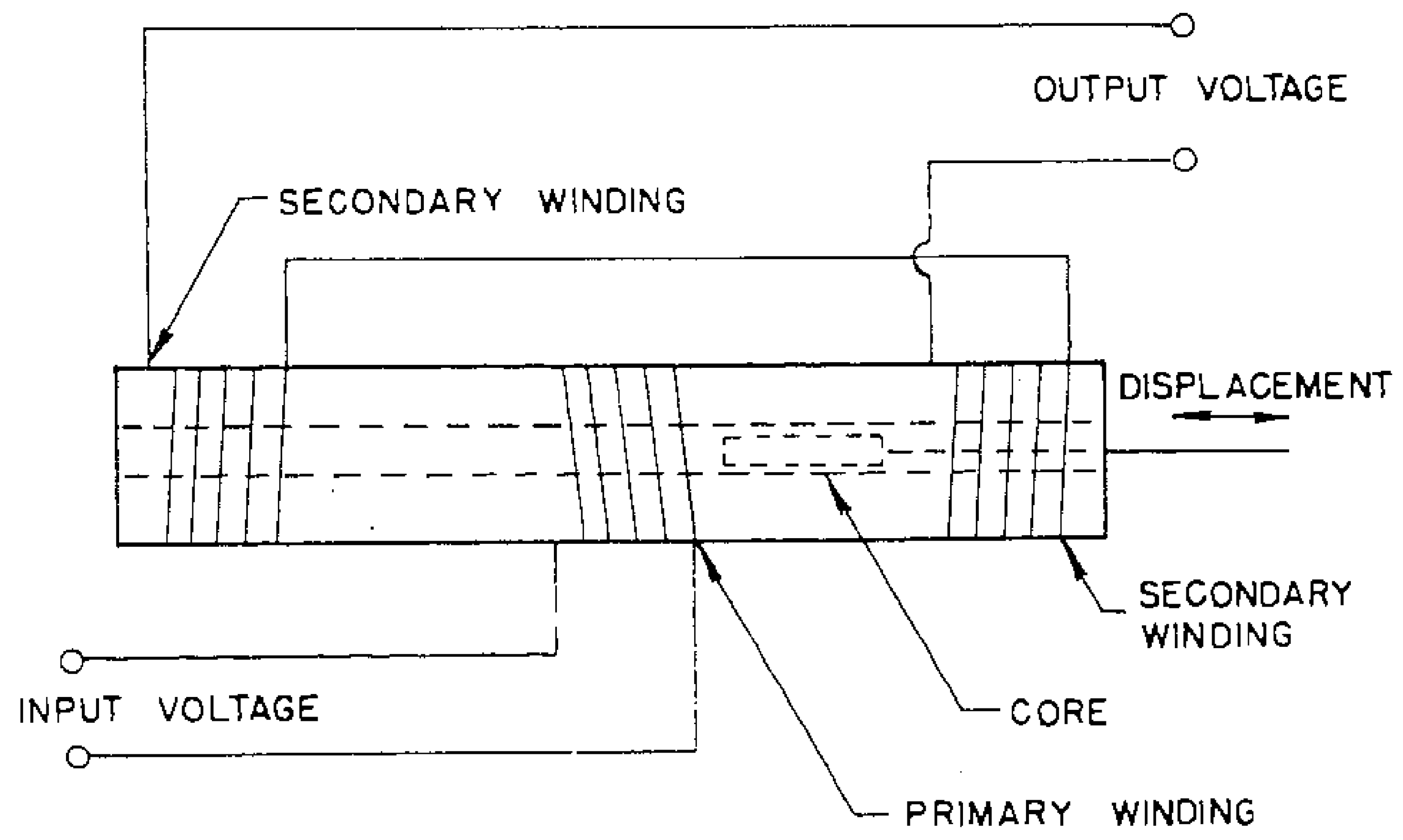

Figure 6–Differential transformer displacement transducer (LVDT).

be varied by movement of a ferrous core. The coupling results in induced voltages in each of the secondary coils which are connected in phase opposition. As a result, there exists a core position such that the voltages in these two coils are equal and 180° out of phase which results in the output voltage of the LVDT being zero. When the core is moved to either side of the zero position, the magnetic coupling will be increased in one secondary coil and decreased in the other coil in proportion to the cone position. The output polarity will depend on the direction of core movement and is compared to the polarity of the AC input voltage. If movement in one direction from the center position results in a signal in-phase with the primary voltage, the movement in the opposite direction from center will produce a signal out-of-phase with the primary voltage (Ambrosius et al., 1966).

Many commercially available LVDTs require 6.3 V (AC) for the input and have an AC output which must be discriminated with respect to the phase of the input voltage. A carrier amplifier is often used to obtain an output reading from an AC LVDT. The amplifier supplies an AC controlled input voltage and provides a discriminator system to obtain the phase relationship between the input and output of the LVDT and rectifies the AC output of the secondary coils.

With some commercially available LVDTs, a modulator, rectifier, and phase discrimination circuit are built into the transducer. The net result is: DC voltage is required as the input and the output is a DC signal. The modulator converts this DC input into an AC voltage required in the primary coil. The AC output of the secondary coils is converted to DC through the rectifier and given a polarity through the phase discrimination circuitry. As a result, care must be taken when selecting an LVDT to insure the desired unit (AC or DC) is obtained. The DC unit is more compatible with recorder or other output devices. Input voltages range from three to six volts and maximum output voltage is often up to 60% of the input voltage.

Smith et al. (1972) used an LVDT to sense the displacement of a vibratory tillage tool during field operation. The field results were used to substantiate a theoretical analysis of the vibratory system.

The displacement range for many LVDTs on the market is from over 40 cm to 0.0002 cm. Normal sensitivity is 0.6 to 30 mV/0.0025 cm. Some advantages of an LVDT over other displacement transducers are insensitivity to temperature, a comparatively high output and impossibility of being mechanically overloaded. The mass of the core restricts the use of the LVDT in some dynamic cases such as high frequencies. The magnetic coupling adds to the inertia force in dynamic cases (Minnar, 1963). Another factor to consider is the excitation frequency which should be at least ten times the measured frequency (Schaevitz Engineering, 1971). For example, if the excitation frequency is 60 Hz, the measured frequency should be less than 6 Hz. Many LVDT with frequency modulator will have frequencies as high as 10,000 Hz.

Rotary variable differential transformers (RVDT) are also available where the coils are shaped in a circular pattern and the core path is circular. A sensitivity of 10 to 20 mV/degree is available.

Variable Capacitance Transducers. As with the inductance transducers there are a number of forms for capacitance units. The electrical impedance of a capacitor is expressed by:

$$X_c = \frac{1}{2\pi fC}$$

where
X_c = capacitive impedance, and
C = capacitance.

The relationship for the magnitude of the capacitance is influenced by various parameters shown by the following equation:

$$C = \frac{0.244\,KA\,(N-1)}{d}$$

where
K = dielectric constant,
A = area of one side of one plate,
N = number of plates, and
d = distance between plate surfaces.

For use as a displacement transducer, the distance between the plates is the most commonly varied parameter (Cook and Rabinowisz, 1963). Change in the dielectric constant is used in determining liquid level. As shown in figure 7, the liquid is the dielectric media between the two electrodes. As the liquid level is changed, the dielectric constant is changed which results in a

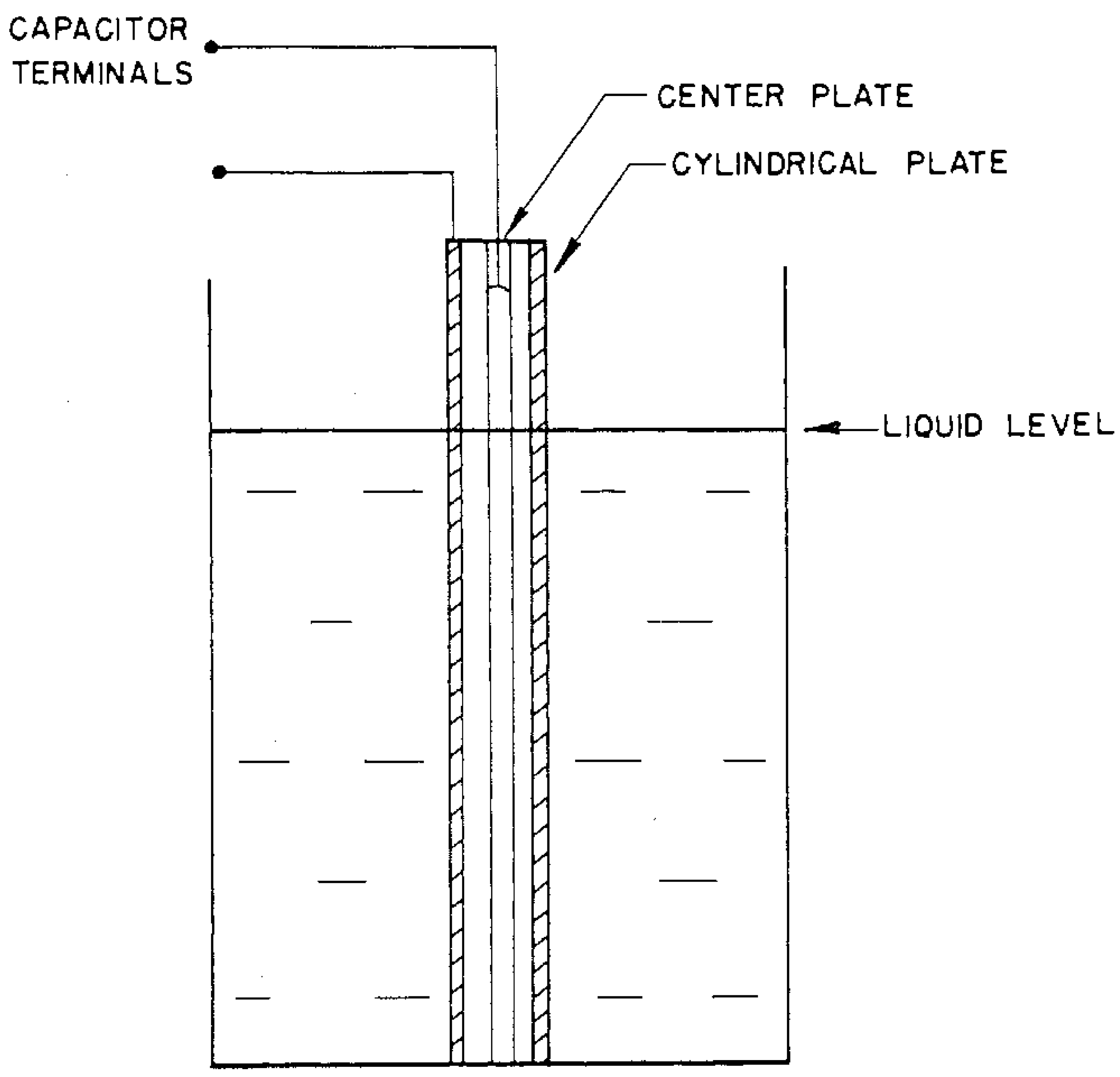

Figure 7–Capacitance liquid level transducer.

variation of the capacitance as reflected in the above equation. By using some electrical system to sense capacitance, the liquid level can be determined after calibration (Beckwith and Buck, 1969).

Figure 8 illustrates a capacitor type transducer where the change in area of the capacitor plates is proportional to the displacement of the movable teeth. As the upper teeth move to the left, the capacitor area is increased until both sets of teeth match, and as they are moved to the right the area is decreased. For this arrangement, linear displacement is determined, but in a similar manner teeth can be cut on a shaft for angular displacement measurement (Lommatsch, 1971).

Problems with these transducers are high impedance and noise. Stray voltages readily affect the signal. The principal advantage is no direct contact between the transducer and the device being evaluated. This capacitive concept is used in other transducers such as pressure, where one electrode is an elastic diaphragm.

Optical Methods of Measuring Displacement. A variety of optical methods are available for displacement measurement. In machine shops, optical methods are used to magnify small dimensions, permitting measurement with simple tools on a projection screen. Light microscopes are often used as a means of determining dimensions.

Flatness can be determined by covering a surface with an optically flat glass, illuminating with a monochromatic light and observing the light bands. Each band represents a deviation of one half wave length of the applied light. With a sodium light source, the wave length is 5890 angstroms (1 angstrom = 10^{-8} cm). Therefore, one ring indicates 2945 angstroms. The virtual absence of rings indicates a very flat surface.

A technique for measuring displacement under dynamic situations, where the amplitude is measurable with a scale, is to use a strobe light. Accuracies of 5% of distances of 2 to 5 cm are possible. With a variable strobe frequency, maximum displacement is easily determined by visual observation.

Another optical transducer consists of a light source, mirror on the object being studied, filter and photoelectric detector. The light from the source is reflected from the mirror to a position on the filter proportional to mirror displacement. The filter has an opacity which varies linearily with the light position. As a result the intensity of the light passing through the filter is proportional to the location of the mirror. A photocell may be used to convert light intensity to voltage signal for input into a recording system (McKinney, 1968).

An optical transducer, similar to the unit just described, was used by McClure et al. (1970) for determining change in dimensions of agricultural products during load. They suggested this transducer may be used to determine size of agricultural products and evaluate plant growth.

Displacement or distance can be measured using fiber optics. A probe called the Fotomic sensor consists of a bundle of several hundred optical fibers each about 5 μm in diameter and terminating at the probe top to form a flat surface. A portion of the fibers (transmitting fibers) are attached to a light source and light is transmitted to the probe tip and emitted onto a target surface. The light reflected by the target surface is picked up by the other portion of the fibers (receiving fibers) and transmitted to an electronic device and focused on a suitable photodetector. The intensity of the reflected light and the output of the photodetector is directly related to the distance between the probe tip and the target surface. One example of such a probe has a diameter of 0.273 cm and having a sensitivity of 0.6 mV/cm. This probe has range of 0.003 to 0.010 cm and a static resolution of 0.04 μm. The target surface may be a surface of a machine component under study (Doebelin, 1983).

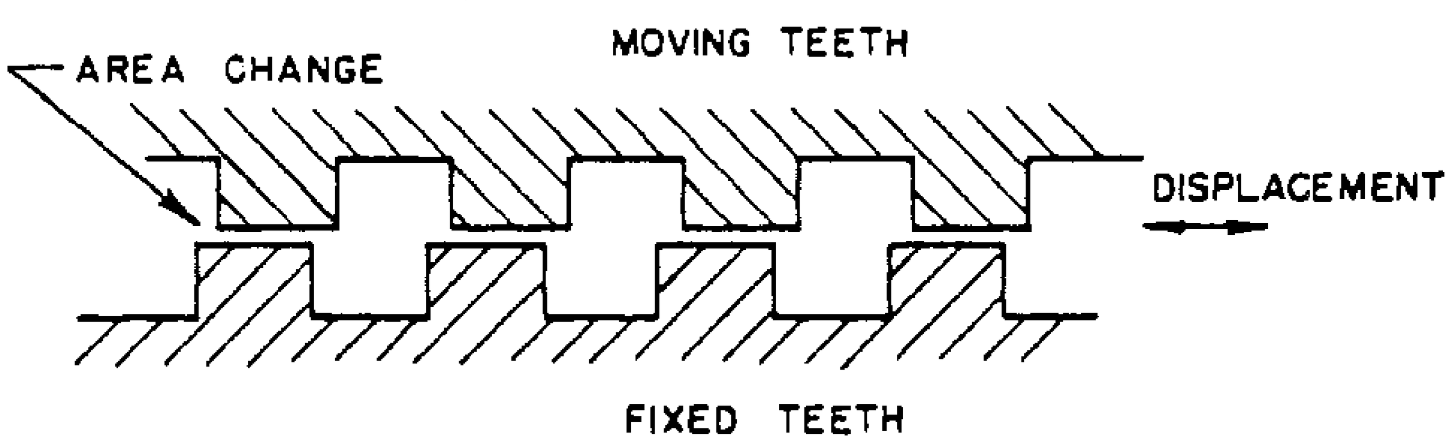

Figure 8–Capacitance displacement transducer.

Lasers are used as a means of determining dimensions. Several different devices using lasers are available but only the laser inferometer is discussed. A helium-neon laser produces two frequencies about 5×10^{14} Hz. This laser signal is split into a reference beam and a measuring beam. The reference beam is converted to an electrical signal having a frequency equal to the difference in the two laser signals which is about 2.0 MHz. This signal is then amplified and input into a counter. The measuring signal is directed to a polarizing beam splitter, which separates the laser signal based on frequency. One frequency signal is reflected about a prism and to a photodetector without change. The other frequency is transmitted to a movable measurement cube corner at the unknown distance. If this corner moves, there is a change in the second frequency proportional to speed. The second frequency is reflected back to prism and combined with the first frequency in the photodetector. The resultant signal from the detector is sent to an amplifier and another counter. The output of the two counters is proportional to the differences in the input of the two frequencies. For this reference signal, the output is equal to 2 MHz, the difference in the two initial frequencies. For the measuring signal, the difference is equal to the initial frequency minus the frequency altered by the measurement cube corner. This difference ranges from 0.5 to 3.5 MHz. A resolution of 0.3 μm can be obtained in a 1 cm range. Many other specialized electro-optical devices are available and described by Doebelin (1983).

