A UNITED STATES
DEPARTMENT OF
COMMERCE
PUBLICATION

NBS MONOGRAPH 114

Survey of Micromanometers

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Institute for Basic Standards
National Bureau of Standards
Washington, D.C. 20234

National Bureau of Standards Monograph 114

Nat. Bur. Stand. (U.S.), Monogr. 114, 62 pages (June 1970)
CODEN: NBSMA

Issued 1970

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
(Order by SD Catalog No. C 13.44:114), Price 60 cents

Library of Congress Catalog Card No. 76–603901

Contents

Survey of Micromanometers

W. G. Brombacher

This survey is concerned with instrumentation for measuring pressures from about 0.001 to 50 mm of mercury (0.13 to 6650 Nm^{-2}), described in publications during the years 1900-1968. U-tube micromanometers and diaphragm-capacitance gages are treated in considerable detail. Other instrumentation described includes gas column manometers; elastic element micromanometers with optical, inductance, resistance wire, strain gage, and vacuum tube transducers; piston gages; vane gages; and centrifugal micromanometers. The measurement of dynamic pressure, atmospheric pressure oscillations, low vapor pressure, and calibration techniques are discussed. Only technical periodicals, books, and government or university laboratory serials were used as sources of information. Details of electrical measurement circuits, amplifiers, and recorders have been omitted. Schematic diagrams of approximately 70 instruments are included. References to the sources of information and available performance data are given.

Key words: Calibration techniques; capacitance pressure gages; gas column manometers; manometers; meteorographs; micromanometers; piston gages; pressure measurement; vane gages; vapor pressure measurement.

1. Introduction

Micromanometers are here defined as instrumentation used to measure gas pressure, either absolute or differential, in the range from about 0.001 to 50 mm of mercury (0.13 to 6650 N/m^{-2}). Gages primarily used to measure pressures below about 10^{-3} mm of mercury are not discussed. This eliminates McLeod gages, radioactive ionization gages, thermocouple-type thermal conductivity gages, radiometer gages, and viscosity gages, although all can be used to measure pressures in the micromanometer range.

On the whole, the discussion has been limited to instrumentation which has been described in technical periodicals, books, and government or university laboratory serials for the years 1900–1968. Patents, catalogs and, to a large extent, progress reports on government contracts have not been searched or referenced.

The emphasis in the descriptions has been on the measuring element or method of measurement, and a summary of performance. Electrical or electronic circuits required for electrical transducers have been for the most part indicated by block diagrams in the figures; details of these circuits have been omitted as not germane to this survey. The principal objective was to review the major sensing elements of the multiplicity of designs which have been developed. Details of mechanical design have been omitted, and in some cases performance data are lacking.

For micromanometers, the unit of pressure commonly used is either the millimeter of mercury, the millimeter of water, or the inch of water. A unit commonly used in vacuum and low-pressure technology is the torr, which is frequently quoted herein. A pressure of one atmosphere equals 760 mm of mercury or 760 torr; 101,325 newtons per square meter (N/m^2); 1013.25 millibars (mbar); 10350.8 mm of water; and 407.513 in of water. All of the liquid columns are presumed to be subjected to standard gravity, 980.665 cm/s^2. The density of mercury assumed is that at 0 °C, 13.5951 g/cm^3. The density of water is that at 20 °C, 0.998207 g/cm^3. In the pressure range here of interest, 1 torr equals 1 mm of mercury. One torr equals 133.322 N/m^2 and 1 N/m^2 equals 0.0075006 torr. See [6009] [1] for additional details.

A gas pressure in the micromanometer range may be measured in four fundamental ways. These are: (a) by means of a balancing liquid or gas column; (b) by the strain produced in an elastic element; (c) by a balancing gravitational force; and (d) by a balancing centrifugal force. Other methods of measuring pressure in the micromanometer range, such as thermal conductivity, viscosity, radiation, and ionization, are more applicable to the higher vacuum ranges and are not discussed here.

The large variety of instrument designs which use these four primary methods for sensing pressure involve the amplification or conversion of the primary signal. Thus the small heights of a liquid column have been amplified by mechanical means (including force balances), by optical devices such as the optical lever and interferometers, and by the various forms of electrical transducers. Gas columns have not been widely used, and then only to produce a balancing pressure.

Elastic element deflections have been amplified mechanically in a large variety of designs, at present to a limited extent by optical means and to a greater extent by a variety of equipment utilizing electrical transducers. In the latter case the transducers have been principally electrical capacitance, electrical inductance, or wire strain gages. Of limited application have been electrical conductance, microwave frequency, and mechanical control of the output of a vacuum tube. The pressure acting on an elastic element has been balanced by a mechanical force, supplied either by a spring or a torsion wire, or by electrostatic force, the

[1] Figures in brackets indicate the literature references at the end of this Monograph.

latter now being favored. Also, the deflection of the transducer itself can be tracked or followed by feedback.

Gravitational force balances include the familiar piston gage, now being applied to measure pressures in the micromanometer range, and vane elements used principally to measure low vapor pressures.

The development and application of centrifugal micromanometers have been quite limited up to the present.

The diversity of the designs found is due (a) to the unique requirements of the variety of applications; (b) to the lack of commercially available instruments for many applications; and (c) to the unique training and experience of the many experimenters who have designed and built instruments for their own use.

The principal laboratory applications for micromanometers have been in investigating gas reactions, in making chemical analyses, in measuring low vapor pressures, atmospheric pressure fluctuations, low gas velocity by impact pressures, and low differential pressures at high pressures. Their principal industrial application appears to be in petroleum refining.

The sensitivity of an instrument is here defined as the smallest change in pressure which can be measured. It will vary with pressure in many cases.

The reader is referred to section 10 for information on the procedure used in numbering the references.

2. U-Tube Micromanometers

2.1. General Considerations

This section will cover micromanometers which depend upon the change in height of a liquid column. Essentially, all of these designs are based upon the use of a U-tube, which differ in the means used for detecting the liquid surface and for measuring the column height.

The pressure or differential pressure can be expressed in terms of the column height, generally millimeters of water or mercury, or converted to dynes per square centimeter by multiplying by the density of the liquid and ambient gravity. When the height of the column is used as the unit of pressure measurement, reduction of the readings to standard conditions of temperature and gravity is theoretically necessary. Unless the accuracy obtainable is better than 0.5 percent (not easily secured in making measurements at pressures below one torr), the corrections can safely be neglected.

Ordinarily, only the difference in the column height in U-tube micromanometers is recorded. Recorders may be devised utilizing an optical lever, so that the position of the light beam on the scale can be photographed, or an electrical transducer, the output of which can be passed into an electrical recorder. The optical interferometer, to be of any practical use, requires a recorder, on which discussion will follow in section 2.5.

In general, the U-tube micromanometer measures a differential pressure, which becomes an absolute pressure if the pressure in one leg is well below the sensitivity of measuring the column height. Mercury is the liquid commonly used in U-tube micromanometers for both absolute and differential pressure measurements; water or an oil ordinarily only for differential pressure measurements. However, oils are now available which have a vapor pressure below that of mercury, so that vapor pressure is not a problem in their use in making absolute measurements. For comparative performance data on 12 liquids see Smith and Murphy [5534]. The primary problem here is that all known oils absorb significant amounts of gases, in contrast to non-absorption by mercury. The customary procedure is to outgas the oil by heating it under vacuum and then to maintain continually a vacuum over it insofar as possible. Other methods of degassing are also used. Thomas, Johnson, and Little [62103] vacuum-distilled the oil into their manometer and continually maintained a vacuum over the oil. Holmes and Jones [63347] mechanically agitated the liquid to facilitate the flow of gas up to the liquid surface by using a magnetic paddle rotated by an external rotating magnet. Tekippe and Ramanathan [6715] reviewed critically the various existing procedures. They described a preferred procedure in which the manometer liquid was alternately frozen by a dry-ice bath and thawed while pumping.

It will be seen in the sections in which particular instruments are described that the best vacuum micromanometers designed before about 1950 had a precision of measurement limited to about 0.001 torr. Since then the sensitivity has been increased by an order of magnitude and more. The best differential pressure micromanometers (using water or oil) have a sensitivity of the order of 0.0001 mm of water (0.00007 torr).

The mercury barometer was originated in the last half of the seventeenth century. During the last 300 years its various forms have incorporated most of the means used in U-tube micromanometers for both detecting a liquid surface and measuring the height of a liquid column. This course of development has been ably presented by Middleton in his "History of the Barometer" [B641].

Literature on manometers and micromanometers previous to about 1900 has not been searched, so that it may well be that the earliest reference given here for a given design does not necessarily fix its originator. As will be seen, the fundamentals of some designs appear to have been presented as new, every 20 years or so.

In classifying micromanometers into types, a number of them could come under at least two groups; their location in the survey is thus largely an arbitrary choice.

2.2. Index Point Detectors

One of the simplest, and quite sensitive, detectors of the level of a liquid surface is an index point. This is a pointed rod of metal, glass, or ivory adjusted so that its tip just touches the liquid surface. The index rod can be fixed to the U-tube and the liquid level adjusted to the touching level, or the index point moved, usually by a micrometer. When the manometer liquid is mercury, the index is above the liquid surface; when it is oil or water, the index point is usually below the liquid surface. One form of the latter is the well-known hook gage.

When the index point is used to detect the level of a mercury surface, the sensitivity is greatly improved by proper illumination of the mercury surface and by securing the reflection of a series of parallel black lines on a white background. Disappearance of the dimple in the mercury, as indicated by the reflected lines becoming parallel, indicates that the point just touches the mercury surface. The point of contact can be determined to 0.001 mm by the above procedure if the mercury surface is bright and clean; cf. Stillman [1408].

An ivory index point is superior to one of metal since there is less sticking of the mercury to the point. Glass index points are also used, generally when the index is in a fixed position.

Readings can be secured more rapidly and the mercury level controlled automatically when the point of contact with the mercury surface is indicated by the make and break of an electric circuit. Here the index point must be a metal and the current through the contact be very small. This method has been little used in micromanometers.

Use of index points in barometers dates back to 1726 [B641]; the Fortin barometer employing a fixed index point in the cistern, back to 1809.

2.2.1. Index Adjustable

The design of a micromanometer with adjustable point indices is shown schematically in figure 1. Here A and B are the cisterns connected by tube C; $P1$ is a reference pressure (which may be a vacuum) and $P2$ is the pressure to be measured. E is a micrometer to which the point index is attached; for our purposes here, F is a duplicate of E, and reservoirs D and J are, for the moment, not pertinent.

When a difference in pressures $P1$ and $P2$ is applied, both micrometers are readjusted so that the point indices just touch the liquid surface. The sum of the changes in reading of the micrometers is the column height.

Threlfall [0401] described this design in 1904 using colored water as the liquid. He measured differences down to 0.01 mm of water.

Hering [0604] in 1906 modified the design so that absolute pressures could be measured. A vertical tube G was attached to tube C in figure 1, which extended downward and terminated in reservoir D of mercury open to the atmosphere. The height of the mercury

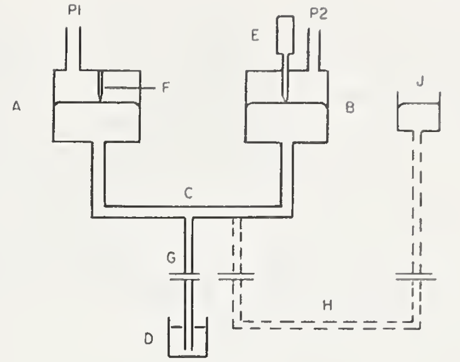

FIGURE 1. *Index point manometers.*
A and *B*, cisterns; *C*, *G*, and *H*, connecting tubing; *D* and *J*, auxiliary reservoirs; *E*, micrometer with a point index; *F*, a point index; *P1* and *P2*, applied pressures.

column from the liquid surface in A to the liquid surface in the auxiliary reservoir D balanced the atmospheric pressure. A fixed index F was installed in cistern A and a micrometer-index combination E in cistern B. The auxiliary reservoir J was adjustable vertically by a screw to bring the mercury level in cistern A into contact with the fixed index F. Readings on micrometer E gave the column height. To avoid, to a large extent, capillary difficulties, cisterns A and B were 25 mm in diameter. Pressures down to 5×10^{-3} torr were measurable.

Muendel [1306] modified the Hering design in two ways. First, cisterns A and B were 40 mm in diameter. Second, a micrometer-index was also installed in cistern A, so that both micrometers were read in measuring a pressure. A mercury seal was used for the micrometer cistern joint. The index points were viewed with a microscope. The micrometer sensitivity was 7×10^{-4} mm per scale division. The accuracy claimed was 10^{-3} torr.

The development of vacuum pumps made both Hering's and Muendel's designs obsolete. Cisterns A and B connected by tubing C, figure 1, are all that is needed. A vacuum pump connected at $P1$ can produce a reference pressure significantly below $P2$. Gerard [6603] describes this micromanometer design in which cisterns A and B were 25 mm in diameter. The accuracy obtained was 10^{-2} torr.

Thomas and Cross [6701] describe a design with U-tube cisterns 50 mm in diameter, capable of measuring a column height of 4 in and pressures from 10^{-2} to 100 torr. Mercury, silicone oil, and water were used as the filling liquids. The index points were brought up from below to touch the liquid surface when water or oil was the liquid. The various sources of uncertainty were investigated and were found for full scale readings to total 6.7×10^{-3} torr for mercury, 0.60×10^{-3} torr for water, and 0.83×10^{-3} torr for silicone oil. For pressures below about 0.1 torr, these errors would be cut in half. It is believed further development would reduce the uncertainty in the measured pressure with the oil manometer to 1×10^{-4} torr.