Ultrasonics. Several examples of displacement measuring devices utilize wave propagation principles. Such sensors use ultrasonic waves which have frequencies outside the range of the human ear. One such device is used in a commercially available camera which has automatic focusing. A drive motor which focuses the camera lens receives a control signal from an ultrasonic range finder.

The principle utilized is an acoustical signal is directed from an electrostatic transducer at a target surface. The signal is reflected back to a transducer. The time required for the signal to travel to the target and back to the transducer is a function of time based on a known wave propagation velocity which is 27.9 m/s.

An ultrasonic device of this nature was used to determine the micro relief of the soil surface (Kolstad and Schuler, 1980). Also ultrasonics have been used to maintain field cultivator at a constant depth. The ultrasonic device was used to control a hydraulic cylinder based on the distance from the cultivator frame to the soil surface (Paulson and Strelioff, 1974).

Rotary Encoders. Transducers used to convert angular displacement to a digital output are referred to as rotary encoders. Some applications of the encoders include numerically controlled machine tools and digital positioning. Some of the characteristics of the rotary encoders are high accuracy, resolution and reliability and immunity to noise. Operation in adverse environment has been very successful with these devices. The basic encoder shown in figure 9 consists of spatially coded patterns on a rotating disk or drum and a stationary pickup device. Three common types of encoders are brush, magnetic, and optical. In the brush system, the disk or drum has a conductive pattern which is in contact with stationary brushes. By identifying which brushes are conducting current, the angular position of the rotating unit can be determined. Magnetic encoders utilize ferrite cores to read magnetic coded patterns on the rotating unit. With the optical encoder, photo-cells sense a light source through an alternatively opaque and transparent disk segments which is illustrated in figure 9 (Review of Digital Rotary Encoders, 1970).

The most common encoder in use is the brush type because of low cost and simplicity of the readout system. The other encoders have the advantage of non-contacting surface.

Velocity Measurement

Most velocity measuring equipment is designed to sense angular velocity. Quite often linear velocity is measured by converting the linear motion to rotary motion and then using angular device to determine the linear velocity.

Mechanical Velocity Transducers

A simple method of determining rotative speed is to count the revolutions made in a defined period of time. Equipment required are a revolution counter and stop watch. This method is convenient to use but has limited accuracy.

A mechanism, similar to a centrifugal mechanical engine governor, is the basis for a hand held velocity transducer, shown in figure 10. An input shaft is attached to the governor mechanism and is placed in contact with the rotating mechanism through a rubber conical tip. Linear velocity can also be measured with this transducer by replacing the rubber tip with a suitable rubber wheel. These instruments are subject to error of several percent (Ambrosius et al., 1966)

A vibrating reed type instrument consists of a number of reeds attached to a base and each forming a cantilever beam with a different natural frequency. When the base is vibrated at a particular frequency, the reed (with the same natural frequency) will have a large amplitude of vibration. The tachometer is placed in contact with the base of a machine with rotating part. No rotating machine is absolutely free of vibration. The primary advantage of this transducer is the absence of wearing parts. The reeds retain their accuracy with time, but they are temperature sensitive (Langford, 1964).

A vibrating wire with a variable length is used to determine engine speed. This wire serves as a cantilever beam with a natural frequency dependent on its length. The base of this device is placed on a machine with rotating components. The length of the cantilever beam or wire is adjusted for maximum vibration. A dial on the base will indicate rotational speed based on wire length.

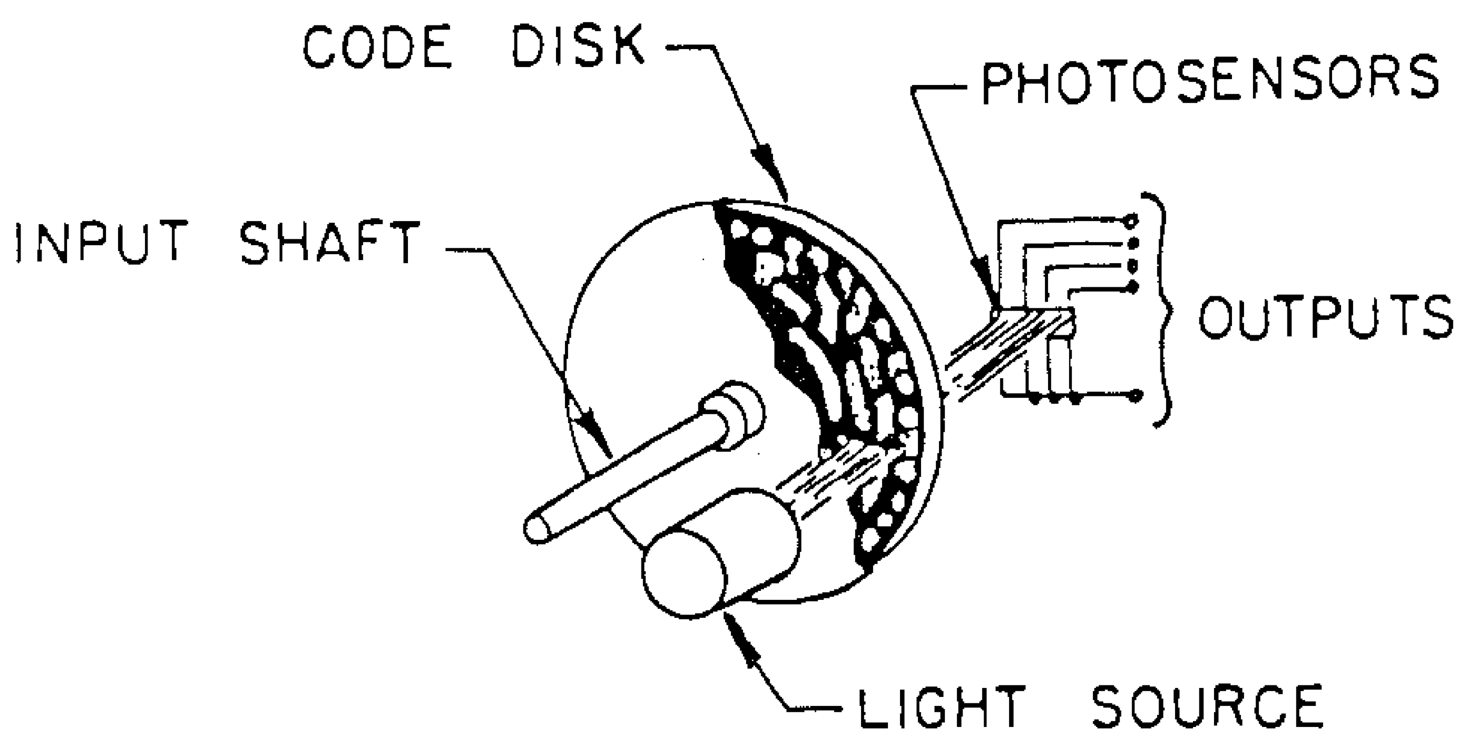

Figure 9–Rotary encoder.

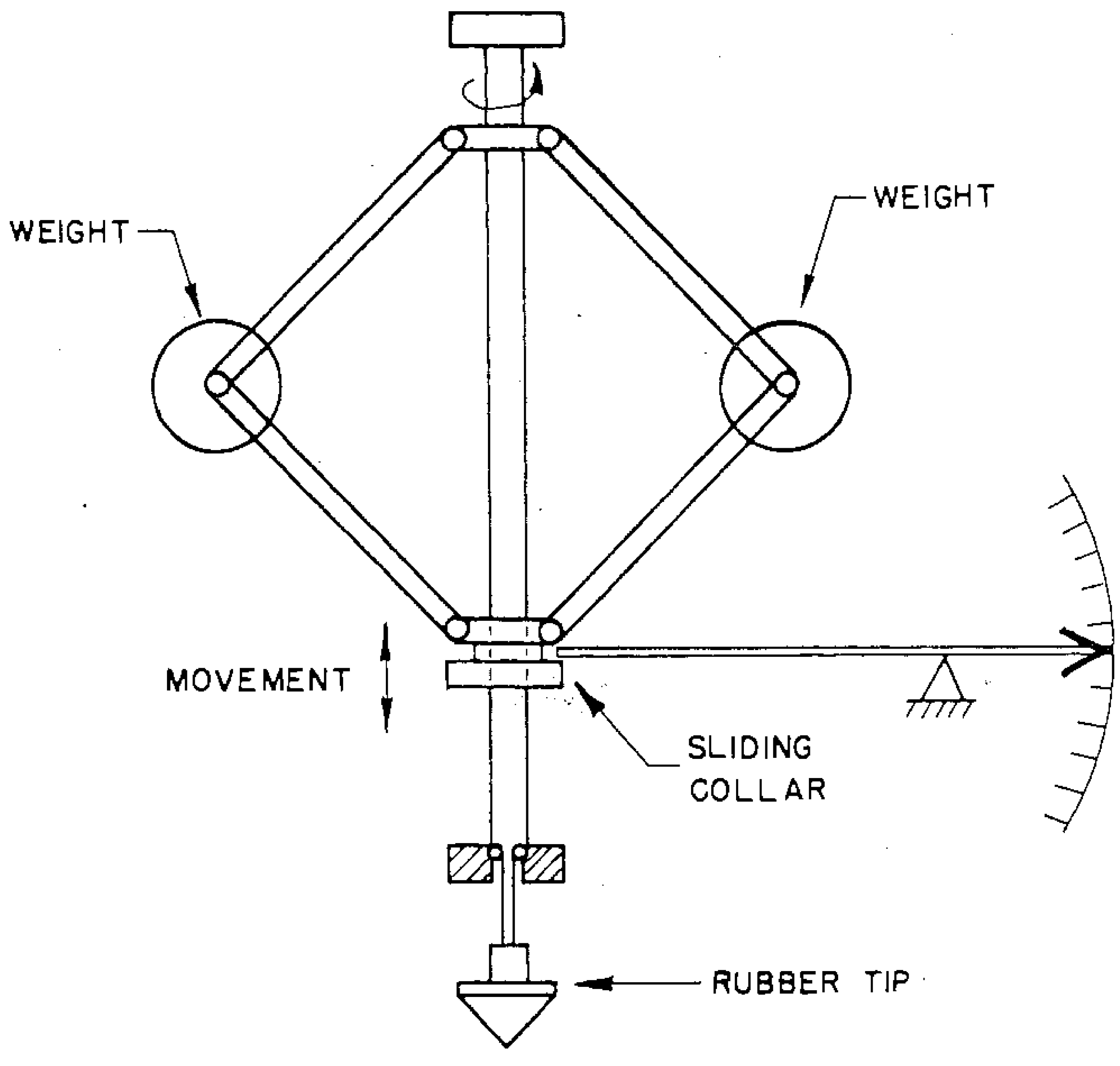

Figure 10–Centrifugal velocity transducer.

Electrical Velocity Transducers

One device for measuring rotational speed is a cam actuated switch or set of contacts. The cam which rotates and has a single lobe or multiple lobes opens the contacts in a manner very similar to an automotive ignition system. A spring mechanism closes the contacts after the cam lobe passes. An electronic counter is needed to indicate the number of times the contacts open and close per unit of time.

A variable reluctance principle can be utilized for measuring both linear and angular velocity. The basic components of such a transducer are a permanent magnet and coil. For linear velocity measurement, one such transducer shown in figure 11 employs a permanent magnet as a seismic mass and a coil surrounding the mass and attached to the housing. The mass is attached to the housing through a spring. As the housing, which is attached to a vibrating body, is vibrated, the mass moves relative to the coil. Lines of magnetic flux are cut, resulting in a voltage being produced in the coil. The magnitude of the voltage is determined by the rate at which the lines of flux are cut, and is proportional to velocity. By surrounding the seismic mass with a silicon

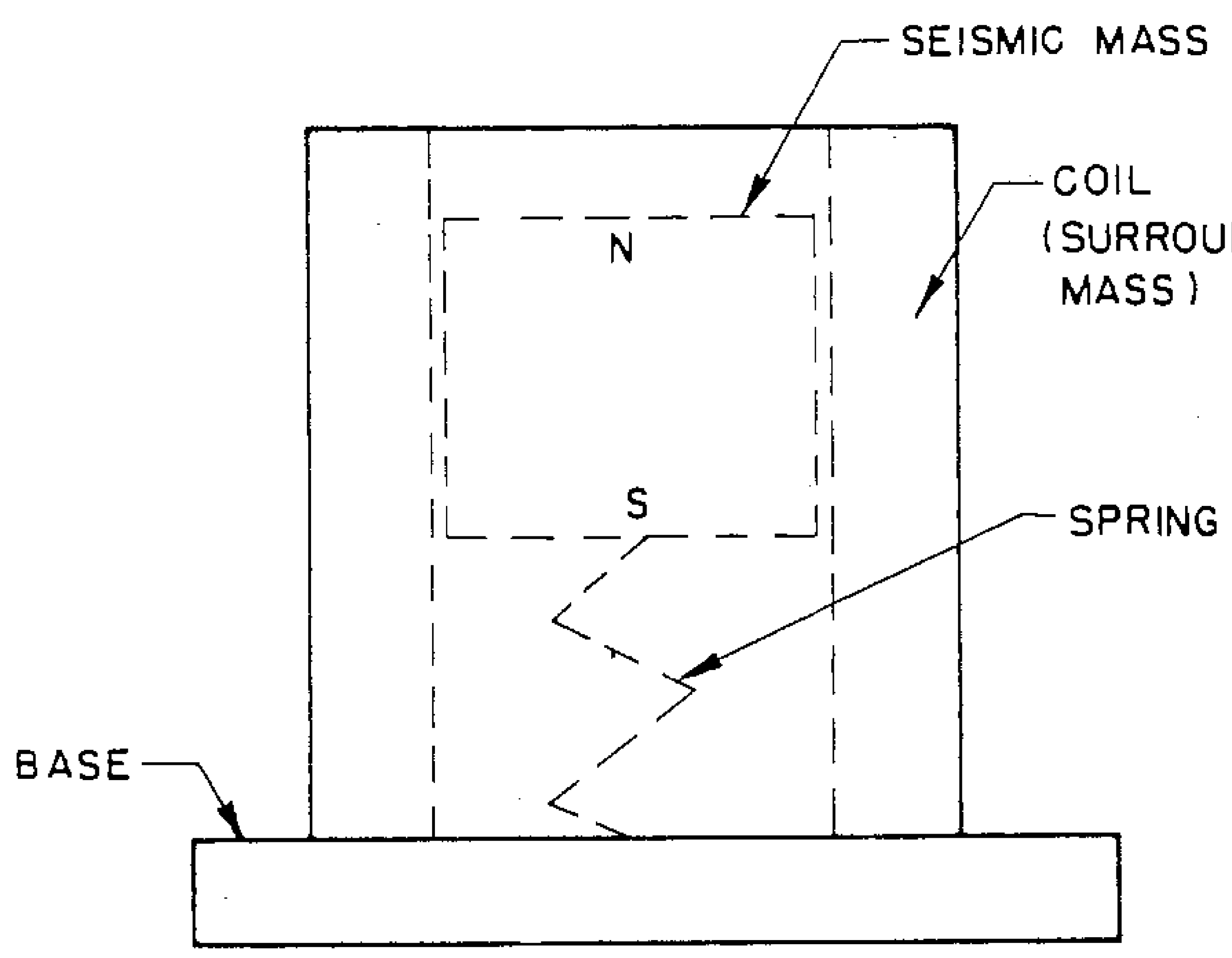

Figure 11–Linear velocity transducer.

liquid, damping can be obtained. In some cases, the coil forms the seismic mass and the permanent magnet is attached directly to the transducer housing. The primary disadvantage of this system is the limited frequency range, usually less than 60 Hz (Neubert, 1963).

For angular velocity, a variable reluctance transducer which is shown in figure 12, consists of a permanent magnet rigidly fixed within a coil. Any variation in the permeance of the magnetic circuit causes a change in the magnetic flux. As the flux builds up or collapses, a voltage is produced in the coil. One method of changing the permeance is placing the transducer, often referred to as a magnetic pickup, near the teeth of a rotating iron gear. As each tooth passes by the pickup, an electrical impulse is produced. By counting the number of impulses for a period of time and dividing by the number of teeth on the gear, the result is the number of revolutions for this time period (Beckwith and Buck, 1969).

Devices called proximity switches or sensors are used to sense rotational speed. An advantage of these devices is that no contact is necessary between sensor and rotational component. Numerous devices are available using various principles of operation. One example is a small magnetically actuated switch. A magnet mounted on a rotating shaft or wheel passes near the switch which opens or closes as it approaches and closes or opens as it recedes. Another device uses a capacitance principle such that as an object on a rotating shaft or wheel changes the dielectric properties near a capacitor sensor. In this case, the objects do not need to be metallic. Plastic and glass can be used. Other proximity devices available include transducers using the Hall effect and using the change in Eddy currents near a coil as a shaft or wheel rotates. Proximity switches are used as part of monitoring systems on farm tractors, grain combines, and agricultural chemical sprayers.

Another electric device for angular velocity measurement is a tachometer generator with an output voltage proportional to the input shaft speed. This type of generator, usually DC for precise applications, has a permanent magnet field and often rated in volts per rpm.

An eddy-current tachometer involves a permanent magnet rotating inside of a conducting, nonmagnetic cup. The permanent magnet which is rotating at the measured speed induces a voltage in the cup producing eddy-currents in the cup. These eddy-currents produce a torque on the cup in proportion to the velocity of the magnet relative to the cup. This torque is countered by a torsional spring as result the cup deflection is proportional to the measured angular velocity. This system provides a very portable speed measuring unit (Doebelin, 1983).

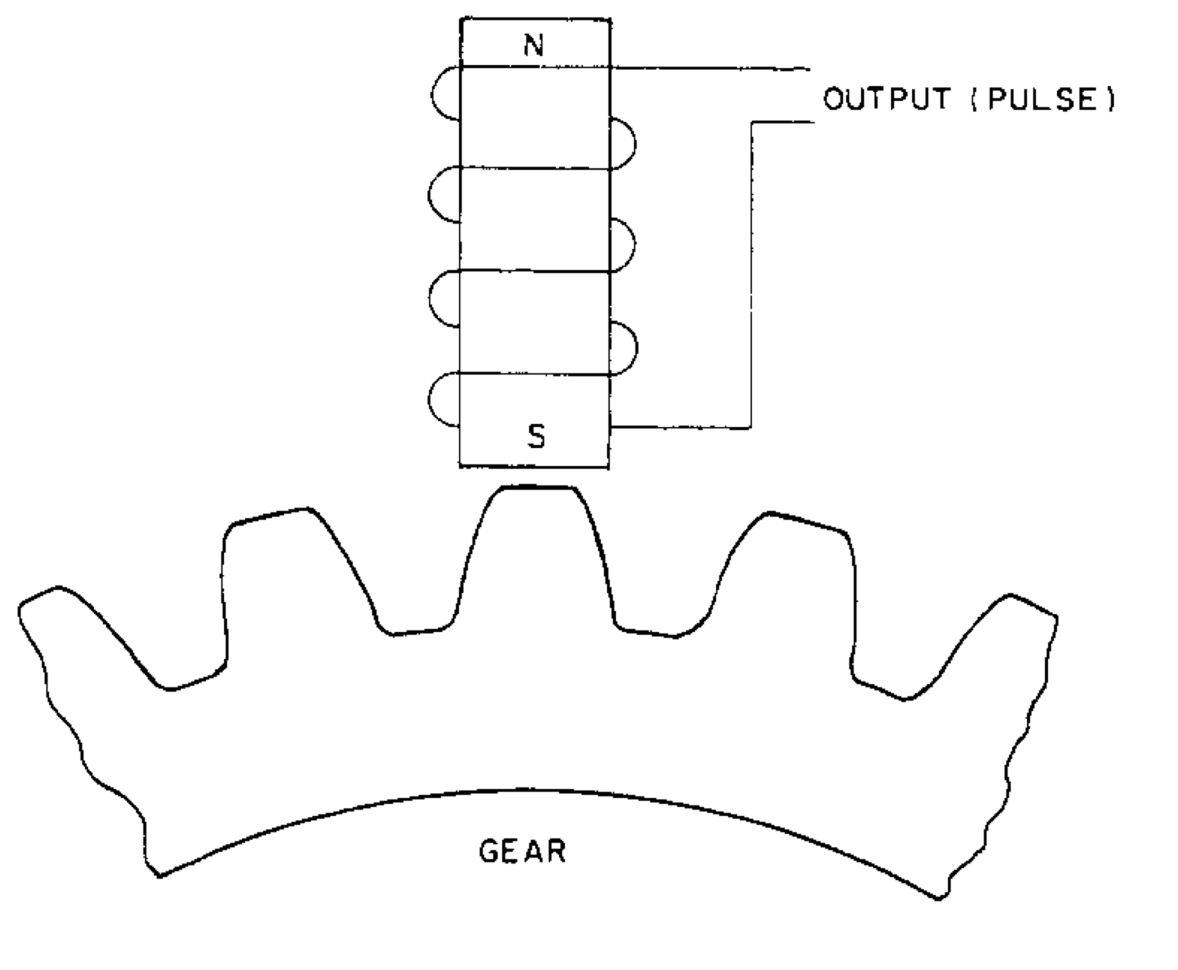

Figure 12–Magnetic pickup.

Optical Methods for Velocity Measurement

Photocells can be used in a manner similar to the magnetic pickup. An arrangement can be made for measuring fan speeds where the blades interrupt the light striking the photocell by passing between the light source and photocell during fan operation. As a result, light intermittently strikes the photocell causing voltage pulses to be produced. The pulses can be counted in the manner used with the magnetic pickup.

Another technique using photocells involves placing a reflective surface on a small section of a rotating shaft or disk. As the reflective section passes a certain point, light from a single source is reflected to the photocell. A pulse of light will strike the photocell once each revolution resulting in an electrical impulse each revolution.

A stroboscope and Strobotac, fundamentally similar instruments, permit objects to be viewed intermittently with a pulsing light. The optical effect results in the motion appearing to slow down or stop. When the object is optically stopped, the speed of the shaft equals the frequency of the pulsing light or is a multiple of the frequency. One primary advantage of the instruments is that no contact is required with the rotating shaft.

The Strobotac consists of an oscillator which controls the rate at which a lamp is flashed. The neon lamp or similar flashing lamp is mounted in a parabolic reflector. By adjusting a dial calibrated in revolutions per minute, the frequency of the oscillator and therefore the rate of which the lamp flashes can be adjusted to the speed of the rotating shaft. The frequency range of this instrument is 10 to approximately 700 Hz.

The stroboscope has a constant light source but a mechanically operated shutter for interrupting the light periodically before striking the rotating device. The frequency of the shutter operation can be controlled so that the shaft appears to stop. The stroboscope is limited to low frequency, below 40 Hz. This limiting value will vary depending on the shutter mechanism design (Ambrosius et al., 1960).

Acceleration Measurement

In testing machine parts, the level of mechanical vibration during operation is often determined because it is an indication of force levels on machine components. The origin of the vibration may be due to rotating or oscillating parts or due to interaction with the terrain or environment surrounding the machine during operation. The transducer primarily used to detect the level of vibration is the accelerometer. In some cases, the level of vibration is an indication of an impending failure.

Accelerometers can be classified into three categories: level, peak, and continuously indicating.

The level indicating transducers are designed to provide a yes or no output indicating whether the acceleration is greater or less than a preassigned value. A simple example, shown in figure 13, consists of a cantilever beam which is preloaded with an electrical contact at the end. When the inertia forces acting on the spring (elastic force of beam) and mass exceed the preload, contact will be broken, and this action may be used to trip an indicator (Beckwith and Buck, 1969). More elaborate forms of this arrangement have been devised. The usefulness of such a device is very limited for measurement purposes but is very useful as an actuating mechanism. If the acceleration exceeds predetermined level, the operation of a machine or mechanism is turned off automatically. Also, such a device is useful while transporting merchandise when it acts as a shock fuse.

The peak indicating accelerometer will provide information for the determination of the maximum acceleration reached during a particular time interval. The transducer, used for linear acceleration, consists of two spheres held in contact with a

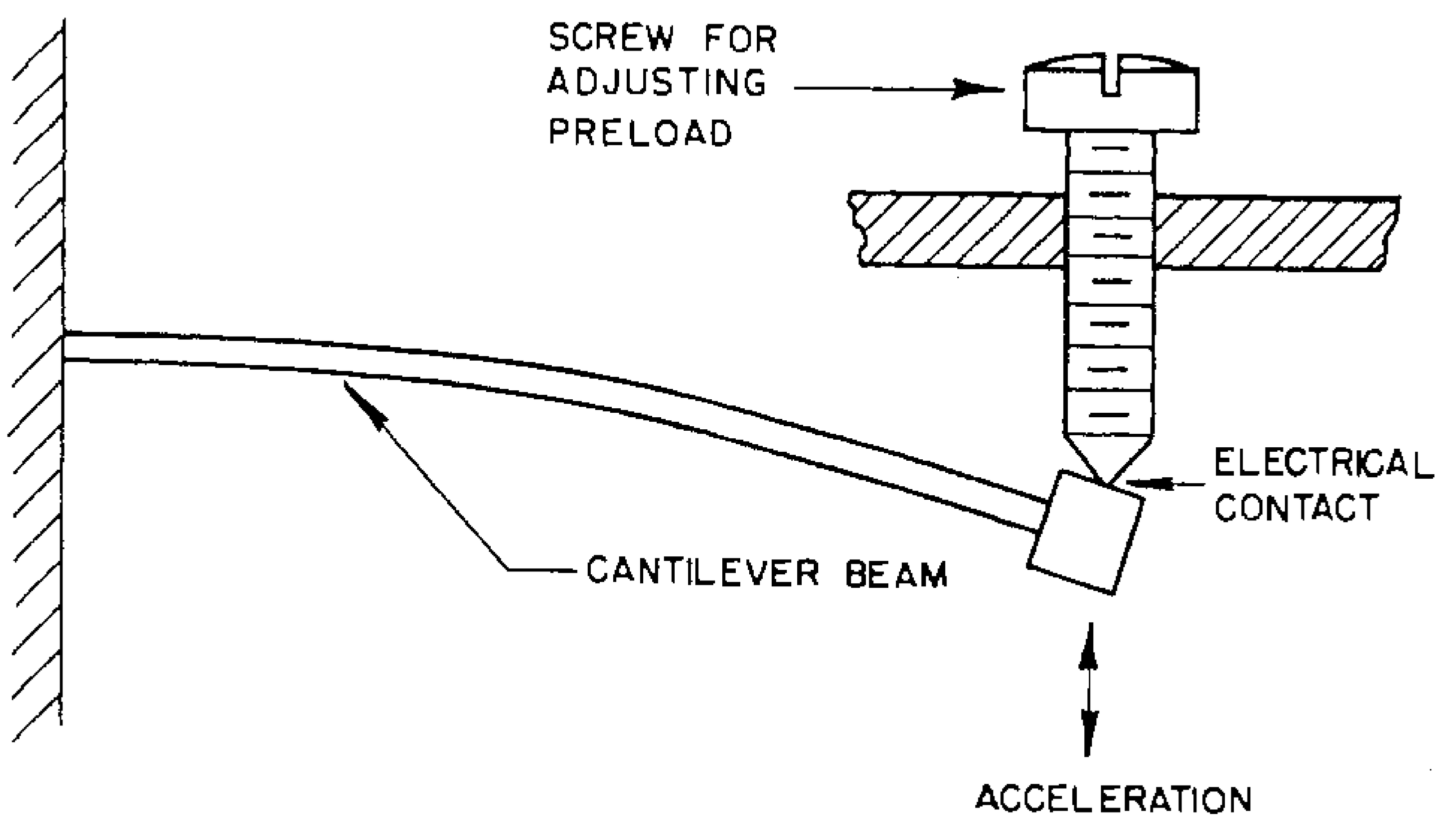

Figure 13–Preloaded indicating accelerometer.

spring, one is made of a hard material and other of a soft material. Examples of materials are steel and copper, respectively. When the transducer is subjected to an acceleration, the hard (steel) sphere makes an indentation on the soft (copper) sphere. Based on previous calibration, the indentation size can be interpreted in terms of an applied force. Dividing the force by the mass of the hard sphere results in the value of the peak applied acceleration.

The continuously indicating accelerometer is by far the most useful because a complete time history of the acceleration is obtainable. This permits a detailed study of the forces and frequencies within machine components and correlation with other dynamic parameters.

This type of transducer consists of a spring-mass system which is subjected to the unknown acceleration. The force exerted by the mass and elastic member, spring, can be determined through force or deflection sensing elements. These parameters, force and deflection, are calibrated in terms of applied acceleration.

With continuously indicating accelerometers, two important transducer parameters are the natural frequency and damping. The natural frequency of the spring-mass system is an indication of the rate of response to changing input. Thus, for a vibrating system with a high frequency, the natural frequency of the accelerometer must be high if its output is to be a correct indication of the applied acceleration. In general, the natural frequency should be two to three times the highest expected frequency of the vibration under study. However, a higher natural frequency often indicates the accelerometer is stiff and insensitive. The sensitivity is inversely proportional to the square of the natural frequency.

Damping is required in all accelerometers because without damping the mass would continue to vibrate after the system was subjected to step input. Also, with accelerations near the natural frequency of the undamped accelerometer, a large output will result. Quantitatively it may be shown that damping of approximately 60 to 70% of critical damping will extend the usefulness of an accelerometer to almost three-quarters of its natural frequency. This magnitude of damping will also eliminate errors due to phase distortion. In the reproduction of a complex wave pattern, phase distortion is the error arising from the lack of linearity between the phase lag of the responding element and the frequency of the components of the applied wave pattern. Fortunately, damping in the range of 60 to 70% of critical produces an almost linear phase lag relation for frequencies up to the natural frequency of the instrument, and thus eliminates phase distortion within the operating range of the instrument (Gibson, 1972 and Myklestad, 1956).

Electrical Acceleration Transducers

In the electro-mechanical accelerometer the motion or force of the mass is converted to proportional electrical signals which can be easily transmitted to a recorder.

A typical seismic system will consist of a small mass supported by a cantilever beam. If strain gages, resistive or piezoresistive, are placed near the base of the beam, the mass displacement, which is proportional to acceleration, may be recorded as a change of resistance of the strain gage circuit. With this system, many design parameters can be varied to obtain various natural frequencies and sensitivities. Damping can be obtained by enclosing the mass and beam in a fluid. Many accelerometers on the market are strain gage type with either bonded or unbonded gages. The piezoresistive gages, which have a large gage factor, are often used in miniature accelerometers weighing a gram or less.

Schuler and Bruhn (1972) used resistive and piezoresistive accelerometers when analyzing the motion of a fruit tree limb subjected to a sinusoidal force. The piezoresistive accelerometers, weighing one gram, an attempt to minimize transducer inertia effects, were placed on the small diameter portion of the limb. The resistive accelerometer, which had a greater weight, was placed near the base of the limb.

Potentiometric transducers utilize a wiper-winding system similar to the transducer shown in figure 2. The position of the wiper with respect to the coil is directly proportional to acceleration. This is accomplished by mechanically attaching the wiper to a mass which is attached through a spring to the vibrating component. Although this device will have a high electrical output, it is useful at low frequencies only.

Another system used as an accelerometer is the linear variable differential transformer with a mass and spring attached to the movable core. In most case, these units are used for sensing small acceleration. When these devices are used, proper damping is often obtained by means of various fluids or through the use of eddy-current damping provided by a permanent magnet incorporated into the design.

The piezoelectric accelerometer has become popular in instrumentation systems (Lion, 1956). The piezoelectric crystal has the ability to generate an electrical potential when subjected to a mechanical strain. The converse, a change in dimensions results when a voltage is applied to the crystal, is also true but not utilized here. Examples of piezoelectric crystals are quartz, Rochelle salt, and some ceramics.

In most designs, a small mass is spring-loaded against a piezoelectric crystal as shown in figure 14. During the period of vibration, the load exerted by mass on the crystal changes with acceleration and the crystal voltage produced is proportional to acceleration. The principal advantages of the piezoelectric acceleromoter are high sensitivity, high frequency range, compactness, and ruggedness. Because of their design some of these accelerometers can produce accurate results up to and above 10,000 Hz.

The piezoelectric accelerometer has a large voltage output but a low current. As a result, the output impedance is very large–usually in terms of gigaohms. The signal from this accelerometer must be fed into an instrument with a high input impedance such as a cathode follower or charge amplifier. To be effective, the cathode follower must be near the accelerometer, but that may not always be convenient. The charge amplifier minimizes the effects of noise and cable length but is more sensitive to temperature. The problem of noise can be reduced by using coaxial cable.

The piezoelectric accelerometer is used extensively to study the vibration response of agricultural machine parts and vibration

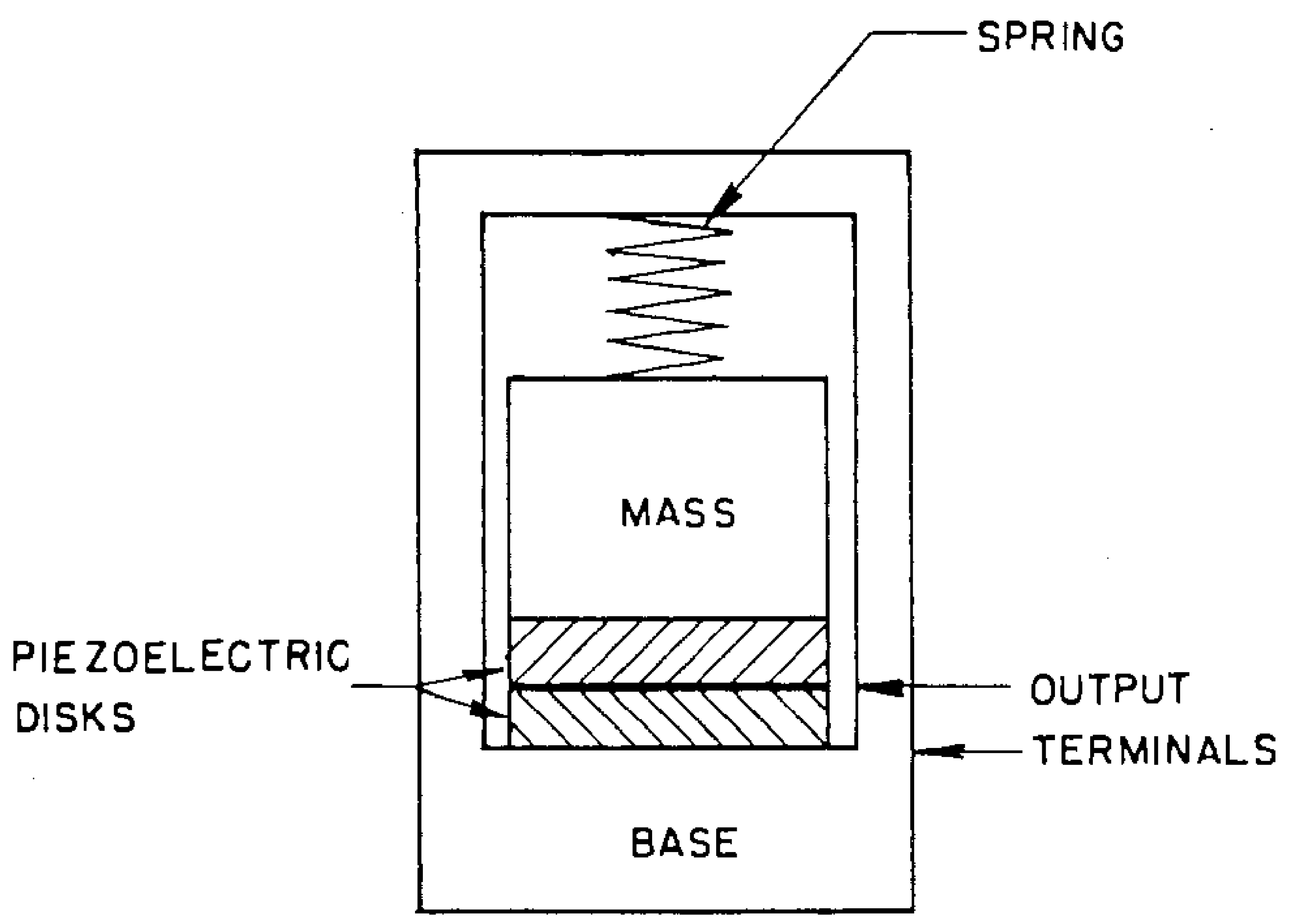

Figure 14–Piezoelectric accelerometer.

exposed to machine operators. When studying the effects of vibration from hand held tools on the operator, Mishoe and Suggs (1973) used a piezoelectric transducer.