Ruska, Kao, Chuang, and Kobayashi [6816] modified the above described design to measure differential pressures up to 96 torr at pressures up to 800 kg/cm^2 (roughly 800 atm). A stainless steel U-tube, 16 mm in bore, had two adjustable micrometers installed as shown at E and F in figure 1. A shaped teflon guide floated on the mercury surface. A stainless steel nail shape pierced the teflon float to extend into the mercury. The micrometers were adjusted manually so that their tips made electrical contact with the nail head, whereupon valid readings were made. The temperature of the manometer was controlled at 40 $\pm$ 0.2 °C. The accuracy claimed was $\pm$0.002 torr.

A digitized barometer depending on a micrometer probe was designed by Brini, Galli, and Gandolfi [6631]. The contact of the probe with the mercury surface was detected electrically and maintained automatically by a suitable electrical circuit. A disk with 20 holes on its periphery was mounted on the micrometer. A photocell picked up light passed through one of the holes. The output from the photocell was digitized. The sensitivity was 1/30 mbar (0.022 torr).

2.2.2. Indices Fixed

2.2.2.1 Rayleigh Micromanometer

The classical mercury micromanometer is that designed by Lord Rayleigh [0101]. Referring again to figure 1, cisterns A and B, bore 25 mm, were equipped with two fixed indices, the points of which were in the same horizontal plane. Reservoir J, together with appropriate pinch-clamps in tubing H, was required to adjust the volume of mercury in A and B so that both indices just touched the mercury at zero differential pressure. Glass tubes, not shown in figure 1, extended upward from cisterns A and B, culminating in two domes for cistern A and one for cistern B. These were the supports for an optical lever. The micromanometer as a whole was mounted on a wooden frame, supported at two points, one midway above the two cisterns which served as a fulcrum, and the other some centimeters away in the plane of figure 1. The latter support was a micrometer screw, the operation of which tilted the whole manometer; the amount of tilt was measured by the optical lever, since the wooden support made use of the micrometer unreliable. When a differential pressure was imposed, the micromanometer was tilted to return the index points back to the mercury-touching position. Absolute pressures were measured, so that $P1$ had to be maintained at a pressure significantly below that measured. The design was such that one torr of differential pressure produced 231 mm deflection on the scale of the optical lever. Rayleigh used the instrument to measure pressures in the range 0.01 to 1.5 torr.

Scheel and Heuse [0903] used Lord Rayleigh's design for pressure measurements up to 5 torr. For greater pressures they modified Rayleigh's design by returning one index to the mercury-touching position by moving one cistern vertically and measuring the motion with a micrometer screw. The required flexibility in glass tube C, figure 1, was obtained by shaping this tube in the form of an elongated horizontal U. The pressure range extended to 30 torr.

2.2.2.2. Pearson Micromanometer

Pearson [3106] developed a design in which the adjustment of the mercury level to the fixed index point is made by lowering an auxiliary mercury column and measuring the volume change in mercury level. In figure 2, A and B are the cisterns of the U-tube. The fixed index point I is in B, which is kept at zero pressure. The U-tube is connected to tubes C and D. Space G contains a fixed amount of dry gas at some pressure below atmospheric. Tube D and cistern E contain mercury. A pressure applied to cistern A causes the mercury in B to rise; cistern E is lowered to restore the mercury level in B to the null position. The vertical displacement h of mercury in tube C is measured on a suitable scale. The pressure P in terms of column height is given by the ratio of the bore areas of C/B times the observed value of h. The amplification B/C obtainable is at best about 100.

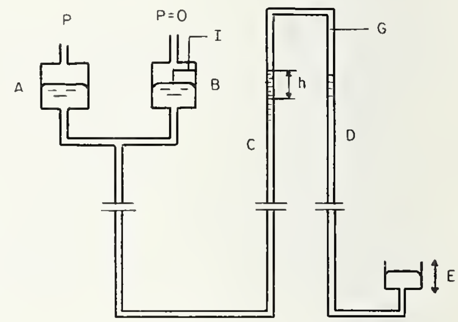

FIGURE 2. *Pearson manometer.*
A and B, cisterns subjected to pressures P; C and D, connecting tubing; E, an auxiliary reservoir; and G, a gas.

Slavianskii [5257] improved Pearson's design in details such as providing temperature control and vibration protection. The pressure range of his instrument was 0.01 to 1.5 torr; the sensitivity is 2×10^{-3} torr, a value indicating a magnification of about 50.

LeRoy [4514] made the fixed index point of tungsten and detected the point of contact with the mercury surface electrically. The adjustment of the mercury level was secured automatically by a solenoid valve which controlled a slow leak into or out of the vacuum system. The necessity for close control of the manometer temperature was discussed. The mercury column height measured was at a maximum about 100 times the pressure in terms of column height. The objective was to achieve an accuracy of 0.01 torr.

2.3. Float Detectors

A float in both mercury and other liquids has been often used as a liquid surface level detector in combination with various schemes for measuring the column height. Some form of guide to insure float verticality is required. The float position will be seriously affected by any change in surface tension of the liquid. If the liquid wets the surface of the float, some creeping of the liquid over the surface of the float will occur; presumably this can be prevented by a nonwetting surface coating on the float. The float clearance between float and cistern walls must be adequate to avoid interfering menisci. The use of a float is attractive in comparison with index points, in that readings of pressure can be obtained directly without the need for any intermediate operations.

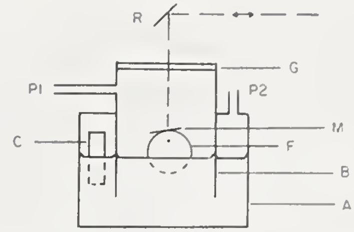

FIGURE 3. *Float micromanometer.*
A and *B*, cisterns, subjected to pressures *P1* and *P2*; *C*, a plunger used for calibration; *F*, a pivoted float; *G*, window; *M* and *R*, mirrors.

2.3.1. Float Displacement Measured Directly

A simple design of a micromanometer using a float is that developed by Betz [3111] for measuring pitot-static pressures in wind tunnel operation. A glass scale was attached to a float and extended well below it into a well forming part of a cistern. The position of this scale, hence of the float, was observed through a lens relative to a reference mark. The scale was illuminated by an electric lamp. The liquid had to be transparent. The sensitivity was 0.2 to 0.3 mm of the liquid column. The above design requires modification if the manometer liquid is mercury. The scale attached to the float must rise above the mercury column. However, the precision obtainable is low compared to other detectors.

It should be mentioned that installing a magnet in the float and a detector of the magnetic field outside of the tube has been successfully used in barometers. While the sensitivity of such a design is not as good as that of index points, it offers one possibility for obtaining readings without manual manipulation of the output signal, if the external detector adjusts to its equilibrium position automatically and its displacement is indicated. This single advantage seems thus far not to warrant its application in micromanometry.

2.3.2. Float Displacement Multiplied

In all of the designs to be described, changes in the float position have been multiplied by using an optical lever. This simple device for magnifying a linear or angular motion had been widely used by physicists up to the time when electronic devices became available. Lord Rayleigh used it in 1901 in his device to measure low vapor pressures; usually he is credited with being the first to do so, but undoubtedly the optical lever is much older and may have been used earlier in pressure-measuring instruments.

A modern design, due to Eichhorn and Irvine [5810], will be described first. In figure 3, *A* and *B* are the U-tube cisterns. The float *F* is pivoted eccentrically and in effect deflects angularly as the liquid column in cistern B rises or falls due to a change in pressures *P*1 or *P*2. A mirror *M* mounted on float *F* turns with the float and deflects a light beam focused upon a scale. The light beam enters and leaves by the glass top *G* of the cistern and is rotated 90° by mirror *R*.

Oil was the manometer liquid, but design modifications to use mercury would not be difficult. A plunger *C* is provided for use in calibrating the manometer. Its insertion into the liquid raises the column height a computable amount. In the instrument constructed, the sensitivity was 1 mm deflection of the light beam on the scale for 3.15×10^{-5} in of liquid column.

The earliest design of the float-optical lever combination appears due to Shrader and Ryder [1901]. Here the U-tube cisterns were separated, as shown in figure 1, and the optical lever was installed above one of the mercury columns. The float, a glass bead, was fastened to one leg of the optical lever and the mirror to the other leg. Two knife edges, supported by wire loops, supported the optical lever. The range of measurable pressures was 0.001 to 3 or 4 torr; the sensitivity, 0.001 torr.

Carver [2301] improved the Shrader-Ryder design in several particulars. He used a steel float with sharp edges in contact with the mercury surface to prevent wetting. The cistern of the U-tube containing the float was enlarged to a bore of 44 mm, reducing the effect of changes in capillarity. The design of the optical lever was refined to reduce uncertainties in position equivalent to 10^{-4} mm Hg. Finally, because ripples on the mercury surface caused by earth tremors were troublesome, producing several centimeters of oscillation of the light beam on the scale, these were prevented by a rigid, massive mounting attached to a concrete pillar. The sensitivity achieved was 10^{-4} torr; accuracy, 2×10^{-4} torr; pressure range, 5×10^{-3} to 1 torr.

Johnson and Harrison [2901] redesigned the Shrader-Ryder optical lever with a view of obtaining greater ease in construction. A system of platinum ribbons and a fine glass rod composed the optical lever. The float had a flat bottom which diminished the effect of the inescapable ripples on the mercury surface. The sensitivity obtained was 9×10^{-4} torr per millimeter deflection of the light beam on the scale; the pressure range was 2×10^{-4} to 0.5 torr.

Newbury and Utterback [3201] constructed a manometer which differed notably from designs previously discussed only in the design of the optical lever. An iron ribbon attached to the iron float turned a horizontal rod as the float moved upward. This rod had jewel bearings. The mirror was attached to the rod. It should be noted that some materials more perfectly flexible than iron would be preferable for the ribbon; the iron ribbon, with time, retains to some extent the curvature of the rod, an effect which affects the validity of any calibration. The sensitivity of this manometer was 10^{-4} torr per millimeter deflection of the light beam on the scale. It was calibrated in a pressure interval, from 10^{-3} to 2×10^{-2} torr.

Spalding [5056] designed a water micromanometer for measuring low air velocities using a pitot tube. He tried first a design in which two U-tubes were used. A float was installed in one of the cisterns of each U-tube. The optical lever was operated differentially by these floats. This design was abandoned because the floats moved laterally, a difficulty which was reduced materially by sprinkling powdered chalk on the water. However, there seems no advantage in this more complicated design over that of one U-tube with a float-optical lever combination in one leg of the U-tube. Spalding's final design was of the latter type. It was novel in that the mirror was horizontal. The design was such that differential pressures down to 2×10^{-3} mm of water could be measured.

Blaha [6609] utilized a float-optical lever detector in a U-tube with a photocell receiver to indicate equality in the pressure in the two U-tube legs. A servomotor controlled by the photocell automatically balanced the pressure to be measured by compressing a metal bellows connected to one of the U-tube legs. The angular motion of the servomotor was measured and was proportional to the applied pressure difference. A silicone oil was used in the U-tube. The pressure range was 20 torr with a precision of 10^{-3} torr.

2.4. Visual and Optical Detectors

This class of micromanometers includes simple U-tubes in which the eye, aided or unaided by a lens system, is used to detect the level of the liquid surface. The column height may be measured by a simple scale or at best by a precision screw. Interferometers have also been used simply as detectors; consideration of these will be deferred to section 2.5.

2.4.1. Column Height Measured by a Scale

The practical limit of sensitivity is about 0.02 mm when a simple scale, vernier, and sighting ring are used to measure the column height. This is inadequate for many applications. See Brombacher, Johnson, and Cross [6009].

The first modification to be considered is to slant one leg of the U-tube, using tubing small in diameter relative to that of the cistern, so as to throw most of the column displacement to the slanted tube. This design has the great advantage of simplicity. Assuming a slanted tube in which the column displacement along the slant is ten times the vertical column displacement, the theoretical sensitivity becomes 0.002 mm in column height. However, capillary effects cause distortions of the liquid surface, whether water, oil, or mercury, which reduce the certainty in its placement relative to the scale. This fact requires that the angle of slant assumed, about 6°, be increased measurably. In any event, the slanted scale needs a vernier to achieve the sensitivity needed to compete with other types of micromanometers, which greatly complicates the design and apparently has not been undertaken.

2.4.2. Column Height Measured by a Precision Screw

The rotation of a screw is a sensitive means of measuring small displacements. Its sensitivity is compatible with that of a point index detector of a liquid level so that this combination has been often used in micromanometers; see section 2.2. With reasonable care in design, a sensitivity of about 0.005 mm is easily achieved, with more sensitivity attainable if the effort is desirable.

Two designs using a slanted tube and a precision screw will be described. In Hodgson's design [2910], a cistern *A*, figure 4, contains a firmly held plunger *C*, the vertical position of which is controlled by micrometer *M*. When a difference in pressures *P*1 and *P*2 existed, the plunger position was adjusted vertically to bring the liquid level in tube *B* back to a marked null position, as observed by microscope *F*, with illumination supplied by light *D* via mirror *E*. The height of the column is given by the change in the micrometer reading. The slant tube had a slope of 1/10. The oil meniscus position could be set to 10^{-4} in (2.5×10^{-3} mm) which, with the tube slant, gave a sensitivity in pressure of 10^{-5} in of oil. This required pushing the micrometer sensitivity to the limit, from which some improvement was obtained by making the plunger area less than that of the free surface of the liquid.

The second design was devised by Parkin in 1921 and is described by Ower [B496]. In principle, the design is simple. A short length of slant tube *ST*, figure 5, is connected by flexible tubing *T* to a fixed cistern. The slant tube was movable vertically by means of a micrometer *MI* so that the liquid surface can always be brought to a fixed mark *M* on the tube *ST*. The vertical

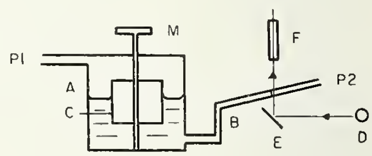

FIGURE 4. *Plunger micromanometer.*
A, cistern; *B*, leg of manometer; *C*, plunger, vertically controlled by micrometer *M*; *D*, light source; *E*, mirror; *F*, microscope; *P2-P1*, differential pressure.