Another type of accelerometer is the variable capacitance one where the movement of a plate is proportional to acceleration. The second plate is fixed. Attached to the movable plate, which is often an elastic diaphragm, is a small mass. The magnitude of the capacitance is related to the acceleration through the changing distance between plates (Coon and Harrison, 1967).

In selecting an acceleration transducer the strain gage, potentiometric and linear variable differential transformer are suited for low frequencies, less than 30 Hz, while the piezoelectric and the piezoresistive are usually designed for higher frequency.

CALIBRATION

All transducers must be calibrated before valid data can be obtained. In most cases, calibration consists of determining the units of output (often voltage) per unit of input, which is the parameter being sensed. Many commercial transducers are calibrated at the factory; for example, in terms of volts/g of acceleration. Quite often the calibration curve is included when the transducer is shipped to show how the calibration factor varies over the useful range of the transducers.

When this information is not available, some means of calibration must be completed by the user of the transducer. Several techniques can be employed to subject the transducer to a known input, which can be constant or steady-state harmonic motion of known amplitude and frequency.

For the simple displacement transducer, a constant known input can be applied and can be determined by using some measuring devices such as scales, micrometers or gage blocks.

For vibrometers, the most often used input is a steady-state harmonic motion of known amplitude and frequency. The sinusoidal voltage is measured by a reliable instrument, and has an amplitude proportional to the velocity input. The amplitude of the velocity is the product of frequency and the amplitude of sinusoidal inputs.

This technique can also be applied to calibration of accelerometers. The amplitude of the harmonic varying acceleration is the product of the amplitude and frequency squared.

By using the earth's gravitational field, a simple method can be utilized to calibrate low range accelerometers. By holding the accelerometer with its sensitive axis parallel to a plumb line and then inverting it through 180°, a two g step calibration is obtained (plus one g and minus one g of acceleration). By orienting the sensing axis perpendicular to the direction of earth's gravity, an intermediate (zero) level of acceleration is obtained.

A method of calibrating an accelerometer is to place it on a horizontal rotating table (centrifuge). The accelerometer is placed on the table some distance from the center of rotation and oriented such that the sensing direction is parallel to the radius of rotation. By knowing angular speed which has to be constant and the distance from the center of rotation to the transducer location, the applied acceleration can be determined using the following equation:

$$A = \frac{R(2\pi f)2}{980}$$

where

A = Acceleration in g (acceleration due to gravity = g), and
R = Distance from the center of rotation and to the transducer cm.

The two preceding calibration techniques result in a constant acceleration being applied.

SOUND MEASUREMENT

The development of machines which produce less noise requires an evaluation of the sound produced and its cause. The diagnosis of the noise problems require an understanding of sound sensing and recording equipment. Sound consists of high frequency pressure waves traveling through a fluid such as air and sensed by the human ear. Sound transducers utilize microphones which are pressure measuring devices.

The fundamental definition of sound is in terms of the magnitude of the fluctuating pressure components in a fluid within the frequency range of the human ear. The most frequently measured parameter is the sound pressure level (SPL) which is defined as:

$$SPL = 20 \log_{10}\left(\frac{P_1}{P_0}\right)$$

where

P_1 = root mean square (rms) sound pressure, microbar, and
P_0 = standard reference pressure, 0.0002 microbars.

The unit of SPL is decibel (dB). Since most sounds consist of numerous frequency signals rather than a simple sine wave, the rms value is used. The reference rms pressure of 0.0002 microbars is an accepted standard which represents the average threshold of hearing for the human ear. As a result, a measured pressure of 0.0002 microbars is equal to a SPL of zero dB.

The dB scale is used because the rms pressure has a large range from 0.0002 microbars (0 dB) for the average threshold of hearing to 3170 microbar (144 dB) the average threshold of human pain. By using the dB scale, sound pressure levels are not additive. For example, two sounds which measure 80 dB (SPL) separately will produce 86 dB (SPL) when combined. This can be determined from the above equation when the rms pressures are considered additive.

Before discussing sound measuring devices, a fundamental understanding of the psychoaccoustic relationships must be understood. The human ear is a nonlinear device for sensing sound; that is, ear sensitivity to sound is dependent on frequency

PRESSURE AND VACUUM

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INTRODUCTION

Measurement of pressure is one of the most frequently performed operations in the entire field on instrumentation. Accurate determination of pressure is essential in research and in industrial applications. Pressure measurement is important as an indirect means of measurement of other variables such as temperature (filled-system thermometers), flow (differential pressure across an orifice), liquid density, and level.

Pressure is the force per unit of area exerted by a gas, liquid or solid. Pressure may be measured as absolute, gage or differential. Absolute pressure is the total pressure exerted by a fluid. Differential pressure represents the algebraic difference in two pressures. Gage pressure is a special case of differential pressure since it is the difference between absolute pressure and atmospheric pressure.

Thus:

$$P_g = P_a - P_s \tag{1}$$

where

P_g = gage pressure,
P_a = absolute pressure, and
P_s = atmospheric pressure at the time of measurement.

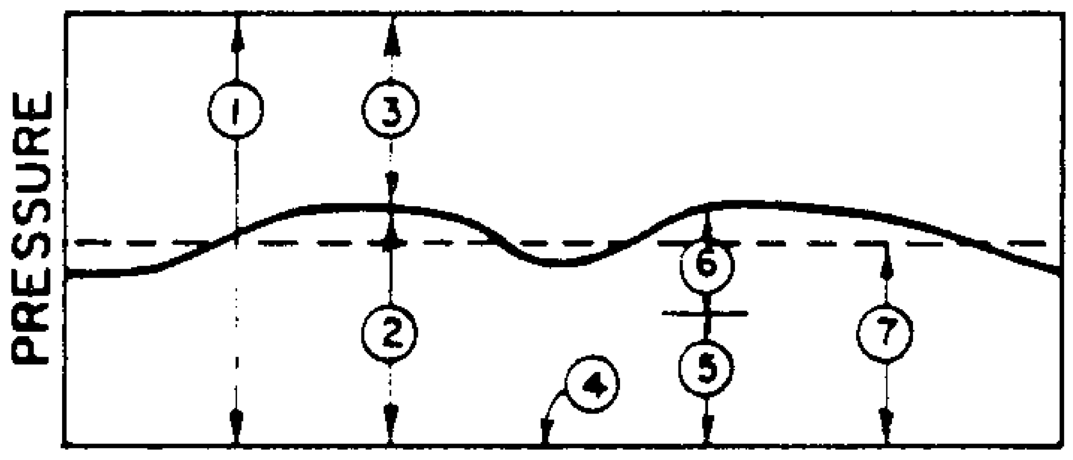
A vacuum may be defined as any gaseous space where the pressure is below atmospheric. Vacuum then, is another example of a differential pressure and is defined as:

$$V = P_s - P_a \tag{2}$$

By comparison of equations 1 and 2, it is seen that a negative vacuum and a positive gage pressure have the same meaning.

The relation between absolute pressure, gage pressure, and vacuum is shown graphically in figure 1. As illustrated by the diagram, atmospheric pressure is not constant, but varies not only with elevation and latitude but also with time and temperature.

Devices for measuring pressure range from the very simple U-tube manometer to extremely intricate electrical pressure measuring systems. In general, liquid manometers, Bourdon tubes or other mechanical pressure measuring elements are used when a static (or steady) pressure is being determined. In cases where the pressure is dynamic (time varying) or where remote reading is desired, it is necessary to use a pressure transducer with associated electronic equipment. A transducer may be defined as an electro-mechanical device which produces an output voltage proportional to the phenomenon, such as pressure, being measured. In other words, it converts any form of energy into an equivalent electrical current or voltage. Transducers at various times have also been called pickups, or sensing elements.



1 - Total or absolute pressure
2 - Atmospheric or barometric pressure
3 - Gage pressure 4 - Zero absolute
5 - Absolute pressure
6 - Vacuum (or reduced pressure)
7 - Standard atmospheric pressure
= 760 mm Hg = 29.92 in Hg = 14.696 psi

Figure 1–Graphical representation of pressure: atmospheric, gage, and absolute.

The units used to designate pressure are as varied as the pressure measuring devices available. The pascal (Pa) is the SI unit of pressure. A pascal is the pressure (or stress) which is produced when a force of one newton is applied to an area of one square meter. In the English system, the most common unit is the pound per square inch (psi). The fundamental unit in cgs units is the dyne/cm^2. A pressure of 10^6 dyne/cm^2 is defined as 1 bar, or for a more convenient unit, 1 mb = 1000 dynes/cm^2. The pressure exerted by a column of mercury 760 cm high, having a density of 13.5951 gm/cm^3 and subject to an acceleration due to gravity of 980.665 cm/s^2 is defined as one atmosphere (1013.250 mb). Other units that are sometimes used are: micron = 0.001 mm of mercury and torr (or tor) = 1/760 of 1 atm, or 1 mm Hg (very nearly). Table 1 (1960) gives conversion factors for the more commonly used pressure units.

MECHANICAL PRESSURE ELEMENTS

LIQUID COLUMN ELEMENTS

By far the most common liquid used in manometers is mercury. With a density of approximately 13.6 times that of water, it provides a convenient scale length for barometers and other relatively large differential pressure measurements. In addition, mercury has a low freezing point of -38° F. Other liquids that are used in manometry are water, organic liquids with densities less than water, and bromide compounds with densities of about three times that of water.

U-Tube Manometer. The U-tube manometer, shown in figure 2a, is used to measure differential pressure. The difference in height, h, is independent of column diameter. For static balance:

$$P_2 - P_1 = \gamma h \tag{3}$$

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TABLE 1. Conversion factors for various pressure units equivalent for unit value in first column*

Pressure, Unit Value	Millibars	Mercury, mm (0° C)	Mercury, in. (0° C)	kPa	lb/in.^{2}	lb/ft^2	Water, cm (20° C)	Water, in. (20° C)
1 atmosphere	1013.250	760.000	29.9213	101.32505	14.69595	2116.22	1035.08	407.513
1 millibar (mb)	1	0.75006	0.029530	0.10000	0.014504	2.0885	1.0215	0.40218
1 mm mercury (mm Hg)	1.3332	1	0.03937	0.13332	0.019337	2.7845	1.3619	0.53620
1 in. mercury (in. Hg)	33.864	25.400	1	3.38636	0.49115	70.726	34.593	13.619
1 gram/cm^2 (g/cm^2)	0.98067	0.73556	0.028959	0.09806	0.014223	2.0482	1.0018	0.39441
1 lb per sq in. (psi)	68.9476	51.715	2.0360	6.89476	1	144	70.433	27.730
1 lb per sq ft	0.47880	0.35913	0.014139	0.04788	0.0069444	1	0.48912	0.19257
1 cm water 20 C	0.97891	0.73424	0.028907	0.09789	0.014198	2.0444	1	0.393
1 in. water 20 C	2.4864	1.8650	0.73424	0.24865	0.036063	5.1930	2.5400	1

1 atmosphere = 10332.3 = Kg/m^2 = 1.03323 Kg/cm^2 = 101.32505 kPa
1 inch = 2.54 cm (old value, 2.54000508 cm; 2 parts per million greater)
1 pound = 0.45359237 Kg (old value, 0.45359243 Kg; 2 parts per 15 million greater)
Density of water at 20 C = 0.998207 grams/cm^2
1 bar = 1000 millibars = 10^6 dynes per sq cm

* This data is from NBS Monograph 8 (Brombacher et al., 1960).

where
P_2 and P_1 = pressures on the two sides of the column,
γ = density of the manometer fluid,
h = difference in height of columns.

The U-tube manometer can be used to determine the relative specific gravity of two liquids if the liquids, such as oil and water, do not mix. The heavier liquid (water) is poured into the tube first; the oil is added, and the specific gravity of the oil is obtained by dividing height A by height B (fig. 2b).

Figure 2c shows the application of a U-tube manometer for the measurement of liquid level in a tank.

A unique modification of the U-tube manometer by Berry (1956) is illustrated in figure 2d. The device provides extreme sensitivity through a small range around the null point. This manometer is easily constructed from thin-wall semi-capillary tubing by bending as shown. Sections AB and CD must be parallel and in the same horizontal plane. A fluid is added to fill the manometer from some point on AB to a corresponding point on CD. Any change in pressure will cause the meniscus in each section to move together throughout the horizontal portion of the manometer. For horizontal travel of the menisci, only viscosity and surface tension forces have to be overcome and no change in pressure occurs. By adding additional fluid, the unit becomes a conventional U-tube manometer.

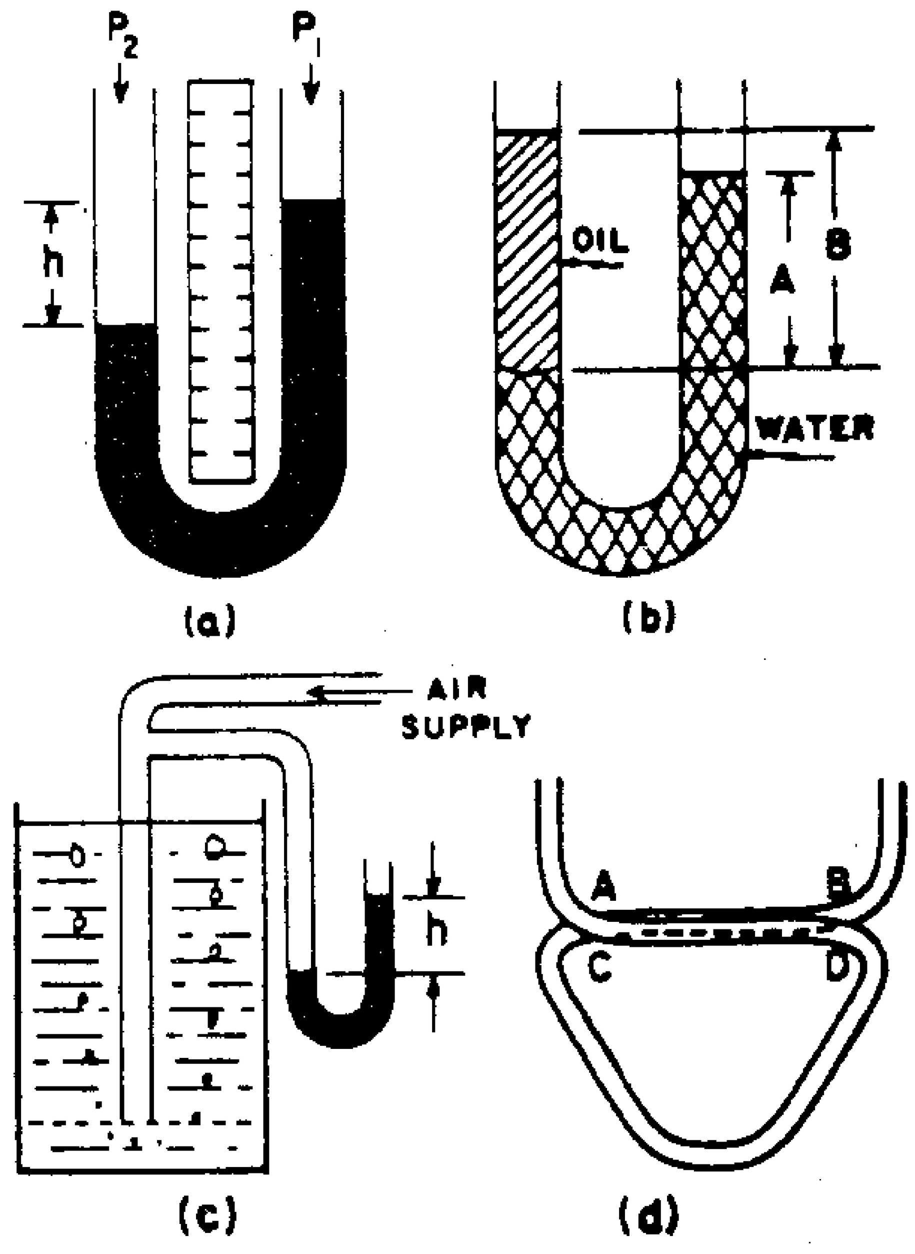

Figure 2–(a) Simple U-tube manometer. (b) Specific gravity determination by use of two fluids (water and unknown) in one open manometer. (c) Manometer for measurement of level in open tank. (d) Special U-tube manometer with sensitive null point.