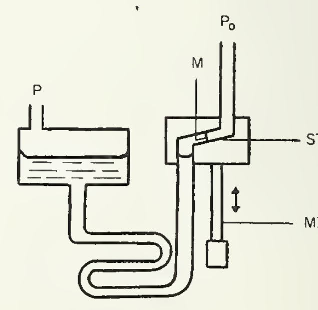

FIGURE 5. *Null micromanometer.*
M, null mark; *MI*, micrometer; *P—P₀*, differential pressure; *ST*, slant tube; *T*, flexible tubing.

motion, measured by the micrometer, is proportional to the height of the liquid column. This design has mainly been used to measure differential pressures with a sensitivity of the order of 0.01 mm of water. To avoid one source of error, the design must be such that changes in internal volume in the flexible tubing with changes in pressure or position are insignificant.

Smith and Murphy [5534] modified the above described gage. For the differential pressure interval 0 to 0.8 in of water, they used a dial gage to measure the vertical motion of the cistern, and for greater differential pressures, a simple scale and vernier, the latter attached to the cistern. The slant tube had a 10° slope. They investigated 12 possible liquids (not mercury) and concluded that silicone oil DC200, viscosity 0.65 cSt, gave the most stable repeatable meniscus. As the pressure is varied, some volume change can be expected in the flexible tubing necessarily used between the slant glass tube and the cistern, which introduces an error. This they investigated. They claim an accuracy of 2×10^{-4} in of water (5×10^{-3} mm) for the low range and 10^{-3} in of water for the high range.

An obvious alternative to the Parkin's design where the slant tube was movable and the cistern position fixed is to arrange the reverse. Diedrichs and Andrae [B301] describe Ensberger's micromanometer, in which an annular cistern could be raised and lowered by a micrometer to bring the liquid surface to the mark on the slant tube. A sensitivity of 0.0001 in of mercury (0.0025 torr) was achieved.

A refinement of the Parkin design was incorporated by Casella and Company in 1931 [B496]. A cistern with a hook gage (fixed index point below the water surface) is provided in place of the slant tube. Both legs of the U-tube are movable vertically for range adjustment. Motion of the cistern with the index point from the zero differential pressure to the index-touching position is measured by a vernier-scale combination. In view of the sensitivity of the hook gage, the measurement could be made to advantage by a micrometer screw. The hook gage is observed through an optical system including means for illumination of the index.

Maslach [5230] installed two precision screws, one along each leg of a U-tube made of 10-mm precision-bore tubing. These screws were connected by a differential which was manually operated. The liquid (butyl phthalate) surface was observed by eye through a lens attached to each screw. Individual hand cranks brought each lens to the liquid surface level. A five-place counter indicated the difference in the liquid column height. A precision of 0.001 torr (approximately 0.01 mm in column height) was obtained over a measuring range from 0.05 to 20 torr.

2.4.3. Photocell Detectors

The next step in the above design would be to substitute a photocell for the eye in detecting a mercury surface. By feedback from the photocell to a servomotor, readings can be obtained automatically. The sensitivity achieved with such an arrangement [5774, 6009, 63250] is now not better than 0.02 mm. In vacuum measurement its chief virtue is that readings can be obtained automatically and that it lends itself to the automatic maintenance of a steady value. It has not been applied to micromanometers, since the greater precision obtainable by other means does not warrant the inherent complexity of the design.

A design for measuring small differential pressures, involving an inverted bell on a balance arm with shutters, one for each of two photocells, is described briefly by Ower [p. 233, B496].

Robertson [5688] used photocells to detect light transmitted through butyl phthalate in a U-tube micromanometer. The light so transmitted was focused on the photocells; the extraneous light was scattered. The output from the two photocells entered a Wheatstone bridge and then an electrical recorder. The best sensitivity was 0.25 mm of water per millivolt across the recorder terminals.

2.4.4. Optical Reflection Detectors

While not particularly useful in a micromanometer, the sensitivity obtainable warrants mention of the primary standard barometer developed by the National Physical Laboratory [6092]. The U-tube is vertical while the optical probe is horizontal, a right-angle prism being used to transmit reflections from the mercury surface to the probe. Two horizontal tubes, movable as a unit on a track, have their axes intersect at a selected angle. A light beam from a lamp at the end of one tube passes through a grid to the mercury surface where it is reflected and passes through the second tube and a grid similar to the first. Maximum illumination is obtained when the axes of the two tubes intersect at the mercury surface. The accuracy of the setting is 5×10^{-4} mm. In the barometer two such probes are used, one for each mercury surface. The U-tubes are 4 in in diameter. The point of maximum brightness is determined by photocells, together with appropriate electrical circuits. The optical tubes are mounted on precision ways. Their positions at the point of maximum brightness are measured by line standards together with optical accessories for viewing.

The merits of somewhat similar optical reflection designs are discussed by Terrien [59192], but these are probably not practical for application to micromanometers.

2.5. Optical Interferometer Designs

For measuring the height of a liquid column, the best techniques in the order of their accuracy and sensitivity are the optical interferometer, gage blocks, and a precision screw. For micromanometers, gage blocks are impractical. The interferometer, while attractive in its accuracy and its function as a detector, is complex in design and requires careful adjustments. Only a requirement for high accuracy warrants its application here.

Interferometers may be used in two ways. In one, the interference fringes are counted as the height of the mercury column changes. In the other, the central fringe produced by white light is used only to detect the mercury surface.

2.5.1. Interference Fringes Counted

Prytz [0501] proposed the use of Newton's rings for measuring small pressure differences, but no evidence was found indicating that an instrument was constructed.

Barus [2104] experimented with an interferometer for measuring small differences from atmospheric pressure. The U-tube legs were separated by a metal partition and had covers of optical flats. Half-silvered glass disks were placed above each mercury surface, so that a single light beam was reflected from each mercury surface and the resulting interference pattern observed with a telescope. Ripples on the mercury, reported by all experimenters as impossible to eliminate from a free surface, were avoided by placing thin glass disks on the mercury surface. The mercury depth was made small, further to reduce surface distortion by vibration. The U-tubes had a bore of 5 cm. Differential pressures in the range 3×10^{-5} to 3×10^{-2} torr were measurable. At pressures above the latter value, the interference fringes disappeared. This was ascribed by Barus to the glass disks on the mercury not remaining horizontal, but was more probably due to the fact that he used white instead of monochromatic light. Barus states that measurements of vacuum would be feasible, a conclusion not to be doubted.

Thomas, Johnson, and Little [62103] have developed an oil manometer specifically for measuring vacuum, in which the interference fringes measure the changes in the liquid level. The design is shown schematically in figure 6. Light from a point source F passes through green filter G to reflector E and through lenses D. Part of the ray passes through window C and optical flat B to the oil surface where it is reflected. Another part of the ray is diverged by prisms J before passing through C and B in order to be reflected from the oil surface of the other leg of the U-tube. The two reflected rays in retraversing their paths give rise to interference fringes which are viewed in telescope H and counted. Tubes lead to the space above each liquid surface so that desired pressures $P1$ and $P2$ can be applied. Temperature inequalities are minimized by the massive brass block K, and by having the overall height of the liquid columns small. The liquid, dioctyl sebacate, has a low vapor pressure but, like other liquids except metals, absorbs gases significantly. The instrument included equipment for distilling the oil into the manometer under vacuum conditions and always maintaining $P1$ and $P2$ at vacuum values, and the technique of operation adopted minimized this source of error. Since the manometer was constructed primarily to determine if the interferometer would work, the fringes were counted by direct observation while the pressure was changing. Obviously, an automatic method of counting fringes is needed. Based on the use of two photocells, such a counter has been developed for application in metrology by Cook and Marzetta [61238]. They found that a pressure change of 10^{-3} torr caused a shift of 55 fringes, which gives a sensitivity of 2×10^{-6} torr for a motion of 1/10 of a fringe.

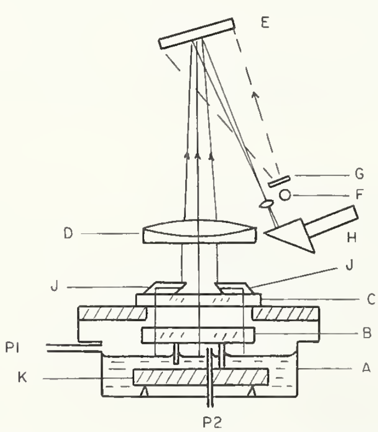

FIGURE 6. *Interferometric micromanometer.*
A, concentric cisterns; *B*, optical flat; *C*, window; *D*, lens; *E*, mirror; *F*, light source; *G*, green filter; *H*, telescope; *J*, prism; *K*, brass block; *P1—P2*, differential pressure.

Peube [63184] has constructed a differential mercury manometer in which changes in the height of the mercury column are measured by counting interference fringes. The mercury surface is covered by a glass plate and in turn by an oil film. The claimed accuracy is 0.1 of a fringe, equal to 0.01 N/m^2 or 7.5×10^{-5} torr.

Aubry and Delbart [65103] developed the Peube design still further, using an interferometer essentially as shown in figure 6 but without brass blocks. Both mercury and a silicone oil were used. The main difference from the design shown in figure 6 was that interferometric measurements were made only on one leg of the U-tube. Aubrey and Choumoff [65330] used the instrument as a standard in calibrating ionization gages at pressures around 10^{-4} torr.

Stevenson and McFadden [6592] describe an interferometric micromanometer using a laser beam. Interference fringes were secured from both legs of the U-tube. The liquid was galvanometer damping oil. Reflections were secured from mirrors in the oil. The probable error was stated as 10^{-4} mm in measuring liquid column height. White light was compounded with the laser beam so as to facilitate counting the interference fringes.

2.5.2. Interferometric Mercury Surface Detectors

Here the interferometer is kept in a fixed position relative to the mercury surface by moving the optical flat, and measuring its displacement. The central fringe obtained with white light is used as the detector of the null. The displacement of the optical flat is usually measured by a micrometer.

Manley [2701] set up an interferometer for each leg of a manometer. The interferometer for one leg of the manometer was used for reference purposes; the pressure above its mercury surface was maintained significantly below that to be measured. A micrometer was used to measure the displacement required to secure the null position of the optical flat, which is a measure of the pressure. The micrometer was calibrated by counting interference fringes. Pressures were measurable in the range 10^{-4} to 20 torr. Ripples on the mercury surfaces were bothersome; like Barus six year earlier, Manley proposed placing thin glass or stainless disks on the mercury surface.

Terrien [59192] reviews three ways in which interference fringes from two mercury surfaces can be used to detect the relative vertical distance between the mercury surfaces of a barometer. One of the methods originates in Japan, another in Russia, and the third is due to Terrien. In all cases, the length of the significant light paths must be equal. This is secured by a displacement of a reflector or reflectors, the amount being a measure of the column height.

In Terrien's design, a beam of white light is reflected from both of the mercury surfaces of the U-tube by means of a Michaelson interferometer. Upon reflection, the beams reverse their paths and are reunited as they issue from the interferometer. If the optical path lengths are exactly equal, and if the mercury surface has infinitesimal ripples (difficult to prevent), the observed fringes are white, not colored. The fringes are detected by a photocell. To obtain exact equality in the light paths, two horizontal prism reflectors are adjusted horizontally as a unit, to increase the light path to one mercury surface and decrease it to the other. The amount of their horizontal motion is a measure of the change in height of the mercury column. The instrument is planned to have a range of 1 atm with an accuracy of 10^{-3} torr, limited by the accuracy of measurements of displacement by a line standard. This design has no significant advantage in accuracy over simpler designs of micromanometers.

The Japanese and Russian interferometer applications require two light sources and two interferometers.

2.6. Electrical Transducers

Changes in liquid column height can be measured directly by changes in electrical capacitance, liquid surface to a metal disk (sect. 2.6.1), or in changes in the electrical resistance secured by a wire immersed in the liquid (sect. 2.6.3). Since the pressure range measurable by using changes in electrical capacitance is small, this parameter is usually used to indicate a null value, necessitating the measurement of a displacement of some sort to obtain the column height. Thus far, measurement of the change in electrical resistance of an immersed wire does not have adequate sensitivity for micromanometers.

Other electrical transducers, such as inductances (sect. 2.6.2), linear transformers, etc., require an intermediate element such as a float. Obviously, these transducers are used to the best advantage as null indicators, requiring measurement of some other parameter to obtain the liquid column height. For one design involving the use of a force balance, see section 2.11.2.

The photocell, also an electrical transducer, has been considered in sections 2.2.1 and 2.4.3.

2.6.1. Capacitance Transducers

Of more historical than technical interest is the design by Simon and Fehér [2905]. A U-tube consisting of a cistern and a slant tube, short in length, had tinfoil wound around the slant tube. A glass cylinder was mounted in the slant tube so that the mercury was constricted to an annulus 0.5 mm thick. Changes in the capacitance, tinfoil-mercury-gas, were measured by two radio circuits nearly in resonance. The frequency of one radio circuit was maintained constant, that of the other monitored by the changing capacitance. The differential output was measured by a milliammeter. The sensitivity was stated as 0.05 torr, the accuracy 0.2 torr.

The design of the pickup proposed by Sasimenko, Kulin, and Shushkevich [6633] is similar to that of Simon and Fehér. The tube of a cistern and tube manometer was surrounded by a short metal cylinder in the vicinity of the liquid surface. An electrical capacitor was formed by the cylinder and liquid which varies with the height of the liquid column. The output of the capacitance bridge was a voltage which could be recorded.

The design by Los and Morrison [5104] is indicated in figure 7. Here *A* and *B* are the U-tube cisterns; *C*1 and *C*2, invar disks forming an electrical capacitance with the mercury surface; *D* and *E*, oscillators; *F*, a mixer; *G*, an oscilloscope; and *H*, an audio signal generator. The cisterns were 8.8 cm in diameter. Changes in beat frequency, produced by changes in the mercury level up to 2.5 torr, were measurable. The reproducibility was 1 to 2 $\times$ 10^{-4} torr in the pressure range up to 0.2 torr and 0.1 percent at higher pressures. The sensitivity was nonlinear, but constant within 5 percent in the pressure range below 0.02 torr. The theory of operation was given.

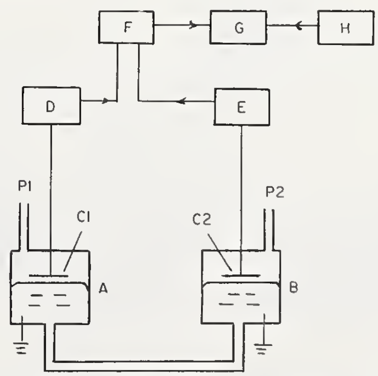

FIGURE 7. *Capacitance micromanometer.*
A and *B*, cisterns; *C1* and *C2*, metal disks; *D* and *E*, electronic oscillators; *F*, mixer; *G*, oscilloscope; *H*, audio signal generator; *P2—P1*, differential pressure.

Constant sensitivity over the entire pressure range is achieved if the capacitance, mercury surface to metal disks, is used to indicate a null. Hutton and Gilheany [58164] designed a micromanometer in which one of the cisterns (*B* in fig. 7) was movable vertically with the displacement measured by a micrometer when capacitance $C1 = C2$. The positioning of the movable cistern to balance the capacitance is carried out automatically by a supporting piston. The operation is initiated by the voltage generated by unbalance in the bridge circuit containing the capacitances. Upon amplification, the signal is fed to a servomotor which drives a pump, which controls the flow of oil to and from the piston. Two micrometers, connected by a precision bubble level, are positioned over the centers of the two covers of the cisterns. As the movable cistern is raised or lowered, its micrometer is adjusted to keep the bubble level horizontal. The differential pressure range of the instrument is two inches of mercury. The uncertainty in reading is 1.6×10^{-4} in (4×10^{-3} mm), about the same as that of the simple U-tube using micrometers with index points to measure the column height.

Long [5304] also designed an instrument relying on the detection of a null position of the liquid level, here the interface of two liquids. Two cisterns, one containing water and the other a mixture of chlorobenzene and mineral spirits, are connected by tubing from the bottom of one cistern into the liquid through the top of the other. A section of the tubing is vertical, so that the liquid interface position is a function of the pressure. A "proximity-switch" is installed outside of the tubing at the liquid interface position at zero differential pressure. To detect changes in the liquid interface level, a substantial difference in the dielectric constant of the two liquids is essential. By means of a relay, the switch operates a servomotor and thereby a precision screw to which one of the cisterns is attached. The vertical motion of the screw is indicated and is proportional to the differential pressure. The use of these two liquids gave a sensitivity 17 times that of a U-tube water manometer. An accuracy of 5×10^{-5} in of water (1.2×10^{-3} mm) is claimed. Seven readings per minute can be obtained. The application is for measuring low airspeeds with a pitot-static pressure head.

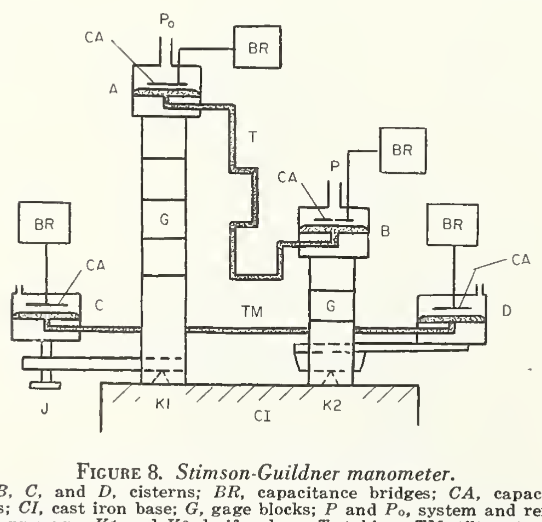

FIGURE 8. *Stimson-Guildner manometer.*
A, B, C, and *D,* cisterns; *BR,* capacitance bridges; *CA,* capacitor disks; *CI,* cast iron base; *G,* gage blocks; *P* and P_0, system and reference pressure; *K1* and *K2,* knife edges; *T,* tubing; *TM,* tilt meter.

Stimson [5579], and later Guildner [62238], designed and continuously developed a mercury manometer for precise measurements of pressure for use in basic gas thermometry. A schematic diagram is shown in figure 8. Two cisterns *A* and *B*, 76 mm in diameter, are connected by metal tubing *T* which has flexible joints so that cistern *A* can be raised or lowered. Gage blocks *G* serve to measure the difference in elevation of cisterns *A* and *B* and hence of the mercury columns. A capacitor *CA* is formed in each cistern by the mercury surface and a metal disk, the latter supported by a glass optical flat. Each capacitor is connected to a capacitance bridge *BR*. The tilt meter *TM* consists of two cisterns *C* and *D* connected by tubing and supported on knife edges *K*1 and *K*2 which are part of the pedestals for *A* and *B*. Cistern *C* can be adjusted vertically by screw *J*. Mercury to metal disk capacitors connected to capacitance bridges *BR* detect changes in the mercury level produced by tilt in the plane of cisterns *A* and *B*. The manometer is mounted on a massive cast iron base *CI*, and is installed in an underground temperature-controlled room. In operating the manometer, a reference position is established for the gage blocks when pressure in *A* and *B* is equal by lowering cistern *A* until the bridges *BR* connected to cisterns *A* and *B* are in balance. Any small residual unbalance is eliminated by adjusting a trimmer capacitor in one of the bridges. To measure absolute pressure *P*, cistern *A* is kept evacuated, and is adjusted vertically with gage blocks until the bridges *BR* connected to cisterns *A* and *B* are again in balance. The added gage blocks give the difference in height of the cisterns and thus of the mercury column. Readings on the tilt meter are taken concurrently and are used to apply a correction for the small changes in tilt of the base *CI* which have been found to occur. The overall results are accurate within 3 parts in a million in the pressure for pressures below 760 torr. The uncertainty increases at pressures below about 100 torr.

2.6.2. Inductance Transducers

Hart [6119] uses the null position of a float, indicated by an inductance transducer and produced by a piston controlling the liquid level, to measure small pressures. The piston motion, proportional to the pressure, is measured by a micrometer. In the design, figure 9, the U-tube manometer consists of concentric legs *C* and $A + B$, or $A + C$ and *B*, selected by operating the valves indicated in the tubing connecting to pressures *P*1 and *P*2. This selection is needed because of limitations in the transducer motion. The float *F* is connected to the movable iron core element of the linear differential transformer *E*. Deviations

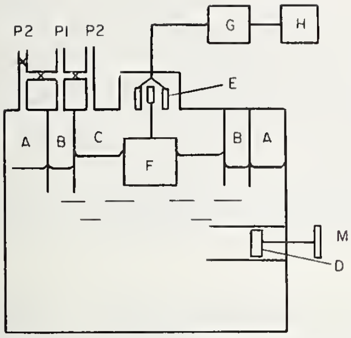

FIGURE 9. *Float micromanometer, null type.*
A, B, and *C,* concentric cisterns; *D,* piston controlled by micrometer *M*; *E,* electrical inductance; *F,* float; *G,* inductance bridge; *H,* potentiometer; *P1, P2,* applied pressures.

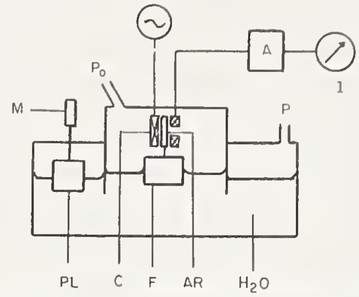

FIGURE 10. *Float micromanometer-inductance transducer.*
A, amplifier; *AR,* armature; *C.* inductance transducer; *F,* float; *I,* voltage indicator; *M,* micrometer; *P—P₀,* differential pressure; *PL,* plunger.

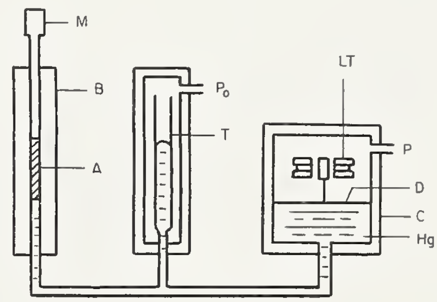

FIGURE 11. *High-pressure micromanometer.*
A, piston; *B,* high-pressure housing; *C,* high-pressure cistern; *D,* diaphragm; *LT,* linear differential transformer; *M,* micrometer; *P_0,* reference pressure; *P—P_0,* differential pressure; *T,* manometer tube.

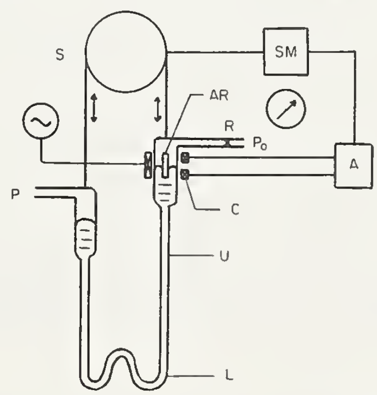

FIGURE 12. *High-pressure micromanometer.*
A, amplifier; *AR,* armature; *C,* coils of inductance transducer; *L,* flexible tubing; *P—P_0,* differential pressure; *R,* restriction; *S,* sprocket; *SM,* servomotor; *U,* manometer tube.

from its position at zero differential pressure are indicated by inductance bridge *G* and potentiometer *H*. Piston *D* is operated by micrometer *M* to bring the inductance back to the null value. The sensitivity is controlled by the cross-sectional area of the piston and also by the combination of cisterns selected. Toluene was the liquid preferred over water, water with an aerosol added, or kerosene. The range of differential pressures measurable varied from 10^{-4} to 1 in of water (2.5×10^{-3} to 25 mm). The stated accuracy is 10^{-6} in of water (2.5×10^{-5} mm). The instrument was designed to measure low airspeeds in a wind tunnel with a pitot-static head. Possibly vacuum could be measured also if a low vapor pressure oil were used as the liquid.

Elgeti and Eckert [65349] employed a simpler design than Hart for the same purpose. In figure 10, a float *F* in one leg of the U-tube is attached to armature *AR*. A commercial inductance transducer *C* detects the float-armature position, the signal is amplified by *A*, and the output voltage indicated by voltmeter *I*. The pressure range was 2.5 mm of water (0.18 torr) with a sensitivity of 3×10^{-5} mm of water. The differential pressure was measurable to 0.001 mm of water with an estimated accuracy of ±3 percent. A plunger *PL* operated by micrometer *M* was used to calibrate the micromanometer.

Golek, Klimek, and Matysik [6819] surrounded each leg of a U-tube manometer with a primary and secondary coil. In effect the arrangement is a linear differential transformer with the change in the mercury level controlling the output of the secondary coil. The input voltage was 220 V ac. The output of each secondary coil was fed to a bridge. The difference in the rectified voltage of the two bridges was measured. The accuracy was stated as 1 percent. The theory governing the operation of the gage was given in detail.

Reamer and Sage [6008] developed an instrument to measure differential pressures at ambient pressures as high as 15,000 psi (1000 atm), at temperatures from 400 to 1500 °F. The precision was 0.05 torr with an estimated accuracy of 0.25 torr. Schematically in figure 11, *C* and *T* form a U-tube mercury manometer enclosed in heavy walled chambers. A flexible metal diaphragm *D* divides chamber *C*, with mercury below and an oil above the diaphragm. A linear differential transformer *LT* indicates the deflection of the diaphragm, but is used only as null indicator. To measure the differential pressure $P - P_0$, the volume of mercury removed or added to restore diaphragm *D* to its null position is measured. To make the measurement, piston *A* enclosed in housing *B* is moved up or down by a precision screw *M* and gearing (not shown) to obtain sensitivity. The motion of the piston was calibrated in terms of $P - P_0$, which had a range up to 1 atm.

Bell [65348] also designed a manometer to measure differential pressures at high pressures, in this case in the range 0.02 to 100 in (0.5 to 2500 mm) of liquid column height at absolute pressures up to 2500 psi (170 atm). An inductance device detects the null position of the liquid surface, water or mercury, and by a feedback circuit raises or lowers one leg of the U-tube to maintain the null. The details are indicated in figure 12. An armature AR floats in U-tube leg U. Its position is detected by fixed-inductance coils C, the output of which, amplified by A, is fed to servomotor SM. The latter rotates a sprocket wheel S, which lowers tube U when a positive differential pressure $P - P_0$ is applied, until the null position is restored. The measured angular deflection of SM equals one half of the liquid column height $P - P_0$. The tubing L is flexible. A restriction R in the connection to P_0 was found necessary. The time lag was 2 min.

2.6.3. Resistance Transducers

The variation of an electrical resistance immersed in a mercury column has the virtue of simplicity, but the sensitivity of designs thus far developed is inadequate. Simon and Fehér [2905] describe one design. A closely wound coil of wire is located in the slant tube of a U-tube manometer. The electrical resistance of the wire above the mercury surface is the pertinent value, since the mercury column practically short circuits the part of the wire still in the mercury. To measure the change in resistance with change in pressure, Simon and Fehér placed the wire in the filament heating circuit of a vacuum tube and measured the output of the vacuum tube with a milliammeter. An accuracy of 0.1 torr was obtained, inadequate for most applications. Capillary irregularities and heat conductivity effects contribute to uncertainties in accuracy.

Stock and Fill [4926] used platinum wires in each leg of the U-tube mercury manometer, and made measurements with an unbalanced bridge.