Fixed-Cistern Barometers. Barometers are used to measure atmospheric pressure (fig. 3a). The glass tube for the fixed-cistern barometer is filled with distilled mercury so it is free from air, moisture or impurities before immersion into the well (Brombacher et al., 1960). The scale of the fixed cistern barometer, which is normally designed to measure pressures below one atmosphere, is calibrated in pressure units but may be graduated in altitude units as well. Fixed cistern barometers are used as a standard for checking altimeters and aneroid barometers. Accuracy, although affected by surface tension variations in the cistern, is usually 0.1 mm of mercury.

Absolute Pressure Gage. A simple absolute pressure manometer, shown in figure 3b, consists of a U-tube with the end of one leg sealed and completely evacuated. The open end is connected to the pressure to be measured.

Well Manometer. The principal advantage of the well manometer (fig. 4) over the U-tube is that a fixed zero reference is established and the pressure difference may be read directly. The ratios of the diameters should be as large as possible to reduce the error due to a change in liquid level in the well.

For static balance:

$$P_2 - P_1 = \left(1 + A_1 / A_2\right)\gamma h \qquad (4)$$

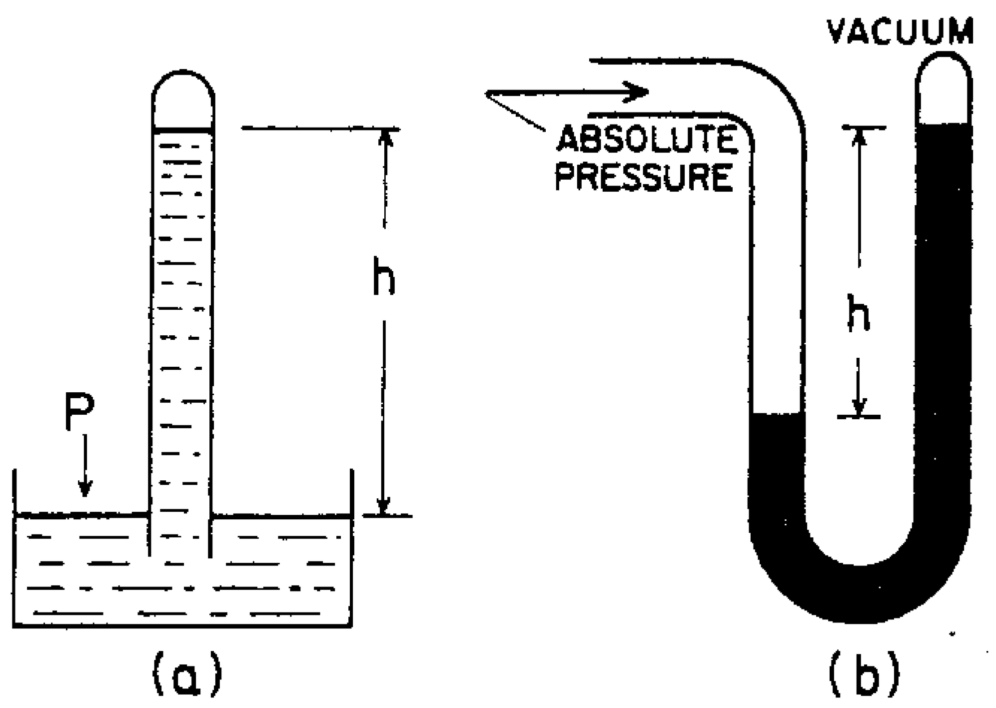

Figure 3–(a) Fixed-cistern barometer. (b) Absolute pressure gage.

TABLE 2. Comparison of pressure transducer systems

Characteristics	Strain Gage	Variable Capacitance	Piezoelectric	Differential Transformer	Variable Reluctance	Moving-contact (Potentiometer)
Typical pressure sensing device	Diaphragm, tube or bellows	Diaphragm	Crystal or ceramic element (used with flat diaphragm)	Bourdon tube, diaphragm, bellows	Diaphragm or twisted Bourdon tube	Bellows or Bourdon tube
Frequency	Low press: 500 Hz High press: 50KHz	10 to 30 KHz	10 Hz to 200 KHz	5 to 50 Hz	50 to 1000 Hz	5 to 50 Hz
Open circuit full scale output	Metal-Bonded: 2 to 4 mv/v Unbonded: 3 to 6 mv/v semiconductor- 25 to 50 mv/v	0.25 v/v	35 to 200 mv/psi	0.1 to 5.0v for 6.3 v input	0.05 to 0.1 v/v	Up to 75 v
Linearity (%)	0.1	0.5	0.5	0.5 to 1.0	0.5 to 1.0	0.2 to 1.0
Hysteresis (%)	0.25	0.02	Negligible	Negligible	0.2 to 0.3	0.5 to 1.0
Response to vibration, noise, acceleration	Low for higher pressure ranges	Low but noticeable	Appreciable, sensitive to electrical "noise"	Low	Low, 0.001 to 0.1% full scale/g	Vibration effects at low ranges (wiper lift-off from element
Allowable overload (%)	Approx. 100	Approx. 100	50 to 100		Up to 600	50
Thermal stability	Excellent for compensated bridge	Approx temp. drift 0.02% °F	Pryoelectric* effect, diaphragm thermal stresses cause drift	Some effect at low excitation frequ.-coil resistance change	Temp. drift 0.02% °F	0.008% °F
Temperature range (°F)	Metal gage: -430 to + 300 Semiconductor: -65 to +250	Up to 250	Quartz: -400 to +500 Ceramic: -65 to +200	-65 to +450 at 6.3v input	-65 to +300	-65 to +200
Remarks - advantages, limitations	Most popular type. Good frequency response. Ac or dc excitation. Easy to calibrate (shunt). Low level output signal.	Low mechanical energy input. Ac carrier excitation required. Temp. sensitive	Excellent high frequency response. Short- term static measurement possible only with special amplifier Must seal transducer and connections from moisture.	High level output signal. Negligible actuating force for LVDT itself. Low frequency response. Vibration sensitive. Ac carrier excitation required.	Available in dc or ac to dc systems with 0-5 v output. Can record with phase or freq. modulated system. Withstand sever shock and vib ration. Least common type of pressure transducer.	Ac or dc excitation. Low cost High output. Sensitive to vibration (use oil damping) Finite resolution except with new carbon film type.

* Causes changes in output proportional to the rate of temperature experienced by the crystal (Huggins, 1962).

MISCELLANEOUS PRESSURE TRANSDUCERS

Many other types of pressure transducers have been devised and are described in the literature. Only a few will be mentioned.

A unique method of pressure sensing has been accomplished by measuring the frequency of vibration in a fine wire. The wire in tension vibrates at its natural frequency. The wire tension and, hence, the vibration frequency is varied due to pressure changes since one end is connected to a diaphragm.

Hill (1959) has reported on an instrument for measurement of respiratory pressures. It is called a defocusing photo-electric pressure transducer and uses a terylene diaphragm coated with a layer of aluminum. This reflecting surface acts as a mirror and may be flat, convex, or concave in shape depending on whether the pressure applied to it is zero, positive, or negative. Reflection of a beam of light on the diaphragm falls on a phototransistor to provide changes in voltage output with pressure.

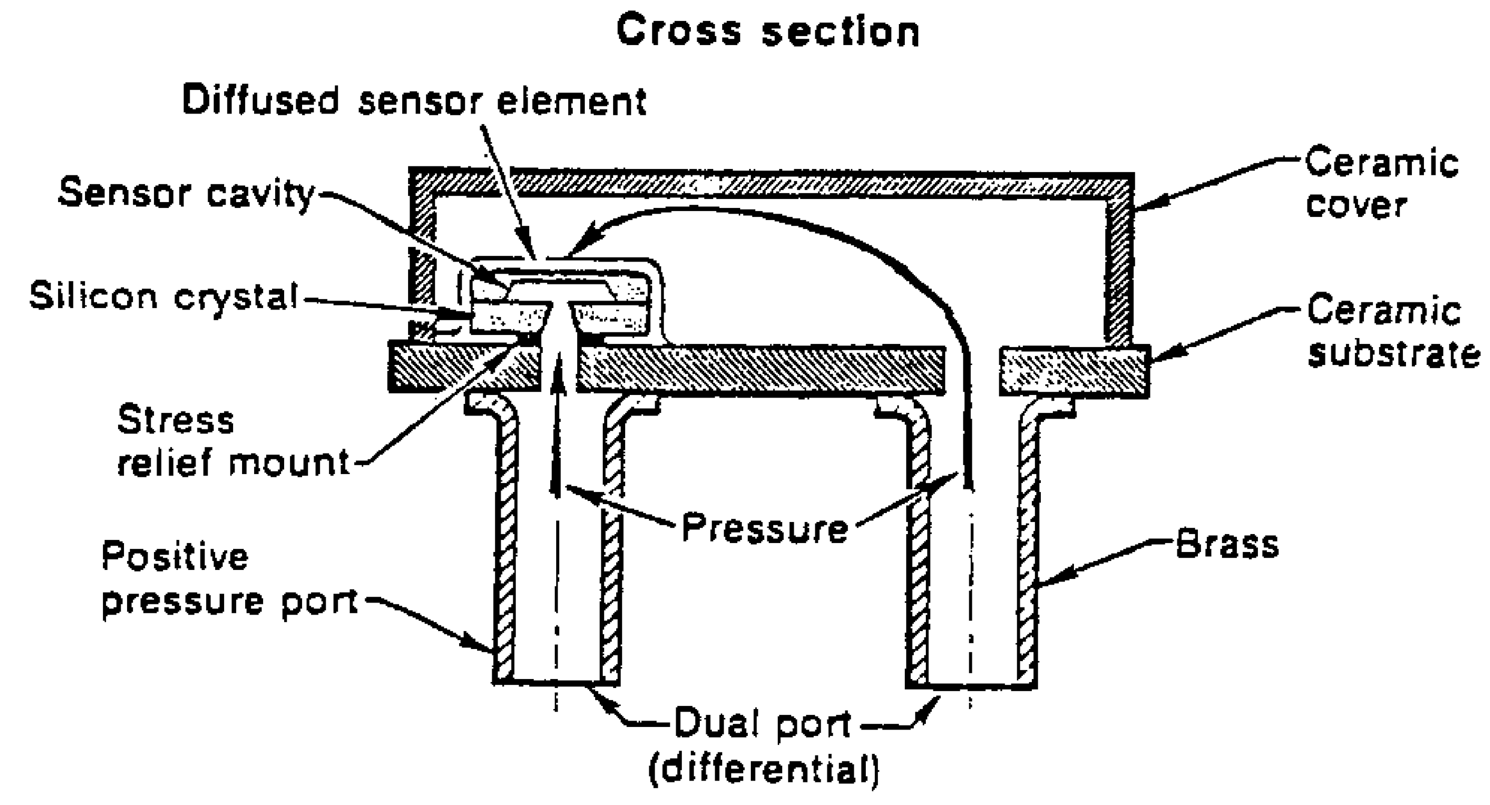

Figure 22–Silicon pressure sensor which includes two ports for differential measurement. Courtesy National Semiconductor Corp. From Teschler (1982).

An instrument known as a hypsometer may be used for indirect pressure measurement by measuring the boiling temperature of a liquid in equilibrium with its vapor. With a direct relationship between the equilibrium temperature and pressure of a vapor-liquid system, the accuracy and speed of response of such an instrument is limited only by the temperature sensing means. The hypsometer has proven itself to be superior to the aneroid as a pressure altimeter. By using a thermistor to detect temperature, Hobrough (1959) reports that the hypsometer is able to operate at the required sensitivity of 0.3 m resolution.

LOW PRESSURE MEASUREMENT—VACUUM

In the past 10 to 20 years, there has been an ever increasing need for high vacuum systems. While the chief requirement was formerly in vacuum tube manufacture, currently high vacuum is used in many fields including freeze drying, materials research, saline water conversion, and test chambers for space research.

The subject of vacuum technology has become a specialized field. Vacuum techniques have gone through a period of development to produce very high vacuum of 10^{-8} mm Hg a few years ago and ultra-high vacuum of 10^{-9} to 10^{-12} mm Hg today.

A conventional vacuum system includes a rotary oil pump, a diffusion pump, a cold trap, the working volume, and a triode ionization pressure gage. Recent electronic means of pumping using low-temperature sorption techniques and getter-ion pumps have been introduced. Getter-ion pumps decrease chamber pressure by chemical reaction of residual gases with an evaporated metal. For an introduction to vacuum techniques, the reader is directed to reference by Rutherford (1963) and Smith (1962). A complete survey of vacuum measurement is presented by Dushman (1962). An excellent bibliography by Brombacher (1961) on vacuum and low pressure measurement contains 1,538 references, 52 of which are books.

A vacuum may be defined as any pressure less than atmospheric pressure. Units used in vacuum measurement are usually millimeters of mercury or Torr, although sometimes the micron is employed. As indicated earlier, the Torr equals 1/760 of an atmosphere of pressure or one millimeter of mercury at pressures in the vacuum range. The unit millimeters of mercury (mm Hg) will be used here. Standard vacuum terminology has been proposed by the American Vacuum Society and the British Standards Institution (Brombacher, 1961). The American proposed classification of degrees of high vacuum is:

High vacuum	10^{-3} to 10^{-6} mm Hg
Very high vacuum	10^{-6} to 10^{-9} mm Hg
Ultra-high vacuum	10^{-9} mm Hg and below

It should be pointed out that many of the previously described liquid and mechanical type pressure measuring instruments may be used for determining vacuum to a pressure of 10^{-3} mm Hg or lower. Examples are liquid manometers, bellow, capsules, and diaphragm gages. The following discussion is directed principally toward vacuum measurement in the high to ultra-high ranges. A great majority of vacuum gages in use may be classified either as absolute manometers, thermal gages, or ionization gages. A few miscellaneous types are also available.

ABSOLUTE MANOMETERS

Absolute manometers are pressure measuring devices which are based on Boyle's law. The best example of an absolute manometer for vacuum measurement is the McLeod gage.

McLeod Gage. The McLeod gage has been used up to the present time as a primary laboratory standard for the calibration of other instruments down to about 10^{-4} mm Hg. However, its accuracy is not high and is in the neighborhood of 1% at higher ranges and around 10% near the low pressure limit.

In operation, a relatively large volume of the gas is compressed into a much smaller volume (sometimes by a factor of 100 000), so that the absolute pressure of the compressed gas can be measured by the simple manometric method. Boyle's law is used in calibrating the scale; consequently, by observing the final pressure and volume and by knowing the initial volume, the initial pressure can be calculated.

Figure 23a illustrates a single-range McLeod gage which obeys the square law (very nearly). In this gage, where the volumetric ratio of compression is not constant, a non-linear scale in which the readings are proportional to the square root of the absolute pressure. The pressure is given as:

$$P \cong \frac{Ah\,h}{V} \cong \frac{Ah^2}{V} \qquad (12)$$

where

A = cross-sectional area of the capillary tube,
h = length of air column in the capillary tube,
V = volume of the bulb.

The gage may be constructed with a fine platinum wire in the capillary tube. Mercury column height may then be measured electrically with a resistance thermometer-type instrument.