Zalma, Guérin, and Fraissard [6811] looped a platinum wire in one leg of a U-tube filled with mercury. The electrical resistance of the wire was recorded with a sensitivity of $1/10\ \Omega$. No details on the pressure sensitivity were given.

Klumb and Haase [3207] investigated the use of a tungsten wire submerged in a mercury column and came to the conclusion that it was of no value in measuring absolute pressures below 1 torr. However, Sidenius [6814] installed a loop of tungsten wire in an oil-filled manometer tube. The wire was heated to 350 °C in air. The heat loss with change in liquid column height was measured as a change in voltage while the electric current in the circuit was maintained constant. The pressure range was 1 to 1000 mm of oil; the resolution was 0.03 mm of oil; and the accuracy ± 1 percent.

2.7. Ultrasonic Transducer

Wallace and Tiernan have announced (October 1968) the development of a sonar mercury manometer, the novelty of which merits including a brief description. A large-bore U-tube, temperature controlled, has a means for generating ultrasonic sound pulses at the bottom of each leg. These pulses traverse the mercury columns and are reflected back at the mercury surface. The electronics is designed so that the time between the return of the two echoes, proportional to the difference in mercury column height, is determined by counting pulses from a clock oscillator. The resolution and sensitivity claimed are 0.001 in of mercury (0.025 torr).

2.8. Linear Amplifiers of Column Height

The designs to be described here include only those in which the primary column height has been linearly amplified by producing a displacement in an auxiliary liquid surface. Where a fixed point index or the interface of two liquids are involved, the discussion is more conveniently given under those headings. This leaves two fundamental designs to be discussed: first, those having gas bubble indication, and second, one in which the volume of the liquid column is transferred to a capillary tube to obtain a long liquid filament.

2.8.1. Gas Bubble Designs

A gas bubble has been used as a detector by a number of experimenters, often unaware of previous developments. A small-bore tube is essential to contain the bubble, this usually being the tubing connecting the two cisterns of the U-tube. Thus, the bubble movement is always much greater than the change in column height. The greatest sensitivity is obtained when the bubble tube is horizontal. The magnification then obtained is proportional to 0.5 D^2/d^2, where D is the bore of the manometer tubes at the liquid surfaces, and d the bore of the bubble tube. Instruments have been built with magnifications up to about 1000. Designs have been proposed in which the bubble motion is an indicator of the pressure change; others in which the bubble is used to indicate a null position secured by tilting, the amount of which is the desired indication.

If the gas bubble is used when the manometer fluid is water or liquid other than mercury, the gas bubble may be partially or completely absorbed. This, of course, can be countered by having the liquid in the saturated condition, which may involve temperature control, since the amount of gas absorbed is a function of temperature. In any event, the rates of absorption and desorption are small enough to permit unaffected readings to be made on a short-time basis. The transference of liquid across the bubble is another source of error. It is avoided in part by enclosing the gas bubble in small-bore tubing and by selecting the liquid, about which more will be said. Inevitably, some liquid transference will occur whenever the bubble moves at least its own length, but this transfer will normally be insignificant.

When mercury is the manometer liquid, it becomes important to have the bubble tube bore as large as possible to prevent sticking of the mercury column and not so large as to permit liquid transfer. The sticking mani-

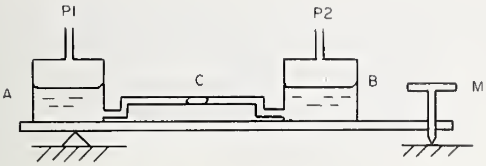

FIGURE 13. *Gas bubble micromanometer.*
A and *B*, cisterns; *C*, gas bubble; *P2—P1*, differential pressure; *M*, micrometer.

fests itself by a variable meniscus height and is a source of error to the degree that a pressure difference exists across the mercury surface. Tapping the tube reduces the sticking, but does not necessarily eliminate it. The use of gas bubble tubing much below about 2 mm in bore introduces a source of intolerable random error in this respect. There is one advantage with mercury; no gas from the bubble is absorbed by the mercury, and distillation of the mercury across the bubble is slow.

The earliest use of the gas bubble indicator appears to be Threlfall [0401], Roberts [0603], and Henry [1201]. The design is shown in figure 13 and consisted simply of cisterns *A* and *B* and bubble *C*; the other parts shown are not here pertinent. Roberts preferred alcohol over water; Henry used either water or carbon tetrachloride. The above-described simple design using mercury was constructed by Hanley [6452] and, using a low-density liquid (unspecified), by Burka [6458]. In both designs a motion of the bubble was about 16 times the change in column height of the liquid. Hanley secured a sensitivity of 0.01 torr in the pressure range 0.01 to 5 torr.

The design shown in figure 13 was developed by Ower [3010, B496]. The entire instrument has a fulcrum at cistern *A* and a micrometer *M* for tilting the entire instrument. It is filled with xylol. Any difference in pressures *P*1 and *P*2 produces a movement of the gas bubble; operation of micrometer *M* restores the gas bubble to the initial zero position. The amount of the tilt is measured and, from a knowledge of instrument geometry, the differential pressure can be calculated. The sensitivity obtained was 5×10^{-6} in of water (1.3×10^{-4} mm). The design is an improvement on the Chattock manometer, described in section 2.9.

Duffy and Norbury [6710] reverted back to the Chattock design with some simplifying changes. Referring to figure 13, the tube connecting the two cisterns was brought into cistern *A* from below and protruded into it. The denser liquid, a mineral oil, was in cistern *A*, the less dense, an alcohol, was in cistern *B*. A gas bubble separated the two liquids in the small diameter protruding tube. When a pressure was applied at *P*2, the position of the bubble was maintained constant by tilting the manometer by micrometer *M*, as in the Chattock gage. From the tilt the differential pressure *P*2 — *P*1 was computable. The sensitivity claimed was 15×10^{-6} in of alcohol (about 2.2×10^{-5} torr).

Young and Taylor [4716] developed a design specifically developed for measuring vacua. The design is shown in figure 14. Pressure is applied to cistern *A* while cistern *B* is maintained at a high vacuum. The mercury columns extend from *A* and *B* down to cisterns *C* and *D*. The upper parts of *C* and *D* and the connecting tubing, except for gas bubble *G* in the horizontal part, are filled with pentane. The application of the pressure causes gas bubble *G* to move; the geometry is such that the pressure equals $x/1056$, where x is the displacement of the bubble. The pressure range measurable is 8 to 83×10^{-3} torr; the estimated accuracy, 1 percent. The theory was presented. The bore of the gas bubble tube was 1.26 mm; reduction to 0.92 mm increased the time for equilibrium from 0.5 to 2 min.

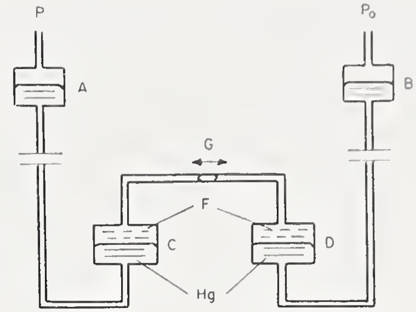

FIGURE 14. *Two-liquid, gas bubble micromanometer.*
A and *B*, cisterns; *C* and *D*, auxiliary cisterns; *F*, pentane; *Hg*, mercury; *G*, gas bubble; *P—P₀*, differential pressure.

2.8.2. Puddington Manometer

The monameter proposed by Puddington [4829], figure 15, is ingenious. As in Pearson's micromanometer, section 2.2.2.2, a volume change is measured. It was found to have little practical value because erratic capillarity significantly affected the accuracy. Los and Morrison of Puddington's group subsequently developed a preferred design of micromanometer [5104] which is discussed in section 2.6.1. In figure 15, *A* and *B* are cisterns which are subjected to pressures *P*1 and *P*2. Capillary tubing *D*, and an auxiliary reservoir *C*, form part of the instrument as shown in the figure. To obtain a reference reading, valve *V*1 is opened, pressures *P*1 and *P*2 are equalized; the volume of mercury

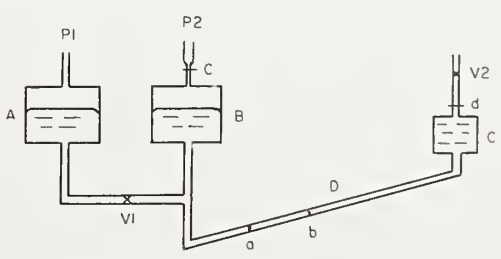

FIGURE 15. *Puddington micromanometer.*
A and *B*, cisterns; *C*, reservoir; *D*, capillary tube; *P1—P2*, differential pressure; *V1* and *V2*, valves; *a* and *b*, liquid level change from *P1=P2* to *P1—P2*; *c* and *d*, fixed marks.

in the system is adjusted (means not shown in fig. 15) to bring the mercury level to mark d on a capillary tube above reservoir C; valve $V1$ is closed and the mercury in C forced to flow until cistern B is filled to mark c in the capillary tube. The mercury surface falls to mark a in capillary tube D; its location on a scale is the zero reading. The mercury is then returned to reservoir C, valve $V1$ is opened, and if needed, the mercury volume adjusted to mark d. A small pressure applied to cistern A results in a rise in the mercury in cistern B. Valve $V1$ is closed, and again the mercury forced to mark c, resulting in a reading b of the mercury surface in tube D. The volume of mercury in the capillary tube between points a and b equals the change in volume of mercury in cistern B, produced by the pressure difference $P1 - P2$, from which $P1 - P2$ can be calculated. In one design, a magnification of 1760 was obtained, that is $1760\ (P1-P2) = b-a$. This involved using capillary tubing D of 0.78 mm in bore; erratically variable capillarity prevented reliable readings of a and b.

2.9. Two-Liquid Designs

Two liquids are used in micromanometers in various designs. A design reviewed at length by Ower [B496], and used for measuring small differential pressures at atmospheric pressure, will be briefly discussed. In its simplest form the manometer is a U-tube with a reservoir at the top of each tube. Two immiscible liquids of different densities are poured into the U-tube so that an interface forms in the vertical section of a tube and the free surface of each is in its reservoir. A differential pressure $P_1 - P_o$ applied to the reservoirs results in a displacement of the interface. It can be shown that

$$P_1 - P_o = [(\rho_2 - \rho_1 + \frac{r^2}{R^2}(\rho_1 + \rho_2)]gH$$

where P_1 is applied to the reservoir containing the less dense liquid; ρ_2 and ρ_1 are the densities of the liquids; r and R are the internal diameters of the tubing and the reservoirs; g is the acceleration of gravity; and H is the displacement of the interface. The reciprocal of the bracketed quantity is the amplification, which Ower states will not exceed 10 or 12 in practice.

Ower also describes a design in which the U-tubes are concentric, again with reservoirs at the top. There is no difference in principle except that the concentric tube design eliminates one of the two tilt errors.

Long's design [5304], described in section 2.6.1, is essentially the same as the above described design, except for the means of indication. The design by Young and Taylor [4716] was described in section 2.8.1.

The Chattock micromanometer [B496] is of the tilting type where an oil separates the water used in the U-tubes and the liquid interface is used to indicate the null to be obtained by the tilt. Ower [3010] substituted with advantage a gas bubble as the indicator of the null; it is described in section 2.8.1.

The earliest micromanometer, usually ascribed to Huygens, circa 1650, may be visualized if tube D in

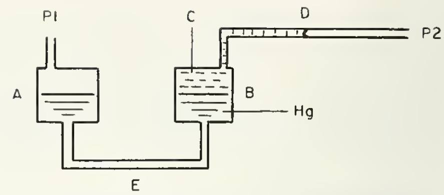

FIGURE 16. *Modified Huygens manometer.*
A and *B*, cisterns; *C*, oil; *D*, horizontal tube; *P1—P2*, differential pressure.

figure 16 is vertical instead of horizontal. An oil was placed on top of the mercury in one cistern. Practically, the rise of oil in the tube is about the same as that in a U-tube manometer with water as the liquid. Huygens constructed a barometer, in which cistern A was elevated to secure a head of mercury of barometric height, and evacuated.

Drucker, Jimeno, and Kangro [1504] modified Huygens' design (possibly not the first to do so) by making tube D horizontal as shown in figure 16. They used sunflower seed oil on top of the mercury; oils with lower vapor pressure, but not lower gas adsorption, are now available. In their design, the amplification in oil surface displacement over that of the mercury column was of the order of 150, a tenfold gain over Huygens' design.

Burka [6458] proposed, but did not construct or analyze a design in which tube D, figure 16, was eliminated and one of the two immiscible liquids was placed in cistern A and the other in cistern B. The interface was formed in tube E. An analysis indicated the best amplification occurred when A and B have equal and large cross-sectional areas and the cross-sectional area of E is as small as practicable. A magnification, as high as 50, of the indications of a U-tube manometer could be secured. The proposed design differs from the Threlfall design using a gas bubble (described in section 2.8.1) only in the substitution of the interface of two immiscible liquids as an indicator.

The design proposed by Brow and Schwertz [4720] is shown in figure 17. It is a variation of Pearson's design, shown in figure 2. The two liquids are water, $L1$, and colored kerosene, $L2$. Pressure $P1$ is applied to cistern A and pressure $P2$ to cistern D. A change in the differential pressure produces a vertical displacement h in the liquid interface in tube C, which is observed. The relation $P1-P2 = Kh$ gives the pressure where K is a constant depending on the geometry; $K = 35$ for the constructed instrument. A sensitivity

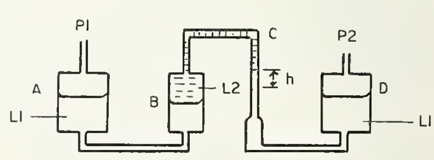

FIGURE 17. *Two-liquid micromanometer.*
A and *D*, primary cisterns; *B*, auxiliary cistern; *C*, capillary tube; *L1*, water; *L2*, colored kerosene; *P1—P2*, differential pressure.

of 10^{-3} in of water was claimed. If mercury is used as the primary liquid $L1$, and an oil for transfer liquid $L2$, small absolute pressures would be measured with about the same amplification factor K, where $P1-P2$ would now be in terms of the height of a mercury column.