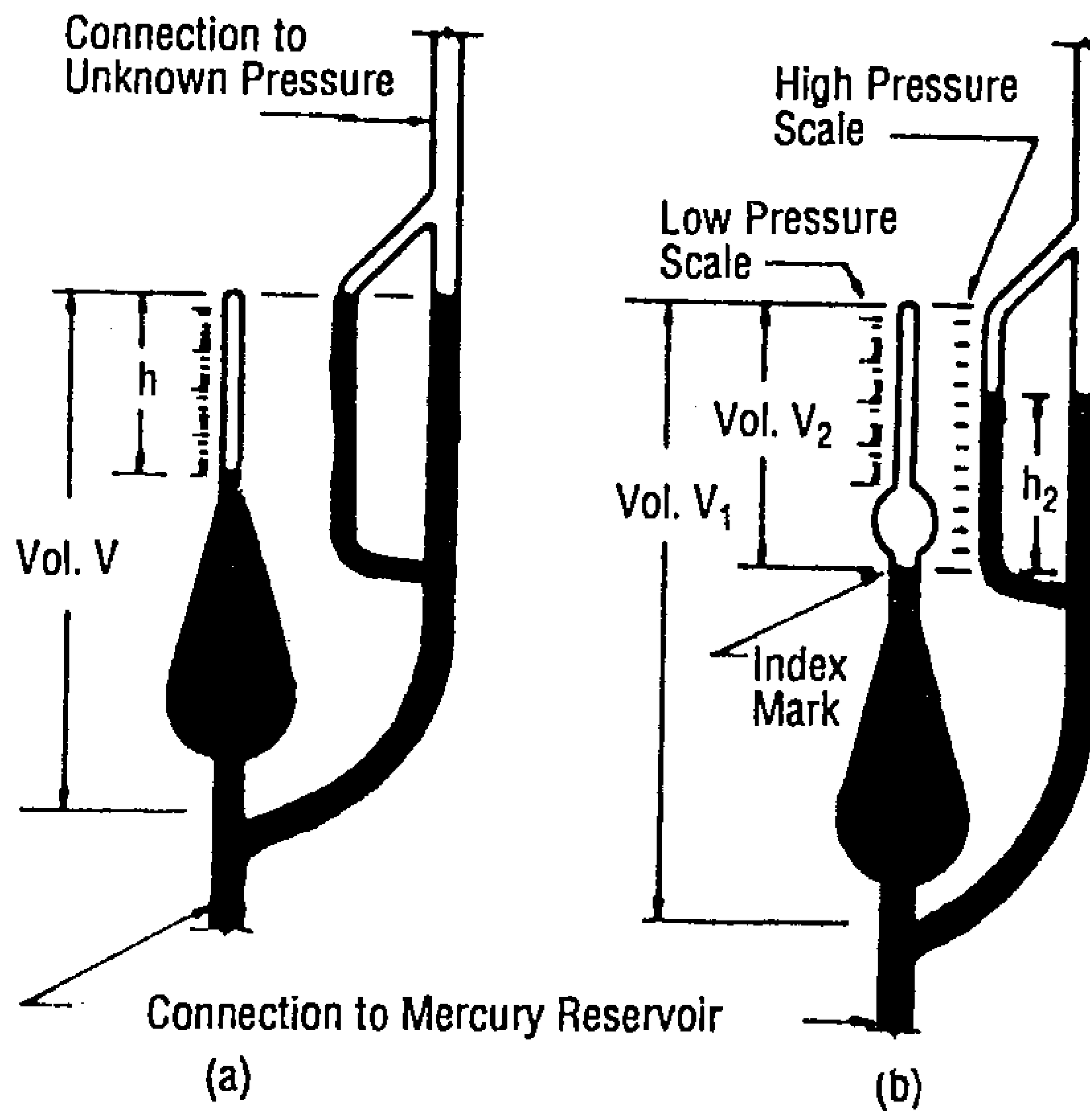

Figure 23–Conventional McLeod gage, with single range (a) and double range (b).

McLeod gages may be constructed in a double range as shown in figure 23b. For the higher ranges of measurement (where volumetric range of compression can be kept constant), a linear scale results. The pressure is then:

$$P \cong \frac{V_2}{V_1} h_2 \qquad (13)$$

The error in assuming the above equations to be correct depends upon several factors. The gas must not deviate from Boyle's law under the conditions of measurement. Also, the mercury must neither affect the gas nor the gas the mercury. The adjacent capillary tubes are made of the same diameter for compensation of capillary depression. Thus, an error in this respect is created when the closed end capillary becomes dirty. The chief source of error is due to variations in the surface tension of the mercury in the capillaries. This effect limits the size of the capillary to about one millimeter in diameter, since the gain in compression ratio is offset by the surface tension error. At high vacuums (low absolute pressure) the error is negligible, but at higher pressures of around 5 mm Hg the error becomes significant or about 5%.

McLeod gages take many forms. One common variation from the gage shown in figure 23 is the tilting McLeod gage. This gage is simply tilted to bring mercury from the reservoir to compress the gas.

THERMAL GAGES

Thermal conductivity vacuum gages are widely used. The principal advantages of this type of gage are continuous indication, an electrical output for remote indication or recording, and a fast response. These gages are normally used in the range from 10^{-3} mm Hg to 1 mm Hg.

The principle of operation of the thermal-type gage is that the thermal conductivity between a heated resistance element and the surrounding atmosphere (gas) is proportional to the pressure of the gas. Since thermal conductivity varies for different gases, these gages must be calibrated for any gas or vapor which might be present in the vacuum system. Thermal gages include the Pirani, the thermocouple, and the thermistor gage. Commercial Pirani and thermocouple gages are shown in figure 24.

Pirani Vacuum Gage. The Pirani gage consists of two identical tungsten filaments connected in adjacent arms of a Wheatstone bridge circuit. As shown in figure 25, one filament is sealed in an evacuated chamber while the other is exposed to the gas whose pressure is to be measured. The evacuated element theoretically provides compensation for variations in ambient temperature and for effects of small voltage variations. The latter effect is more significant than the ambient effect.

Thermocouple Vacuum Gage. The simplest version of the thermocouple gage consists of a resistance wire whose temperature is measured by a thermocouple hot junction welded

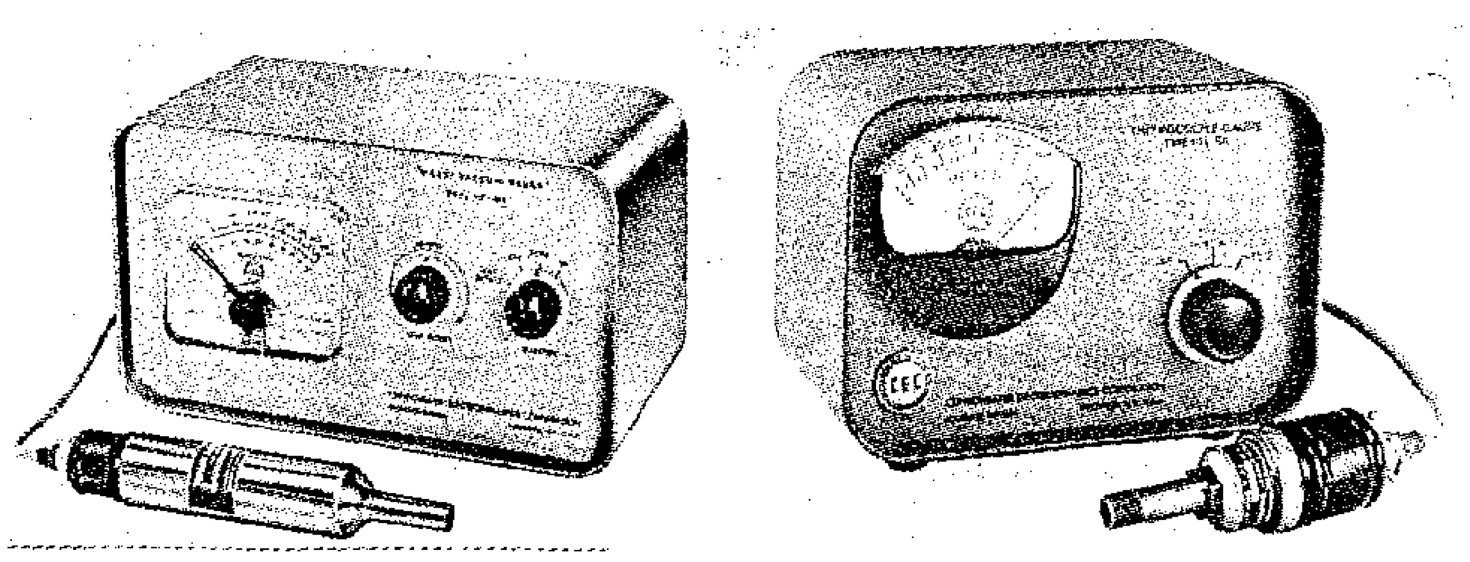

Figure 24–A Pirani vacuum gage (left) and a thermocouple vacuum gage (Consolidated Electrodynamics Corp.).

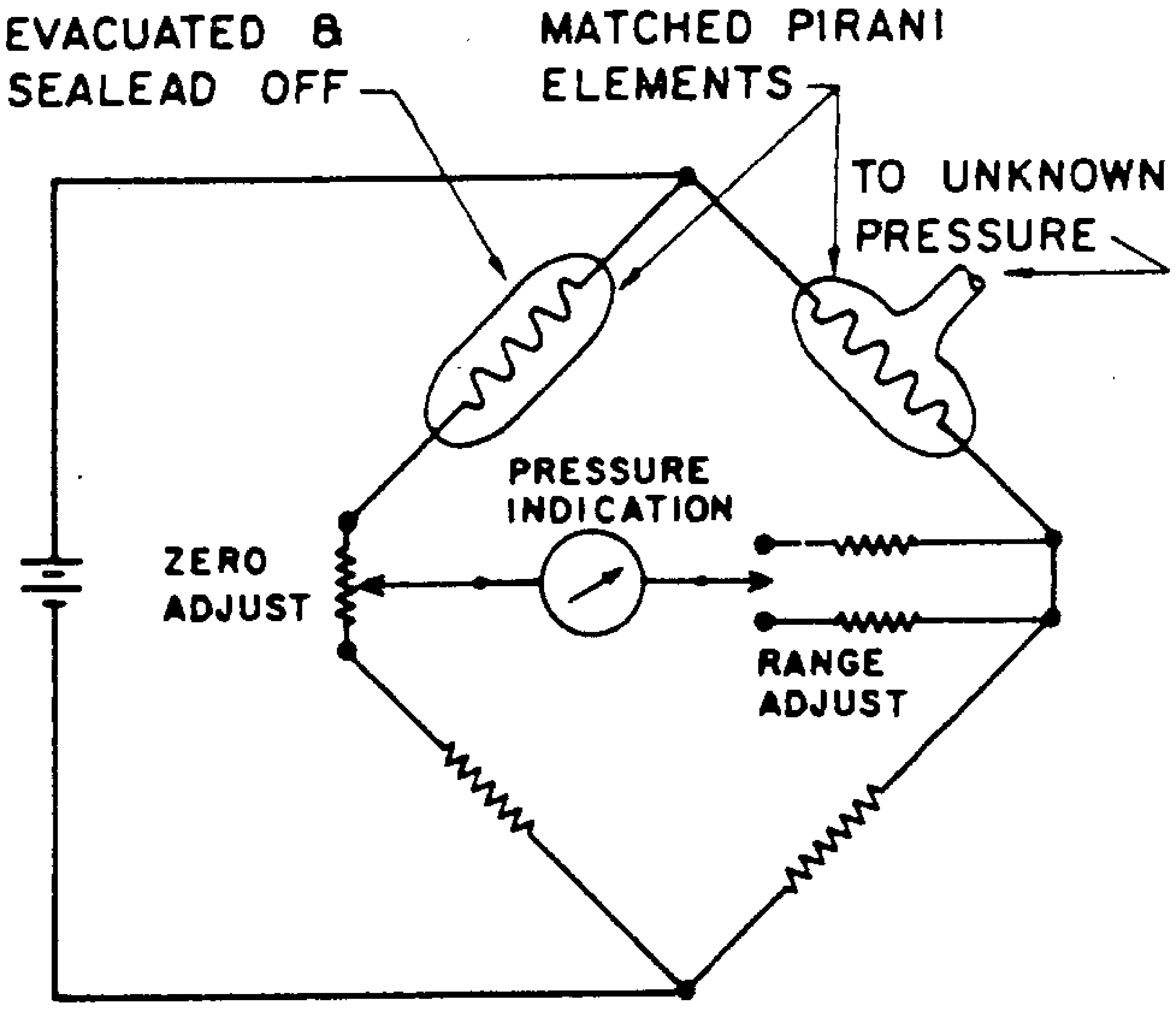

Figure 25–Basic circuit for a Pirani gage.

to the mid-point of the heater wire. The temperature of the junction is a function of the gas thermal conductivity, which in turn depends upon the pressure.

By connecting several thermocouples in series, a thermopile-type gage is made which requires no separate heater wire. This gage with a larger output can operate at lower temperatures than the thermocouple gage and thus does not tend to decompose vapors to the same extent.

The output from the thermocouple and thermopile gages can be detected on a millivolt potentiometer. Often sufficient output is available to drive a low-resistance DC microammeter. The thermocouple gage is simple, rugged, and relatively inexpensive. They are less susceptible to drift than the Pirani gages. However, Pirani gages with two scales are more accurate and are more sensitive as leak detectors .

Thermistor Vacuum Gage. The thermistor gage is similar in principle to the thermocouple gage except that the wire temperature is sensed by a thermistor. Thermistors may also be used as the sensing element in a bridge circuit as a Pirani gage for pressures of 10 mm Hg or lower.

IONIZATION GAGES

Ionization gages produce ions by collisions between gas molecules and high velocity electrons or other particles. Below a pressure of approximately 10^{-3} mm Hg, the formation of ions varies linearly with pressure. The degree of ionization is determined by measuring the ion current. Ion current can be expressed in terms of pressure.

Basically, ionization gages are of two types: cold-cathode (Phillips or "discharge") and hot-filament gages. Cold-cathode tubes are less expensive than the hot-filament gages since they require no amplifier. An accidental exposure to high pressure will not harm the cold-cathode gage, as there are no filaments in the sensing tube to burn out. Cold-cathode gages cannot be degassed as easily or as rapidly as hot-filament tubes. Due to the higher operating voltage causing a breakdown of carbon products, cold-cathode gages are more easily contaminated than hot-filament types. On the other hand, certain gases react chemically when exposed to the heated element of the hot-filament-type gages. Cold-cathode sensing tubes are made of metal and are, therefore, more rugged than the glass, hot-filament tubes.

Triode Vacuum Gage. This gage is one of the most popular devices for measuring gas under high-vacuum conditions. Electrons from a thermionic (hot-filament) cathode are accelerated toward and beyond a positive grid (150 V). Ions are formed by the collision of electrons with the gas molecules in the tube. The number of positive ions formed is proportional to the gas pressure. These ions are collected on a negative electrode (ion collector).

Phillips Ionization Gage. The Phillips gage, developed by Penning, reduces the effect of chemically-active gases reacting with the filament as with the hot-filament gage. Electrons are ejected from a cold-cathode of thorium or zirconium by bombarding it with positive ions that have been accelerated by the cathode potential. The electrons ejected are made to travel in a long helical path towards the anode by means of a magnetic field. With the long path, more ionization is produced per electron than if no magnetic field were present.

The gas-discharge current is a result of an involved set of interactions in which electrons, positive ions, and photoelectric X-rays take part. As a result, the output current is not linear with pressure as in the case of the triode gage. Furthermore, the Phillips gage is not as accurate as the triode gage. A typical pressure range is from 10^{-6} to 10^{-1} mm Hg.

Radioactive Ionization Gage. This novel type of cold-cathode gage, described by Lafferty and Wanderslice (1963) and called the "Alphatron", produces ionization by radioactively emitted alpha particles. These particles, from a radium source, ionize the gas. The small ionization current is highly amplified so that the output can be read on a microammeter.

Like the Phillips and the triode gages, the sensitivity depends on the kind of gas being measured. By employing two ionization chambers, it is possible to produce a gage with linear output for air from 10^{-3} to 10^{3} mm Hg.

An advantage of the Alphatron over the triode gage is that there is no filament to burn out. An advantage as compared to the Phillips gage is the fact that there is no possibility of chemical reaction between the gas and the cathode. It has good response and is not damaged when suddenly exposed to high pressures. Precautions must be taken in using the gage to avoid any physiological effects from radiation.

Gages from Ultra-High Vacuum

Until 1948, ionization gages were limited to measuring pressures of 10^{-8} mm Hg, while pumping equipment could produce lower pressures. Nottingham discovered the X-ray effect about this time. As electrons strike a metal part (grid), they produce soft X-rays which eject photoelectrons from the ion collector. This effect makes it impossible to distinguish the photoelectrons leaving the ion collector from the positive ions arriving at the collector. In 1950, Bayard and Alpert developed an inverted ionization gage which reduced this X-ray effect by decreasing the surface area of the ion collector. With this gage, pressures to about 10^{-10} mm Hg could be measured.

In 1958, Redhead and Hobson of the Canadian Research Council designed an ionization gage similar to the Phillips gage but with a cold-cathode discharge in crossed electric and magnetic fields. It has the advantage of no X-ray limit and no vapor pressure due to a hot filament. This inverted magnetron gage produces a linear pressure-ion current over the range from 10^{-13} to about 10^{-14} mm Hg.

Other Vacuum Gages

Several other principles have been used to develop vacuum gages, although at the present time few of these gages have gained appreciable acceptance.

One type is known as the rotating viscometer gage. A cylinder rotates about a stationary, pivoted armature. The gage deflection (somewhat similar to a cradle dynamometer principle) is due to the momentum transfer between the rotating and stationary parts and is proportional to ambient pressure.

Radiometer-type gages, such as the Knudsen gage, depend on the difference in kinetic energy of molecules striking a hot and a cold surface to produce a momentum or movement to a torsion suspension carrying a mirror. Light is reflected from the lightweight mirror to a translucent scale. The greater the rotation of the torsional suspension system, the higher the pressure.

Mass spectrometers have been used for high vacuum measurements. Pressures in the neighborhood of 5×10^{-10} mm Hg can be measured (Lafferty and Wanderslice, 1963).

A summary of operating pressure ranges for different types of vacuum gages is given in Table 3.

Calibration of Vacuum Gages

The McLeod gage, until the present time, has been used extensively as the calibration standard for pressures down to about 10^{-4} mm Hg. The gage is desirable as a standard because all measurements are dimensional, but accuracy is relatively poor at the lower ranges. Well-made Knudsen gages have been used for calibration for pressures down to 10^{-5} mm Hg, but the instrument is very delicate for general calibration purposes. Ionization gages, although built to rigid specifications, are not suitable as primary standards, since the gage characteristics change with time and the gages are not linear throughout all ranges.

A technique for vacuum gage calibration is described by Roehrig and Simons (1963). The system uses cascaded, differentially pumped stages to provide relatively accurate gage calibration over the range of 10^{-9} to 10^{-3} mm Hg. The accuracy is believed to be ±10%.

Dynamic Pressure Measurement

There are many factors to consider in the selection of a pressure transducer for a particular application. Many of the instrument characteristics, such as static accuracy, sensitivity, temperature (or environmental) limits, overrange pressure, hysteresis, and linearity, have been discussed above. Other considerations may be transducer size, weight, corrosion tolerance, type of output signal, and instrument cost. For

TABLE 3. Summary of approximate operating ranges for various types of vacuum gages

Vacuum Gage	Pressure Range, mm Hg.
Mercury manometer	10^{-1} to 10^{3}
Evacuated bellows	1 to 10^{2}
Alphatron	10^{-3} to 10^{3}
Thermistor	10^{-3} to 1
Thermocouple	10^{-3} to 1
McLeod	10^{-4} to 1
Pirani	10^{-4} to 1
Philips (cold-cathode)	10^{-5} to 10^{-2}
Knudsen	10^{-8} to 10^{-2}
Triode (hot-filament)	10^{-9} to 10^{-3}
Bayard-Alpert	10^{-9} ro 10^{-4}
Inverted magnetron (cold cathode)	10^{-12} to 10^{-4}
Mass spectrometer	10^{-14} to 10^{-5}

FLOW

J. A. Replogle, G. S. Birth

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INTRODUCTION

Regulated fluid flow is an essential feature of advanced civilization. Industrial, agricultural, and municipal processes, as well as domestic conveniences, require controlled flow systems. Closely related to regulation is the need for flow measurement. Techniques of flow measurement have developed over a period of many centuries. Classical examples include the flow measuring devices of Henry Pitot, in 1732, and J. B. Venturi, in 1791, which still bear their names. Because of its relatively long history and the multitude of improvements and new developments, complete coverage of the subject is beyond the scope of this chapter. Instead, an effort has been made to assist the reader in selecting a flow measuring system compatible with his particular installation and instrumentation requirements. Emphasis is placed on briefly describing the most usable devices and methods for research and industrial applications and in guiding the reader to reference material for more complete coverage of a particular device or system. Less emphasis has been placed on the older, more generally familiar methods in order to permit better coverage of newer, or less conventional methods that may be of help to the researcher or field engineer.

Many new flowmeters have resulted from the present industrial requirements for handling large volumes of flowing fluids and for the control of flow rate in continuous industrial processes. In general, even these new fluid meters can be divided into two functional groups. One primarily measures quantity, the other measures rate of flow (Harrison, 1980).

All flow measuring systems consist of two distinct parts, each of which performs different functions. The first, called the primary element, is in contact with the fluid and causes some type of interaction. The secondary element translates the interaction between the fluid and primary element into the desired unit of measure. The secondary devices can be varied almost indefinitely, but the primary elements depend on a few simple physical principles for their operation. These physical principles thus provide a natural system for classifying flowmeters. This system is used as the basic outline for the presentation herein.

Table 1 lists many of the general types and classes of flowmeters and indicates their standard accuracy, usual operating ranges, and their usual application, such as pipe-line flow, open-channel flow (canals, streams, etc., where a cross-sectional area of flow can be defined), and open air flow (or ocean current measurements where a cross-sectional flow area is not easily defined). Some meters can be adapted to several of these applications. When such is the case, the primary or most convenient application is indicated in Table 1 by a numeral 1. Secondary and tertiary applications are indicated by numerals 2 and 3, respectively. When a meter is shared about equally by more than one application, such is indicated by giving both applications identical number ratings. Also indicated are those meters that can operate satisfactorily with granular materials or with liquids entraining solids.

QUANTITY METERS

Quantity meters measure isolated quantities of fluid through the primary element, either by weight or volume. Usually, containers of known capacity are alternately filled and emptied, permitting essentially uninterrupted flow of the metered supply. Quantity meters (except weighing meters and turbine meters) are also known as positive displacement meters (Stoll, 1962; Walker, 1966). In these meters the flow passes through the primary element in isolated or nearly isolated quantities. These quantities are counted and indicated in terms of volume units by the secondary element or register. Ideally, the chamber containing the isolated quantity in a positive displacement meter should be sealed so tightly that the fluid cannot enter or leave the chamber under any pressure difference to which the meter would normally be subjected. Such a seal is called a positive seal, which is difficult to obtain under practical conditions.

A capillary seal attains a practical degree of measuring-chamber tightness by virtue of the strength of the surface tension of a film of the fluid between two of the chamber surfaces which do not actually touch. The clearance between these surfaces must be very small compared to the length of the shortest path that the fluid would travel between them in escaping.

Most quantity meters drive a counter directly to register the total flow, hence, rotating seals are required, and the operation of the counter places an added frictional load on the meter. In situations where these factors present a problem, the movement of the primary element can be sensed by electromagnetic induction. Because these are moving parts, they are subject to wear and should receive regular maintenance checks. They should not be used with fluids containing solids or abrasive materials. Entrained air in liquids will be measured as liquid in the volumetric quantity meters, so an air trap should be placed upstream from the meter to remove the air.

Quantity meters are normally considered to have higher accuracy than rate meters. Except for the turbine meter, they maintain good accuracy into the low flow range as well. With special secondary elements, quantity meters are sometimes used to measure rate.

GRAVIMETRIC METERS

Weighers. Weighing is a primary standard of flow measurement. Accuracy of weighing devices is routinely considered to be better than ±0.1%. Because of this, they are frequently used to calibrate other meters. Weighing or gravimetric meters, in their simplest form, involve weight determinations with a tank mounted on a beam scales (Rouse,

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Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval of the product to the exclusion of others that may also be suitable.

TABLE 1. Characteristics of flowmeters

		Applications								Range of maximum flows		
		Gas	Liquid	Granular solids	Pipe flows	Open channels	Open air	Useful rangeability	Standard accuracy	Gases	Liquids	Remarks
QUANTITY METERS												
Gravimetric meters	Weighers	1	1	1	1			100:1	0.1%		No limit	
	Weigh belt		1					100:1	1.0%		No limit	
	Weigh wheel		1					100:1	1.0% r		No limit	
	Weigh dump		2	1	3	2		100:1	1.0% r		No limit	
Volumetric meters	Metering tank		1	1	1	2		10:1	1% r		No limit	
	Nutating disk		1		1			10:1	1% r		1-4000 l/s	Clean liquids
	Gear or lobed impeller	1	2		1			10:1	1% r			Clean fluids
	Sliding vane reading	2	1		1			10:1	1%		20-30000 l/s	Clean fluids
	Rotating vane	2	1		1			10:1	1%			Clean fluids
	Dethridge meter		1		2	1		3:1	3% fs†		50-150 l/s	
	Reciprocating piston		1		1			20:1	1% r		0.01 l/s-750 m ^{3}/s	Clean liquids
	Oscillating piston		1		1			20:1	1% r			Clean liquids
	Diaphragm or bellows	1			1			20:1	1% r		0.01-250 l/s	
RATE METERS												
Differential meters	Venturi tube	1	1		1			5:1	1.5% fs	50 l/s-250 m3/s	1 l/s-50 m ^{3}/s	Can use with slurries
	Twin-throated venturi	1	1		1			5:1	1.5% fs	50 l/s-250 m3/s	1 l/s-50 m ^{3}/s	Clean fluids
	Orifice	1	1		1			5:1	1.5% fs	2 l/s-25 m3/s	0.1 l/s-200 l/s	
	Flow nozzle	1	1					5:1	1.5% fs	50 l/s-250 m3/s	1 l/s-50 m ^{3}/s	
	Centrifugal flow element		1		1			3:1	1.5% fs	50 l/s-250 m3/s	1 l/s-50 m ^{3}/s	3-5% error if calibrated ikn place
	Pitot tube	1	1		1	1	2	3:1	2% fs			Small differential reading
	Linear resistance	1	2		1			10:1	1% fs		0.1-100 l/s	No pressure recovery
Variable area meters	Glass tube	1	1		1			10:1	1.5% fs	10-300 l/s	0.0005-10 l/s	
	Slotted cylinder and piston		1		1			10:1	1% fs			
Variable head and area meters	Sharp-crested weir		1			1		20:1	1.5% fs		-1 m ^{3}/s but no particular limits	Under field conditions 5% is usual accuracy
	Broad-crested weir		1			1		35:1	2% fs			
	Short-throat flume		1			1		35:1	3% fs		No limits	Special designs exceed 1000:1 range
	Long-throat flume		1			1		>75:1	2% fs			

TABLE 1. Characteristics of flowmeters (continued)

		Applications								Range of maximum flows		
		Gas	Liquid	Granular solids	Pipe flows	Open channels	Open air	Useful rangeability	Standard accuracy	Gases	Liquids	Remarks
RATE METERS (Continued)												
Force displacement meters	Target	1	1		1	2		5:1	1% fs			
	Vane		1		1			5:1	1% fs			
	Ball	1	1		1			5:1	2% fs			
	Vanable weight	1	1		1			10:1	1.5% fs			
	Hydrometric pendulum		1			1		3:1	5% fs			
	Pendvane	1	1					15:1	3% fs			
	Integrating float	1	1		1			5:1	5% r			
	Jet deflection	1	1		1		1	10:1	5% fs			
Force momentum (mass)	Axial flow mass	1	1		1			10:1	0.5% r*	0.1-100 Kg/s	0.5-1000 Kg/s	
	Radial mass	1	1		1			10:1	1% fs†			
	Massometer			1	1			10:1	1% fs			Can handle foams & slurries
	Magnus effect	1	1		1			10:1	1% fs			
Force velocity meters	Turbine	1	1		1			15:1	0.5% r	0.25 l/s-150 m^3/s	0.0002 l/s-3 m^3/s	
	Turbine compount	1	1		1			1000:1	0.5% r	0.25 l/s-150 m^3/s	0.0002 l/s-3 m^3/s	
	Propeller	1	1		1	1	2	15:1	1% r	0.25 l/s-150 m^3/s	0.0002 l/s-3 m^3/s	
	Aerovane	1					1	1:100	1% r			Dynamic response error 7% or greater
	Vortex velocity	1	1		1			10:1	0.5% r	10 l/s-1 m^3/s		
	Cup-type	1	1		2	1	1	15:1	1% r			
	Float velocity	2	1		2	1	2	10:1	5% r			
	Chemical velocity	2	1		1	1	2	20:1	1.5% r			
Thermal meters	Hot wire anemometer	1	2		1	2	1	20:1	1.5% r			
	Hot film anemometer	1	1	1	1	1		20:1	1.5% r			
	Thermocouple anemometer	1			2		1	20:1	1.5% r			
	Thomas meter	1			1			20:1	1% r			
	Boundary layer mass	1	1		1			50:1	1% r			
Chemical dilution techniques	Continuous addition of tracer		1		2	1		1000:1	2% r			Requires accurate concentration analysis
	Slug injection method		1		2	1		1000:1	2% r			
Special metering methods	Electromagnetic		1		1			20:1	1% fs	0.0001 l/s-3 m^3/s		Conductive liquids only
	Ultrasonic		1		1	2		20:1	1% fs			
	Nuclear magnetic resonance		1		1			10:1	2% fs			
	Optical-ring laser	1	1		1			10:1	1% fs			Requires transparent pipe and fluid

* Reading.
† Full scale.

TEMPERATURE

J. B. Simpson, C. A. Pettibone, G. A. Kranzler

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INTRODUCTION

Temperature is one of the four basic quantities which form the basis of our scientific measuring system. Of these four basic quantities, only temperature is an intensive quantity where the final value from combined bodies is not the sum of the original values. To measure temperature, two things must be established—a reference temperature and a rule for measuring the difference between a particular temperature and the reference temperature. Temperature alone of the four prototype quantities possesses this requirement.

All modern temperature measurements take as their fundamental origin the thermodynamic temperature scale. With a definition derived from the second law of thermodynamics, this scale is satisfying theoretically but not easy to realize in practice. Therefore, the International Practical Temperature Scale of 1968 (IPTS-68) was chosen in such a way that its temperatures closely approximate what would be measured on the thermodynamic scale (Benedict, 1969b). This practical scale assigns values for the temperatures of 11 reproducible equilibrium states and includes formulas that relate the indications of calibrated standard instruments to the scale. Fixed points, temperatures, and measurement methods for the International Practical Temperature Scale of 1968 are shown in figure 1.

The ultimate user of a temperature measuring instrument receives a calibration traceable directly or indirectly to a standardizing laboratory. In the United States, it is the responsibility of the National Bureau of Standards to establish, maintain, and assume custody of physical measurements. The Bureau accepts selected types of temperature measuring instruments for calibration for use as reference for working standards where precise temperature measurement is required.

Calibration of a given temperature measuring device is generally accomplished by subjecting it to some established fixed-point environment or by comparing its readings with those of some more accurate (secondary standard) temperature sensor which has, itself, been calibrated. Accurate resistance thermometers, thermocouples or liquid-in-glass expansion thermometers are commonly used as secondary standards. Fixed-point standards using the melting points of various metals and the triple point of water are commercially available.

The Celsius scale has its zero at the ice point, a value of 0.01° C at the triple point of water, and its 100° mark at the temperature of pure boiling water under standard atmospheric conditions. The Kelvin scale has its zero at absolute zero, a value of 273.16 K at the triple point of water, and like the Celsius scale 100° between the ice point and the boiling point of water.

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The Fahrenheit scale has values of 32 and 212° F at the ice point and the boiling point of water, respectively. Thus,

$$°F = 9/5\,°C + 32 \qquad (1)$$

or

$$°C = 5/9\,(°F - 32), \qquad (2)$$

where F is degrees Fahrenheit and C is degrees Celsius.

The Rankine scale has scale increments equal to the Fahrenheit scale, but with its zero at absolute zero. Therefore,

$$°R = °F + 459.69, \qquad (3)$$

where R is degrees Rankine.

Any property of the material having a predictable rate of temperature variation may serve as a temperature indicator. In general, however, four basic methods of temperature measurements are used:

- Thermal expansion
- Thermoelectricity
- Resistance
- Radiation

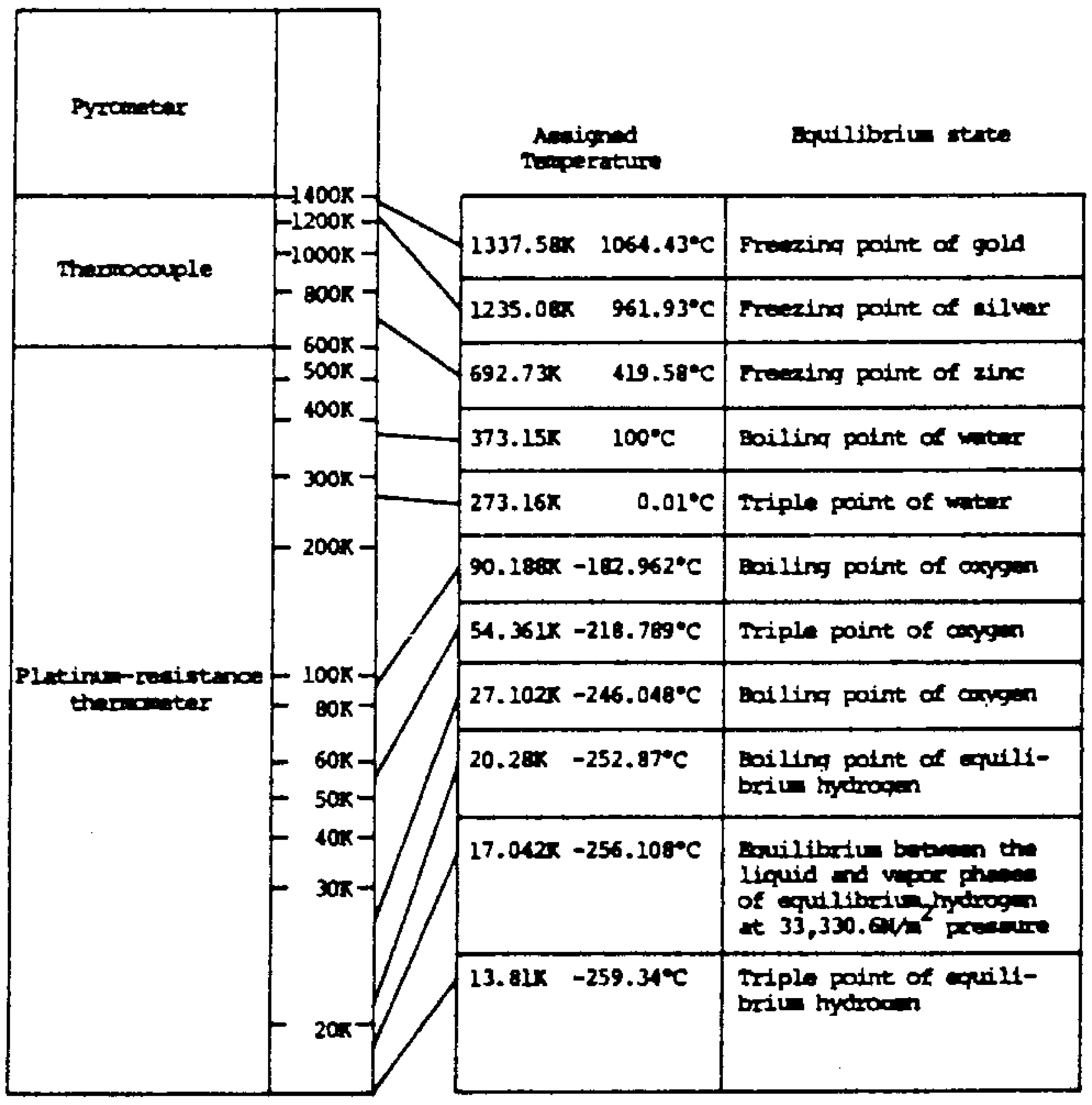

Figure 1–Schematic of the international practical temperature scale of 1968 (Gray and Finch, 1971, p. 34).

compensation approach eliminates two computational steps which are required with software compensation. However, this method is more restrictive since the electronic ice point for each instrument will normally be calibrated for only one thermocouple type.