2.10. Inverted Bell and Cartesian Diver

In an instrument often imprecisely but conveniently called a cartesian diver, an inverted bell B floats on mercury, forming a concentric U-tube as shown in figure 18. Neglecting capillary forces, the weight of the bell, plus controlling weight C, and the force due to the gas pressure acting on the upper surface of the bell, are balanced by the buoyant force of the mercury plus the force due to the gas pressure under the bell. For measuring low absolute pressures, the gas under the bell is evacuated, for which purpose valve V is provided. The system pressure $P1$ is admitted to container A. Displacement of bell B is measured by a scale on rod or metal strip E, using disk D as a reference. An increase in pressure $P1$ results in a downward force on bell B, equal to the product of the pressure increase and the cross-sectional area of bell B. This force is balanced by the increase in buoyancy of bell B as the liquid level rises inside B. In practical designs, the displacement of E is about 10 times that of the corresponding height of the mercury column. The theory of operation is given by Germann and Gagos [4311]; the instrument is described by Reilly and Rae [B533], who describe an alternative and probably more sensitive method of indication. Blase [60227] proposes, without details, the use of a differential transformer for measuring the displacement of rod E; a complication not worthwhile for a simple, rugged, low-sensitivity instrument such as this.

While not entirely germane here, the application of the cartesian diver to pressure control should be mentioned. The upper end of rod E, figure 18, could be equipped with a disk or a needle to seat at disk D. $P1$ is now connected to a vacuum source, and tube F to the system the pressure of which is to be maintained constant. If the pressure rises above the set value, the valve at D opens, and gas is pumped out through $P1$ until the falling pressure in A causes valve closure. If pressures below the set pressure can develop in the system, it is seen that another controller is needed which would be a second manostat of the same design, except that the valve at D is set to open if the pressure falls below the set pressure, and the manostat is connected to an appropriate source of pressure. Gilmont [4633] develops the underlying theory of the manostat and [5169] describes a number of designs for various applications. Oxley and Stockton [6623] describe a pressure regulator in which a photocell senses the position of the diver, and in turn controls the valves.

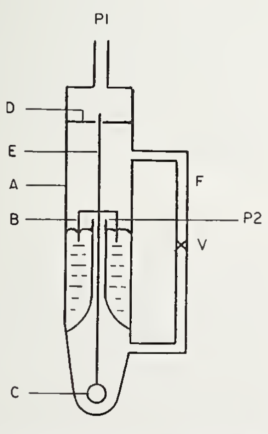

FIGURE 18. *Cartesian diver.*
A, tube subjected to pressure *P1*; *B*, diver subjected to pressure *P1—P2*; *C*, weight; *D*, reference disk; *E*, rod connected to *B* and *C*; *F*, tube; *V*, valve.

The instrument developed by Hindley [4702] may be called either an inverted bell or a gasometer-type micromanometer. It is useful only for measuring differential pressures differing slightly from ambient atmospheric pressure. Commercial versions differing essentially from Hindley's design in the means of indication have been available in past years, but seem not to have been described in technical publications. The application of a commercial version as a standard is briefly described by Perls, Kaechle, and Goalwin [5305]. Referring to figure 19, identical inverted cups B dip into reservoirs of kerosene or other low-density liquid. The spaces above the liquid in cups B are connected to pressures $P1$ and $P2$, the difference between which is to be measured. Cups B form two arms of a balance, pivoted at C; any change in the balance, normally due to a change in $P1-P2$, is indicated by pointer E moving over scale S, observed with the aid of optical magnification. The fulcrum is a beryllium-copper strip normal to the plane of figure 19, its center fastened to balance arm D and its ends fastened securely, so that the forces acting on cups B are balanced by the elastic twist of the fulcrum strip. The torques to be measured are very small; the necessity of eliminating friction is obvious. The changes in buoyancy of the cups with pressure changes are small, so that the major forces are produced by the vertical pressure difference across the cups. The pressure range for the instrument as constructed was 10^{-3} to 0.05 torr.

An inverted bell instrument utilizing photocells, described by Ower, is briefly discussed in section 2.4.3.

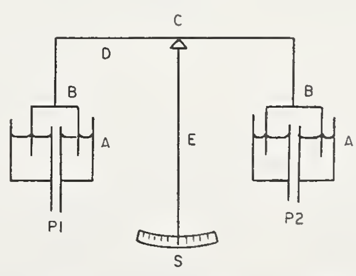

FIGURE 19. *Inverted bell micromanometer.*
A, cups; *B*, inverted cup or cell; *C*, fulcrum; *E*, pointer; *P1—P2*, differential pressure; *S*, scale.

2.11. Force Balance Designs

The use of weights to return a significant part of the instrument to a null position is attractive in view of the inherently high accuracy of weights. However, in micromanometers, the force to be applied is small, so that frictional and other extraneous forces must be minimized in practical designs.

2.11.1. Hickman Gage

Hickman [2903] describes a design used in manufacturing vacuum tubes to measure pressures in the range 0.01 to 5 torr. The entire instrument is free to turn about fulcrum *D*, figure 20, and is balanced by the buoyant force of float *F* in reservoir C containing mercury. The equilibrium position when pressures $P1$ and $P2$ are equal is indicated by arm *E* when opposite to a mark at *H*. A pressure increase in $P2$ causes the mercury level to fall in cistern *B* and arm *E* to rise to H'. Weights applied at *G* return *E* to position *H*. The differential pressure, $P2-P1 = KW$, where W is the weight added to *G*, and K is a constant depending upon the geometry. A rough calculation indicates that K equals 1/150 when $P2-P1$ is in torr units and W is in grams. Note that the buoyant force on *F* remains constant when arm *E* is in null position *H*. Hickman expected and encountered difficulty with errors caused by erratic capillarity. This he reduced by using a wetting agent on the surfaces of the mercury, either butyl phthalate or tetra-ethylene-glycol methyl ether; these in turn introduced errors due to their absorption of the ambient gases.

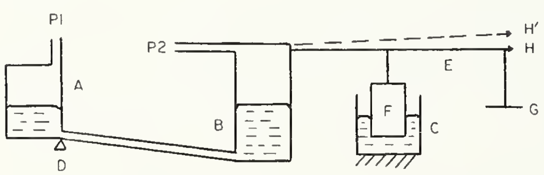

FIGURE 20. *Buoyant force balance micromanometer.*
A and *B*, cisterns; *C*, reservoir; *E*, pointer; *F*, float; *G*, weight pan; *H* and *H'*, *null* ($P2-P1=0$) and position when *P2* exceeds *P1*.

2.11.2. Kemp Gage

Kemp [5945] utilized weights to balance an elastic stress caused by the shift in liquid in the U-tube due to a pressure change. The cistern *A*, figure 21, is firmly held, while cistern *B* is held by elastically identical tubes $T1$ and $T2$ fastened to *A*. The reference pressure is P_0. Any increase in pressure *P* causes the liquid in cistern *B* to fall, and in cistern *A* to rise. The loss of liquid in *B* is balanced by a change in the stress in tubes $T1$ and $T2$, while maintaining a difference in column height proportional to $P - P_0$. To determine the null position of the liquid surface in *A*, an inductance transducer *E* is used, one element of which is mounted on float *F*. Weights are added at C to bring the transducer and the float back to null. The pressure difference $P-P_0 = KW$, where W is the weight applied at *C*, and K is a constant depending upon the

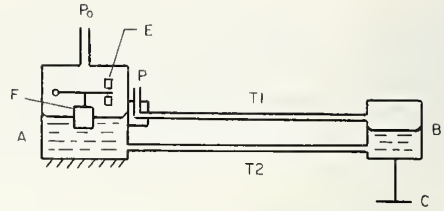

FIGURE 21. *Elastic force balance micromanometer.*
A and *B*, cisterns; *C*, weight pan; *E*, inductance transducer; *F*, float; P_0, reference pressure; $P-P_0$ differential pressure; *T1* and *T2*, tubes, elastically alike.

elastic characteristics of the tubing and the U-tube geometry. Water was the manometer liquid used. At first sight, it appears that a vacuum could be measured with the same numerical accuracy but in millimeters of mercury instead of millimeters of water, but only experimentation can verify this conclusion. The differential pressure range of the instrument extended to 5 mm of water; at the upper part of the range the estimated error was 0.01 mm of water; at 0.01 mm of water, the estimated error was 5×10^{-4} mm of water.

2.11.3. Ring Gage

One of the advantages of the ring gage is the possibility of measuring small differential pressures at high absolute pressures, since a metal ring can have the strength to withstand high pressures. This application has received some attention, but needs no further consideration here except to mention Schmidt's discussion [3601].

Hickman [2903] describes a ring gage found to be useful only for rough measurements of vacuum. The gage consists of a tube in the form of a ring. An airtight disk at the top secures two pressure compartments. Mercury is in the lower third of the ring. The ring, in Hickman's design, is pivoted at its center and restrained from deflecting angularly by a spiral spring of small stiffness. A difference in pressure across the airtight disk causes the ring to deflect angularly until the restoring torque of the spring equals the torque produced by the unbalance in the mercury columns caused by differential pressure. The measured angular deflection is a function of the pressure difference.

Blase [60227] outlines briefly a design of a pivoted ring gage in which the null position is restored by weights, or automatically by a force produced electrically. He states that the latter type is available commercially in Germany.

2.11.4. Weighing Barometers

Weighting barometers or manometers should be mentioned, in view of their great sensitivity. These are described by Middleton [B641] as barographs. The classical design has the barometer tube suspended from one arm of a precision balance and otherwise free, except for the lower end dipping into a cistern of mercury. As the mercury level in the tube changes, so does the tube weight.

Brown [6704] describes a variation from the above-described design. One leg of a U-tube is suspended from a precision balance and is connected by flexible tubing to the other leg and to a source of vacuum. Deviations from the weight of the tube at zero differential pressure give the absolute pressure P in absolute units by the simple relation

$$P = mg \left(\frac{1}{A_1} + \frac{1}{A_2}\right) \tag{1}$$

where mg is the change in weight of mercury column from zero differential pressure and A is the cross-sectional area of the U-tubes. Overall accuracy claimed is $\pm$ 0.001 in of mercury (0.025 torr). While the required flexible joints to the weighted barometer tube received considerable attention, there lingers some doubt that all possible sources of joint error have been eliminated.

3. Gas Column Manometers

Gas columns in relatively long U-tubes can be used to obtain small computable pressure differences if the temperature or gas composition of one leg differs from that of the other.

Fry [1308] had an inverted U-tube filled with air. The temperature of each leg was controlled. The pressure difference at the bottom of the legs of the U-tube is proportional to the difference in the reciprocal of the temperatures multiplied by the height of the U-tube. This pressure could be varied by tilting the U-tube, in effect reducing its height. The difference in pressure thus obtained was used to calibrate micromanometers. Pressures below 0.1 torr are obtainable.

Simmons [5488] designed an instrument for measuring small differential pressures at approximately atmospheric pressures produced by a pitot-static tube installed in a wind tunnel. The upper ends of two long vertical tubes were connected respectively to the pitot tube and the static tube. The temperature of the air-filled tubes was controlled; that connected to the static tube was the hotter. The airspeed in the wind tunnel was adjusted so that the pressures in the two vertical tubes were equal. To determine equality in the pressures the two tubes were connected at the bottom, with two smoke-filled reservoirs in the connecting tubing. A short tube between the reservoirs was viewed by a microscope to detect the passage of smoke, in one direction or the other. The absence of smoke motion indicated pressure equality. From the geometry and the temperature of the vertical tubes, the difference in the applied pressures was computed. The pressure range of the instrument as constructed and operated was 0.5 to 14 dynes/cm^2 (3.8 to 105 $\times$ 10^{-4} torr), with a sensitivity of 0.0005 dynes/cm^2 (3.8 $\times$ 10^{-7} torr).

Both Threlfall [0605] and Lynn, Corcoran, and Sage [5614] used the gas-column manometer to measure the density of a gas. The gas of unknown density was admitted at the top of one leg of a long U-tube (over 100 in high), and a gas of known density to the other leg. Two cisterns were installed, one at the bottom of each leg and connected by a tube with a horizontal section. The cisterns contained a liquid, methyl alcohol in the case of the Lynn design, with a gas bubble in the horizontal tube section. The displacement of the bubble is a measure of the pressure difference at the bottom of the two legs. The temperature of the U-tube legs was maintained constant at selected values. From a knowledge of the column height, the differential pressure, gravity, and the density of the reference gas, the density of the test gas can be computed. Lynn obtained a sensitivity as good as 2 $\times$ 10^{-6} in of methyl alcohol (roughly, 3 $\times$ 10^{-6} torr).

Herskovitz [6629] applied a Michelson interferometer to measure the change in light path of a gas column in order to measure the gas pressure. Briefly the number of fringes counted is a function of the index of refraction of the gas and the length of gas column traversed by the light beam. The index of refraction is a function of the gas density, from which the gas pressure can be calculated, if the gas temperature is known. It also varies with the gas composition, which must therefore also be known. The gas sample was sealed in a cylindrical container. The light beam was reflected from an optical flat at the bottom of the container. A monochromatic light source was used. A change of 0.1 fringe was measurable which was equivalent to a pressure change of about 1 torr for atmospheric gases. Further development could increase the sensitivity, perhaps into the micromanometer range, but the chief drawback is that the gas composition must be known.