The small magnitude of thermocouple voltages means that noise and transient voltages may influence the accuracy of temperature measurements (Morrison, 1977; Lewis, 1990). Noise rejection circuits are an integral part of present generation thermocouple measurement instruments to minimize extraneous voltages. Guarding, shielding, and twisted extension wires should also be employed for long thermocouple leads to reduce the incidence of magnetically induced voltages.

Simple verification and diagnostic procedures should be incorporated in any long term thermocouple temperature measurement installation to improve reliability and to minimize system errors. These include:

Documentation. Thermocouple systems are easy to use and encourage the use of large amounts of data. Systems and channels are sometimes changed. Record all events that could even remotely affect the measurements. Documentation can provide insight into reasons for unexplained changes in system performance.

Replicated readings. Replications will improve data reliability and identify problem areas.

Periodic tests. Test accessible thermocouples in an ice bath to verify thermocouple and system performance.

Thermocouple resistance. A sudden change in the resistance of a thermocouple circuit should act as a warning. Sudden changes may indicate an open wire, short, or change due to vibration fatigue, galvanic action, wire deterioration, or other causes. A technique known as offset compensated ohms measurement may be used to measure thermocouple resistances (Omega Engineering, 1987).

Thermocouples are widely used for remote temperature measurements, especially where large numbers of readings are needed. However, there are also many applications for which they are not well-suited and where other temperature measuring devices are preferable. They seldom displace the purely indicating thermometers for direct, non-recording observations of temperature at accessible locations. The resistance thermometer has greater inherent sensitivity, making it possible to measure a smaller fraction of a degree, and it does not require a fixed reference junction. In the range of temperatures above 500° C the radiation pyrometry is also competitive. Specific application information and assistance is available from thermocouple and instrument manufacturers and their representatives.

RESISTANCE THERMOMETRY

This discussion of resistance thermometry will cover resistance thermometers, thermistors, and integrated circuit units which exhibit changes in electrical resistance with changes in temperature.

RESISTANCE THERMOMETERS

These units are widely used for precision temperature measurements in both laboratory and industrial applications (Carr, 1972). Their operation is based on changes in electrical resistance with changes in temperature. All metals possess this characteristic, but only platinum, nickel, and copper generally exhibit acceptable resistance, temperature, manufacturing, and costs characteristics for industrial purposes. Some properties of these three metals are given in Table 1.

In practice, the maximum temperature measured will be well below the melting temperature of the sensing metal to prevent contamination at elevated temperatures.

The relationship between temperature and resistance can be adequately described by an equation of the form:

$$R_t = R_0\,(1 + at + bt^2 + ct^3 + \cdots)\,, \qquad (4)$$

where

R_t = resistance at temperature t,

R_0 = resistance at reference temperature, usually 0° C.

and a, b, and c are constants. The number of terms used depends on the material, temperature range, and accuracy desired. In many cases, covering limited temperature ranges, only the first constant, a, is required. This constant is referred to as the temperature coefficient of resistance and is defined as the ratio of change of resistance to the resistance at 0° C, or

$$a = \frac{R_1 - R_2}{R_0} \text{ per degree} \qquad (5)$$

Table 2 gives comparative resistance versus temperature values for common resistance elements.

Sensing elements are available in a number of different forms. The resistance units may be encased in stainless steel bulbs for the measurement of corrosive fluid temperatures. Open type sensors give faster response, but are limited to non-corrosive atmospheres. Various configurations are available for measuring surface temperatures, but care must be exercised to prevent thermal strains from introducing spurious outputs.

Resistance temperature detectors (RTDs) are available with resistances ranging from about 10 to 15,000 ohms. The single most common resistance value is 100 ohms at 0° C. Higher resistance values are less affected by lead wire and contact resistance variations.

INSTRUMENTATION FOR RESISTANCE THERMOMETERS

As with instrumentation for thermocouples, newer instruments have largely replaced deflection and null-balance measurement methods. Inexpensive hand-held or panel meters use specialized circuitry with dedicated computers or microprocessors to transform measured analog signals directly into temperature readings, in any desired temperature scales. They may also be transmitted to data acquisition systems for analysis, storage, and control purposes.

Unlike thermocouple instrumentation, no reference junctions are needed for RTDs. The resistances of these units are directly proportional to the absolute temperature. However, the actual resistance of installed RTDs is difficult to measure, since many measurements are made remotely. Lead wire resistances and changes in lead wire resistances with temperature will have significant affects on resistance readings. In practice, specialized circuits are utilized to transform RTD resistances into voltage signals which are used to determine measured temperatures.

Bridge circuits have been widely used to amplify the small resistance changes that take place in RTDs with changes in

TABLE 1. Resistance thermometer metals (O'Higgins, 1966, p. 257)

Materials	Temperature coefficient of resistance ohms/ohm °C at 0°C; Range 1 - 100°C	Melting point, °C	Range limits, °C
Platinum	0.00392	1773	-263 to545
Nickel	0.0063 - 0.0066	1455	-190 to 310
Copper	0.00425	1083	-40 to 125

TABLE 2. Comparative figures on resistance vs. temperature for three metals normally used for resistance thermometers (O'Higgins, 1966, p. 258)

Metal	Ratios of resistances at following temperatures and 0 C, R_t/R_o											
	-200 °C	-100 °C	0 °C	100 °C	200 °C	300 °C	400 °C	500 °C	600 °C	700 °C	800 °C	900 °C
Copper	0.117	0.557	1.000	1.431	1.862	2.299	2.747	3.210	3.695	4.208	4.752	5.334
Nickel	---	---	1.000	1.663	2.501	3.611	4.847	5.398	5.882	6.327	6.751	7.156
Platinum	0.177	0.599	1.000	1.392	1.773	2.142	2.499	2.844	3.178	3.500	3.810	4.109

temperature and to transform RTD resistances into voltage signals. These bridges may be excited from either a-c or d-c sources. Direct or rms currents through the resistance elements of 2 to 20 ma are common. The resistance change due to the current heating effect is usually negligible, depending on sensing elements and heat transfer conditions.

Figure 14 shows a typical Wheatstone Bridge circuit with the RTD (resistance R3) being connected as a 2-wire bridge.

At balance (Vo = 0):

$$R3 = R2R4/R1 \tag{6}$$

which will be proportional to the absolute temperature of the sensor unit.

Lead wire resistances may significantly affect bridge readings. Figure 15 shows a 3-wire bridge circuit with equal lead wires in arms 2 and 3 of the bridge to minimize lead wire resistance effects. Four-wire bridges are also used, depending on accuracy as well as bridge non-linearity and resistance requirements.

Classically, bridge equations and resistance-temperature relations were used to determine the temperature of interest. Today, however, the output voltage will be detected by a measurement instrument with a dedicated computer to determine measured temperatures directly. Instruments with selector switches and multiple programs are available for use with different RTD types.

While the resistance variations of the RTD in a bridge circuit may be quite linear with changes in temperature, the output of the bridge will not be linear for large resistance changes. The 4-Wire Ohm measurement system shown in figure 16 will alleviate this problem for some RTD applications (Omega Engineering, 1987).

This circuit uses a current source and a remote digital voltmeter. The bridge-completion resistors are replaced by a single reference resistor of appropriate size and rating. The output voltage will be directly proportional to the resistance of the RTD, and will be insensitive to the length or resistance of the lead wires. This voltage may also be detected by a computer- or microprocessor-based instrument to indicate measured temperatures directly and transmit temperatures to data acquisition and control system.

THERMISTORS

A thermistor is a semi-conductor which exhibits a change in electrical resistance with a change in temperature. Most thermistors are made from metallic oxides whose resistances decrease with increases in temperature, thereby reflecting a negative temperature coefficient of resistance. This is in contrast to metals which exhibit increases in resistances with increases in temperature. Thermistors are also available with positive temperature resistance coefficients, and with temperature coefficients that change from negative to positive at transition temperatures, making them useful for specialized switching applications.

Within limits, thermistor resistance is almost entirely a function of its temperature (Doebelin, 1966). They are available with acute temperature sensitivity with negative temperature resistance coefficients of 6% per °C, in contrast to a positive temperature resistance coefficient of 0.4% per °C for a platinum resistance thermometer. A typical 2000-ohm thermistor with a temperature coefficient of 3.9% per °C at 25° C will exhibit a resistance change of 78 ohms per °C change in temperature, compared with 7.2 ohms for a platinum resistance bulb with the same basic resistance. This high sensitivity makes the thermistor an unusually effective transducer for temperature measurement, control, and compensation, particularly where accuracy and high resolution are important.

The resistance-temperature relation is generally of the form:

$$R = R_o e^{\beta\left(\frac{1}{T} - \frac{1}{T_o}\right)} \tag{7}$$

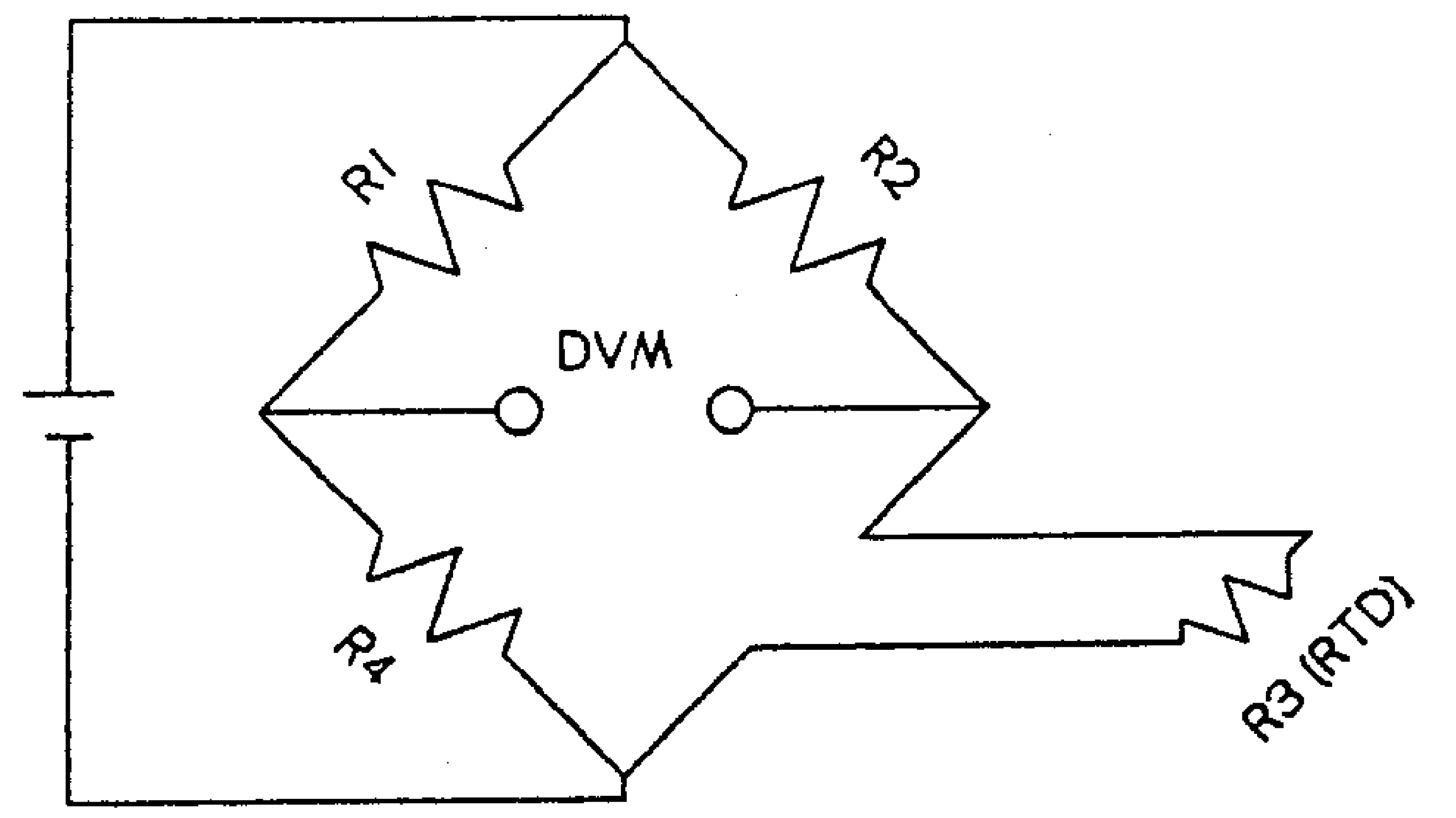

Figure 14–A 2-wire bridge circuit used for RTD temperature measurement.

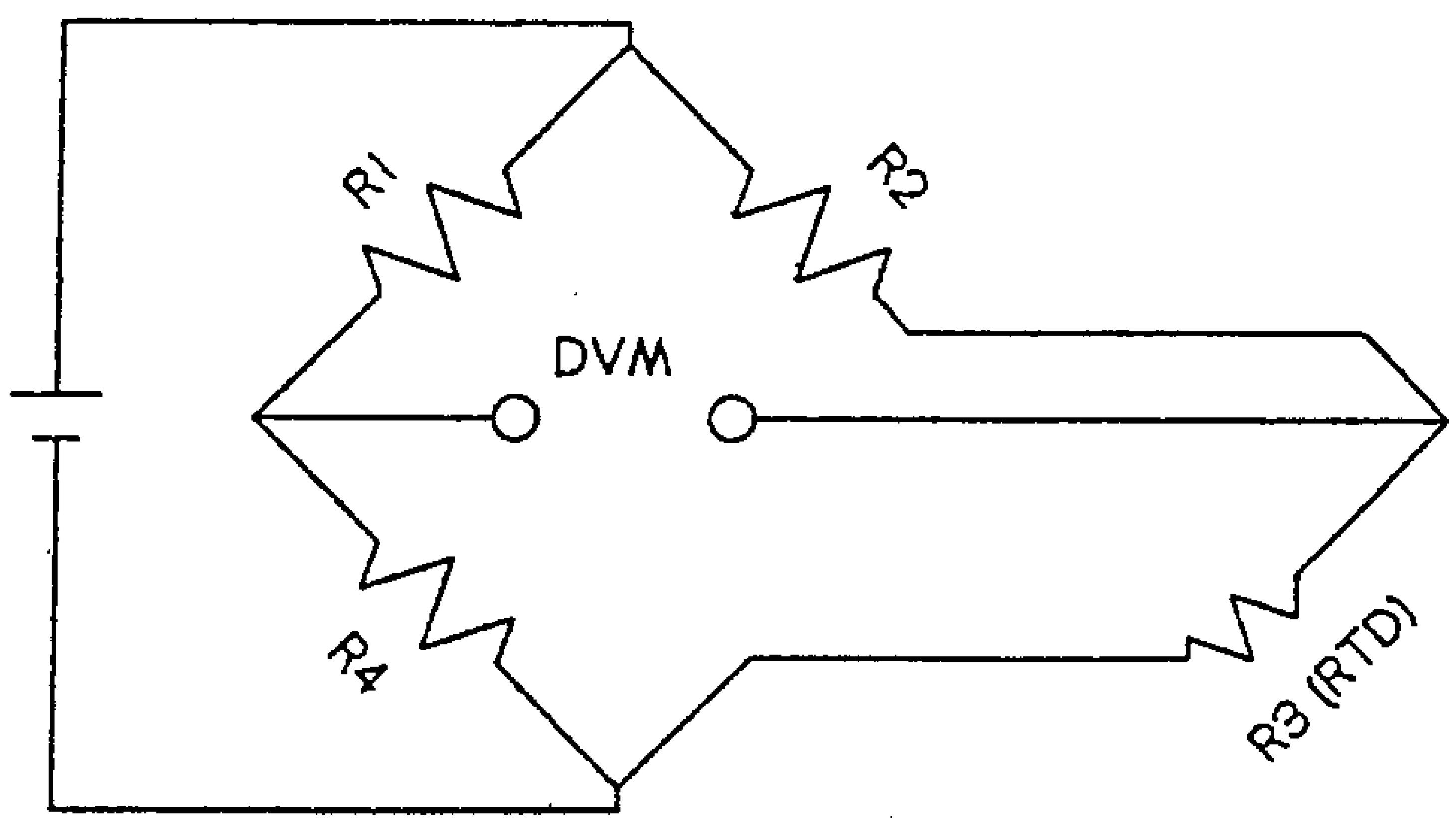

Figure 15–A 3-wire bridge using identical lead wires.