4. Elastic Element Micromanometers

4.1. Primary Elastic Elements

In general, in a micromanometer of this type, an elastic element is interposed between the system in which the pressure is to be measured and a reference system. If the reference system is at zero or constant pressure, absolute pressure is measured; if the reference pressure is not zero and variable, differential pressure is measured. If the reference pressure is atmospheric pressure, gage pressure is measured. If atmospheric pressure is measured, the instrument is an aneroid barometer.

The pressure sensor may be either a flat or corrugated diaphragm or capsule, or a Bourdon tube, or a bellows. Its deflection under presure is generally amplified either by mechanical, electrical, or optical means. Before considering these transducers, the fundamentals of the various sensors will be reviewed.

Van der Pyl has compiled a bibliography on diaphragms and aneroids [60231] containing 171 abstracts, and also one on Bourdon tubes and Bourdon tube gages [5384]. Wahl [5796] has prepared a survey on flat diaphragms listing 41 references. The first two listed were issued as ASME preprints and therefore unfortunately are probably available only in the Engineering Societies Library in New York. Attention is called to the book on elastic elements of instruments by Andreeva [B622].

On many of the designs to be described, data are given on the accuracy or sensitivity of the indication as obtained by the designer. These values may not be the ultimate obtainable; subsequent improvements in the construction of the pressure sensor, diaphragm, Bourdon tube, or bellows, and the development of better materials may have by now made greater sensitivity possible.

4.1.1. Diaphragms

Metal diaphragms may be either flat or have one or more corrugations. Flat diaphragms are initially more sensitive than corrugated ones of the same diameter and thickness. By controlling the number and shape of the corrugations, a wide range of pressure-deflection relations is obtainable with corrugated diaphragms, including deflections linear with pressure. In the case of flat diaphragms, buckling (oil-canning) is avoided by placing them under radial tension, created thermally during installation. The manufacture of corrugated diaphragms to have identical sensitivity seems practically impossible, so a selection process must be used.

Way [3411], and others, have developed theories governing the relation of pressure to strain for both the edge-free and the edge-clamped flat diaphragm without radial tension. Only the edge-clamped, thin diaphragm, with initial radial stress, is of interest here. Wahl [5796] indicates that a theoretical analysis of the latter case has not been made.

Theodorsen [3108] has discussed practical problems involved in flat diaphragm gages used in aeronautical research. His theory indicates that the diaphragm deflection is directly proportional to the differential pressure. On the other hand, his data, and that of many other experimenters, show that the deflections may be either linear or nonlinear with pressure. Probably the method of clamping (Carter, et al. [4927]), and to a greater degree, the amount of initial radial tension, account for the variations from linearity. Theodorsen emphasized the necessity of having the diaphragm under initial radial tension to avoid an unstable zero. His significant contribution was to determine that the abnormally large temperature effects were caused by differential expansion of the various materials composing the pressure cell. The differential expansion changed the initial radial tension, aggravating the temperature effect. Incidentally, he compensated for temperature changes by soldering a central disk of a different metal to the diaphragm; this was necessary where instrument temperature was not controlled. Carter [4927] machined the diaphragn and support out of a solid block of metal; the minimum diaphragm thickness was 0.004 in, too thick for a micromanometer.

Usually flat diaphragms now used are of metal. However, some experimenters have made use of plastics or a rubber in order to obtain greater sensitivity. One possible objection to the use of plastics or rubber is the tremendously greater effect of temperature changes on the stiffness.

The theory covering the elastic deflection of corrugated diaphragm capsules has been developed by Griffith [2807] and Grover and Bell [4832] and for clamped diaphragms by Haringx [5795]. These theories have been summarized by Wildhack, Dressler, and Lloyd [5772], together with a theory by Dressler [59194], for both the free (capsule) and clamped corrugated diaphragm. Computations using Dressler's theory practically require the use of an electronic computer. A theory, checked by experiment, was also developed by Akasaka [5583] in Japan.

For a given deflection of a corrugated diaphragm, the central force equals about 0.4 of the product of the pressure and the area of the diaphragm. For a thin flat diaphragm this value is about 0.25 [5772].

Corrugated diaphragms are generally formed, when small quantities are required for experimentation, by hydraulically pressing a flat blank into a die; instrument manufacturers find this procedure too slow and expensive and use two dies in a press with the blank between the dies. By suitable heat treatment and pressure cycling, equivalent performance can be secured from diaphragms made by either process.

Some data on the effect on the pressure-deflection curves of various corrugation shapes, depths, and numbers are summarized in [5772]. However, more data are needed to complete the picture.

The corrugations are generally concentric. Diaphragms thinner than 0.002 in (0.025 mm) are hard to handle. Cordero, Matheson, and Johnson [5771] describe a diaphragm having radial corrugations formed from brass 0.001 in thick. The required pressure-deflection relation was that $P = kd^{1/2}$ over the pressure range -30 to $+30$ dynes/cm^2 (2.2×10^{-2} torr).

Capsules constructed of several corrugated diaphragms are commonly used in instruments where the deflection is multiplied by levers and gears. Where electrical or optical means are used to obtain an indiction, a single diaphragm, flat or corrugated, is usually used.

In micromanometers measuring low absolute pressures, the reference pressure should be low to avoid stressing the diaphragm unnecessarily, and is generally maintained by a pump at a value significantly below the system pressure.

4.1.2. Bourdon Tubes

Bourdon tubes are flattened or elliptical tubes bent into various shapes, commonly to form either a circular arc or a helical coil, and rarely, a spiral. One end is fixed where the gas (or liquid) is admitted and the other end free to deflect. The deflection is angular.

An outstanding characteristic of Bourdon tubes is the small ratio of torque developed by the tube to the pressure causing it. The Bourdon tube gage is widely used for measuring differential pressures above about 5 psi (250 torr). In the micromanometer range, helical coil Bourdon tubes of glass or quartz have had some application, as will be described later.

It should be mentioned that extensive work has been done on the theory of Bourdon tubes, culminating in that proposed by Dressler [65341]. See also Vasil'ev [65340].

4.1.3. Bellows

Metal bellows are particularly useful as pressure sensors when a large deflection and force are required. They have, however, not been manufactured to have the sensitivity required for micromanometers. Accordingly, they have been used in micromanometers in special situations only.

Manufacturers' catalogs are generally relied upon for performance characteristics. The force developed by a bellows is the pressure change times the average of the cross-sectional area fixed by the outer and inner radial diameter of the convolutions.

4.1.4. Performance Criteria

All of the elastic sensors—diaphragms, Bourdon tubes, and bellows—have elastic defects and are temperature sensitive. Elastic defects are of two kinds, one independent of time and the other time dependent. Both occur simultaneously and are hard to separate in practice. Hysteresis is due to the fact that the strain, or deflection, depends upon the direction which the stress, or pressure, is applied. Drift is the continued change in strain with time after a stress is applied. Obviously, a measured hysteresis will include some drift as well as the hysteresis independent of time. Drift is quite rapid initially and tapers off with time, but actually may continue indefinitely if the stress is great. Experiments indicate that no matter how fast a pressure cycle may be imposed (drift therefore small) or how slowly (drift cancelled out) some hysteresis will be evident, indicating a component independent of time.

The effect of temperature is due to both the thermal expansion (especially in constructions using dissimilar materials) and the thermal change in the modulus of elasticity. The coefficient of the latter is of the order of 10 times greater than the former for most metals. Notable exceptions are certain nickel alloys. Generally, thermal expansion causes a zero shift, while a thermal change in the modulus of elasticity causes a change in the sensitivity to pressure. Usually the situation is not that simple, since side effects may occur, such as thermal expansion changing the radial tension in a flat diaphragm and, thus, the sensitivity to pressure. In practice, micromanometers are commonly used in air-conditioned rooms, which minimizes temperature errors.

The main improvement in performance of diaphragm elements has come from the development of materials which can be hardened by heat treatment after forming the diaphragm. The old standbys, phosphor bronze and nickel silver, hardened only by cold working, still find application when the utmost in performance is not needed. Beryllium copper [4417], with about 2 percent beryllium, is now generally used when instrument temperature changes are not a factor. Ni-Span-C, an iron-nickel-chromium-titanium alloy, has a temperature coefficient of elasticity of nearly zero over a limited, but useful, temperature range, and otherwise a performance about equal to that of beryllium copper. The improvement can be measured by the fact that phosphor bronze corrugated diaphragms had a useful deflection of about 2 percent of the diameter 30 years ago, and now, with either beryllium copper or Ni-Span-C, this figure is up as high as 7 percent, without significant increase in the elastic hysteresis or drift.

For diaphragms unstressed except when a small differential pressure is applied, as is normally the case for micromanometers, the elastic defects, hysteresis, and drift, can be below about 0.01 percent of the total pressure change. This assumes the use of selected materials such as beryllium copper, or steel in the case of flat diaphragms, all properly processed. Extraneous effects such as those caused by poor clamping, or the use of soft solder, must be found and eliminated. Also, the closer the procedure of calibration simulates the conditions of use, particularly in the time rate of application of pressure, the smaller will be the uncertainty in the measurement. Normally, the elastic defects are not a limiting factor in the accuracy of micromanometers.

If the diaphragm is normally in the stressed condition, as is the case in aneroid barometers where the diaphragm capsule is evacuated and its exterior subject to atmospheric pressure, the elastic defects are much larger. It is difficult to give a valid single number for the effect which will cover the many possible designs and conditions of use: approximately, in the diaphragm capsules in aneroid barometers, hysteresis can be held to 0.1 percent of the pressure change and the drift to about 0.2 percent. This percentage is for a large pressure change; for small pressure changes the percentage will be somewhat greater.

What has been said about diaphragms applies equally well to metal bellows. These are available commercially in beryllium copper and Ni-Span-C, so that about equal performance can be obtained.

Only Bourdon tubes of quartz (fused silica) or glass are of interest here. Quartz has a very low drift and elastic hysteresis compared to that of metals and thus finds application in micromanometers of high repeatability, in making pressure measurements. However, sensitive quartz Bourdon tubes respond sensitively to any imposed vibration. The temperature coefficient of elasticity, while less than most metals, is still appreciable. Sosman [B271] gives $+12 \times 10^{-5}$ per degree C for the temperature coefficient of rigidity; that for Young's modulus will not differ substantially. Note that fused silica stiffens with increase in temperature in contrast to the behavior of most metals.

4.2. Secondary Elastic Elements

Torsion wires or filaments, usually of tungsten or fused quartz, are often used to restrain the angular deflection of vanes (see sect. 6) or spoon-shaped Bourdon tubes (see figs. 27 and 43). Their elastic quality is thus as important as that of the Bourdon tube. The performance characteristics of fused quartz have already been discussed. It remains to be said that the apparent modulus of rigidity of both tungsten and fused quartz filaments increases as the diameter of the filament decreases from about 1 mm [B271].

In micromanometers in which the pressure element deflection is multiplied mechanically, hairsprings are installed on the pointer shaft to obviate backlash. Although the spring torque on the pointer shaft is small, the elastic properties of the hairspring require some attention. The hairspring deflects with pressure changes and its stiffness (amplified by the amplifying mechanism) is an addition to the stiffness of the pressure element. Elinvar hairsprings are available commercially made of alloys of characteristics similar to that of Ni-Span-C.

Helical springs are used in some designs of mechanical instruments to maintain the pressure element, usually a diaphragm capsule, in the null position. Its deflection is a measure of the pressure change. Obviously here the elastic properties of the spring materials are important. If temperature effects are not important, the springs can be made of available good quality alloy steels. Otherwise, isoelastic alloys can be used [5691].

4.3. Sensor Deflection Measured Mechanically

4.3.1. Deflection Amplified Mechanically

The differential pressure gage with amplification of the deflection of a diaphragm, diaphragm capsule, or Bourdon tube by levers, sector, and pinion driving a pointer over a scale, is an old development. Improvements in performance have followed from those found necessary in aneroid barometers, aircraft speed indicators, and particularly in aircraft altimeters. In micromanometers, when a corrugated diaphragm capsule is the sensor, the uncertainty in measurement is at best about 0.1 torr, with a practical limit to the range of about 20 torr. Friction and backlash in the multiplying mechanism are the chief difficulty in securing greater accuracy.

To obtain greater sensitivity, a leather diaphragm backed by a plate or D-spring to give stiffness, or a synthetic rubber diaphragm, have been used as the sensitive element. Such instruments were used initially to measure draft in power plants and are called draft gages. Their pressure range is as low as 1 in of water (roughly 2 torr); the sensitivity is about 0.05 torr. The uncertainty is at best about 0.1 torr.

Aneroid barometers and altimeters as commonly designed will not be discussed in detail, since they hardly can be called micromanometers; however, some designs having high sensitivity will be covered later. Data on the accuracy of precision aneroid barometers in surveying has been given by Kissam [4418]. On the performance of aviation altimeters, Johnson [4833] covers their behavior in dives and climbs and Gracey [65343] outlines recent developments.

Bourdon tubes mechanically connected to an indicating pointer have little application as micromanometers. Modern efforts to increase their sensitivity are discussed by Van Kuyk and Huston [65344].

4.3.2. Deflection Not Amplified

Two designs in which the diaphragm deflection is measured directly are of some interest. The first is the Goldschmidt aneroid barometer dating back to about 1877. In figure 22, D is an evacuated diaphragm capsule which deflects freely except to control the position of lever $L1$. A similar lever $L2$ is positioned by micrometer A. To make a measurement, the markers $E1$ and $E2$ are brought into coincidence by the micrometer as viewed by microscope M. The change in reading of the micrometer, about twice the deflection of the capsule, is a measure of the change in the atmospheric pressure. Practically, as an aneroid barometer the sensitivity limit is about 0.1 torr; assuming the use of several diaphragm capsules, the sensitivity could be pushed to perhaps 5×10^{-2} torr at the risk of increasing the elastic defects significantly.

The second design proposed by Spence [4021] is shown in figure 23. To measure the pressure of corrosive gases, a glass bellows B is connected to a vertical capillary tube C. The bellows is filled with mercury with a free surface in the capillary tube. An increase

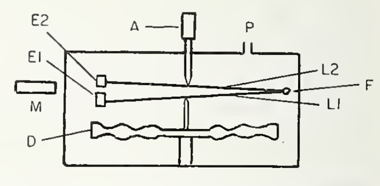

FIGURE 22. *Goldschmidt aneroid baromter.*
A, micrometer; *D*, evacuated diaphragm capsule; *E1* and *E2*, markers; *F*, fulcrum; *L1* and *L2*, levers; *M*, microscope.

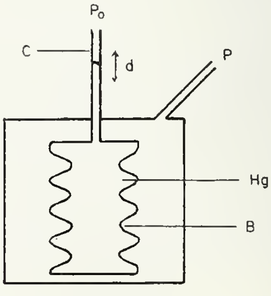

FIGURE 23. *Corrosive gas manometer.*
B, glass bellows; *C*, capillary tube; *d*, deflection of mercury column; P_0 and *P*, reference and applied pressure.

in P compresses the bellows and forces the mercury to rise in the capillary tube. In the design described by Spence the deflection in the tube is about one-fifth of that of a U-tube manometer; obviously this is not a micromanometer. However, it would be possible to increase the sensitivity of the elastic element and to have the capillary tube horizontal in order to approach the sensitivity of a U-tube manometer.

A Bourdon tube of glass to withstand high pressure applied externally was designed by Foord [3405]. A long glass pointer was attached to the free end of the Bourdon tube. Its angular deflection, observed on a scale, measured the pressure. The sensitivity was a pointer deflection of 0.54 mm per torr. The vibration sensitivity was not mentioned.

4.3.3. Force Balance Systems

The discussion here will be limited to the instrumentation where the balanced condition is obtained manually. Two types are described, one in which the restoring force is a spring and the other, a solenoid.

Electrical null detectors, which lead to the use of feedback to maintain the balance, will be considered later.

A classical example of the first type is the Paulin aneroid barometer. A schematic diagram, lacking some of the detail of the null detector, is shown in figure 24. A description and some performance data were given by Werkmeister [3114]. The evacuated diaphragm capsule D is kept in the null position, or at least centrally, by helical spring F. The latter is adjusted manually by a precision screw M, with provision in the design to avoid applying a torque to the spring. A pointer P rotated with the screw indicates the pressure on scale S, which may cover as much as two revolutions. To detect the null position, a rigid frame H moves vertically with the central area of the diaphragm. Metal strips $J1$ and $J2$ are attached to H and the case of the instrument. Strips $K1$ and $K2$ are attached to $J1$ and $J2$ and to opposite sides of a disk on the shaft of tendency pointer TP. Thus, any deviation of the diaphragm from the null causes H to move and, through strips J and K, to rotate pointer TP, the position of which is indicated on a second scale. Actually, the mechanism of transferring the motion of strips J to pointer TP is somewhat more complicated than shown. As constructed, the tendency pointer is normally about five times as sensitive as the pressure-indicating pointer P. Under normal conditions of use, the accuracy obtained in precision types is about 0.1 torr, with a sensitivity of about 0.05 torr. One drawback of this type of instrument is the necessity of making a manual adjustment to obtain a reading. This is obviated by a feedback to maintain the null, of which a number of types are described herein; one applicable here is described in section 4.5.3.5.3. It remains to say that the Paulin barometer could be used to measure gage pressure in the micromanometer range merely by opening the diaphragm capsule to the system pressure to be measured. The obtainable accuracy would be improved, but not enough to make such application worthwhile.

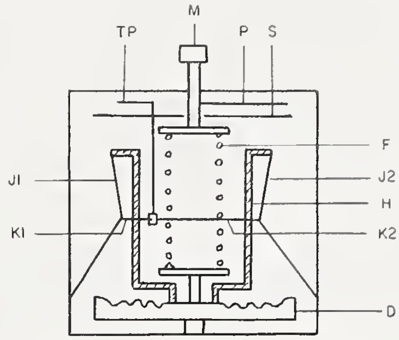

FIGURE 24. *Paulin aneroid barometer.*
D, evacuated diaphragm capsule; F, helical spring; H, rigid frame; $J1$ and $J2$, metal strips; $K1$ and $K2$, offset metal strips; M, micrometer; P, pressure indicating pointer attached to M; TP, tendency pointer indicating null.

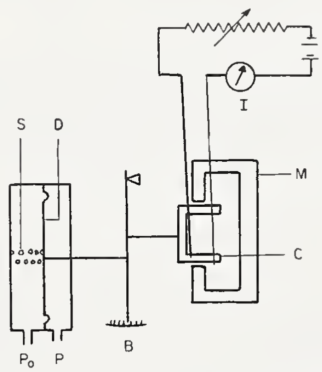

FIGURE 25. *Electromagnetic force balance.*
B, balance detector; C, balancing coil; D, diaphragm; I, microammeter; M, permanent magnet; $P—P_0$, differential pressure; S, helical spring.

The instrument described by Blase [60227] restores the null position of the diaphragm by a solenoid. Referring to figure 25, D is a diaphragm, S a helical spring, and M and C form a solenoid. When the diaphragm deflects due to increase in pressure P, the current in coil C is increased to restore the diaphragm null as indicated by the position of lever B. The current through microammeter I is a function of the pressure. Blase states that a commercial instrument is available for measurements in the range 0.05 to 0.15 in of water (0.093 to 0.28 torr).

4.4. Optical Transducer

The most common design uses a light beam reflected from a mirror which is turned by the deflecting pressure sensor. Less common are those depending on optical interference such as Newton rings.

4.4.1. Light Beam Transducer

The deflection of a diaphragm, less often of a Bourdon tube, has been amplified by an optical lever by many experimenters. The essentials of the design are

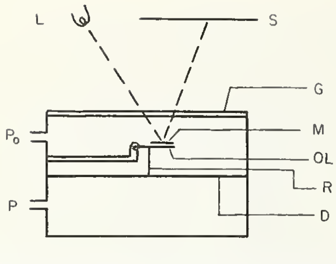

FIGURE 26. *Optical lever micromanometer.*
D, diaphragm; *G*, glass window; *L*, light; *M*, mirror; *OL*, optical lever; *P—P$_o$*, differential pressure; *R*, rod actuating *OL;* *S*, scale.

shown in figure 26. The diaphragm *D*, as it deflects, rotates the optical level *OL* by means of push rod *R*. A support *F* for the fulcrum of *OL* must be provided. A mirror *M* is attached to *OL* which reflects a light beam from *L* to scale *S*. The light beam is obtained from a single linear filament bulb and may be focused on the scale by a simple lens system.

Kenty [4008] lists various designs of micromanometers up to 1940, including optical types, required for particular applications. Some of these require a small volume of the measuring chamber and, in Kenty's case, ruggedness. A few modifications of the optical type are described below.

Kornfeld and Klingler [2904], in measuring the absolute pressure of NO_2, constructed the corrugated diaphragm and other parts in contact with NO_2 of a noble metal in order to avoid chemical reaction. The lowest range of their several instruments was 0.40 torr, and the sensitivity, 0.01 torr. The diaphragm deflection was nearly linear with pressure.

Stewardson [3007] used a flat diaphragm, either of glass or mica, to measure absolute pressure. The sensitivity obtained was 5×10^{-4} torr per millimeter deflection of the light beam.

Hurst [4114], to obtain high sensitivity, used a rubber diaphragm with a centrally attached aluminum disk. Otherwise, the design is as indicated in figure 26. The sensitivity obtained was 3×10^{-4} torr per millimeter scale division.

Grigorovici [3904] mounted a mirror on a rod attached firmly to a glass diaphragm near its outer edge. The deflecting diaphragm in effect rotated the mirror and thus the light beam. The pressure range was 0.1 to 5 torr; sensitivity 0.002 torr; and accuracy 2 to 3 percent.

Crompton and Elford [5722] used an optical lever to measure the deflection of an evacuated diaphragm capsule. A concave mirror was used. They were interested in the pressure range from 0 to 20 torr. The sensitivity obtained was 0.1 torr per millimeter light beam deflection on the scale. The accuracy at 1 torr was 1 percent.

Buckmaster and Mears [58173] initiated the development of a sensitive aneroid barometer for altitude surveying. Briefly, two corrugated diaphragm capsules control the angular position of a mirror pivoted by flexure strips. A light beam passes through a glass scale, 20 lines per millimeter and is reflected by the mirror to pass through an index reticle. The reading system was a microscope with a magnification of 50×. The expected altitude sensitivity was 5 ft, equivalent to about 0.1 torr at sea level.

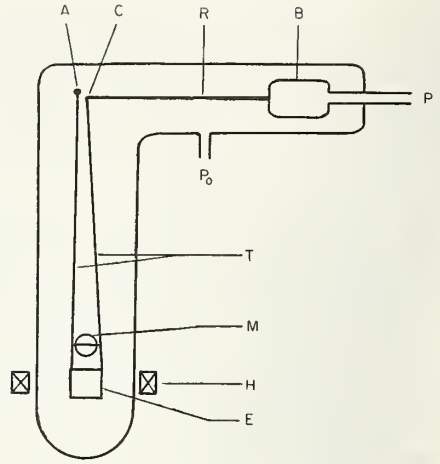

FIGURE 27. *Spoon Bourdon tube–bifilar micromanometer.*
A, adjustable support; *B*, spoon Bourdon tube; *C*, end of rod *R;* *E*, aluminum sheet; *H*, damping magnet; *M*, mirror; *P—P$_o$*, differential pressure; *T*, silk thread.

At this point the discussion turns to Bourdon tube micromanometers with optical magnification. The Bourdon tubes were earlier made of glass; in modern designs, of fused quartz. Eight references are listed here; perhaps a dozen more could be found, dated before 1930.

In an early development by Landenburg and Lehmann [0606], a thread connected the free end of a glass Bourdon tube to a mirror, free to deflect angularly as the Bourdon tube deflected. A light beam was deflected from the mirror to a scale. The sensitivity obtained was 0.03 to 0.05 torr. The necessity of avoiding chemical reactions present with other forms of micromanometers led to this design.

Both Lewis and Style [3718] and Amphlett, Mullinger, and Thomas [4831], used a mirror on a bifilar suspension. The latter used a quartz Bourdon tube wound in the shape of a truncated cone. (see fig. 28) while Lewis and Style used a glass "spoon-shaped" Bourdon tube. The latter, viewed edgewise, is a segment of a circle, and has a rod attached to the free end. The older instrument [3718] was far more sensitive, and is therefore described here. In figure 27, *B* is a plan view of the spoon-shaped Bourdon tube with a long light rod *R* attached, to magnify the deflection perpendicular to the page. A silk thread, attached to *R* at *C*, and to an adjustable support *A*, supports the mirror *M* in a bifilar suspension. An aluminum sheet *E* in the thread loop supplies damping in the field of magnet *H*. Note that the sensitivity increases the closer *A* and *C* are together. When the separation of *A* and *C* was 0.13 mm, the light beam reflected from the mirror had a deflection on the scale 2 meters away of 1 mm for 4×10^{-5} torr. The spoon Bourdon itself deflected 8 mm for a pressure change of 10 torr.

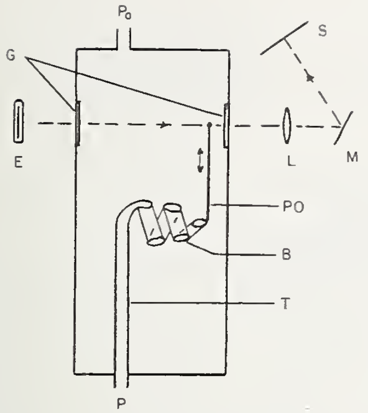

FIGURE 28. *Optical beam–Bourdon tube micromanometer.*
B, helical glass Bourdon tube; *E*, electric light; *G*, glass windows; *L*, lens; *M*, mirror; *P—P₀*, differential pressure *PO*, pointer; *S*, scale.

Yorke [4513] designed a somewhat similar micromanometer which was vertical with the following components, starting at the top: support, filament. mirror, filament, helical Bourdon tube, inlet tube. and support. The sensitivity reported was not great, 4 to 5 mm light beam deflection per torr.

Ewing [5580] substantially modified Yorke's design, mainly to ease the glassblowing. A truncated cone Bourdon tube, figure 28, has a 5-cm pointer *PO* attached to its free end and an inlet tube and support *T* at its fixed end. A small bead at the end of *PO* is in the optical path of light from filament *E*, through windows *G*, lens *L*, and mirror *M*, to scale *S*. The greatest sensitivity is obtained when *PO* is attached to *B* so that the bead has the most vertical motion. The optics are such that an image of the bead is superimposed on the filament image on the scale. The sensitivity was an image deflection of 16 mm per torr.

Barnartt and Ferguson [4312] had a filament connecting the free end of a horizontal pyrex spoon Bourdon tube to a short length of capillary tube, the axis of which was horizontal. The latter was angularly deflected as the Bourdon tube deflected. A mirror attached to the capillary tube reflected a light beam to measure the deflection. The sensitivity obtained was 0.02 torr and in one design was 5×10^{-3} torr; the device withstood an overpressure of 50 torr.

Aylett [60228] described a robust design somewhat similar to that described above. Here the free end of the glass spoon Bourdon tube was connected to a balance wheel by a platinum wire. The deflection of the Bourdon tube turned the balance wheel against the slight torque of a hairspring installed to prevent backlash. A mirror was attached to the balance wheel which, with the usual light source and scale, completes the description. For a scale 1 m from the mirror the light beam deflection was 5 cm per torr. For a pressure range of $\pm$ 2 torr, the hysteresis did not exceed 0.01 torr.

Heiland [5172] describes an aneroid barometer for surveying, designed by Graf and intended for sale by Askania-Werke (Berlin), which is essentially the same in design as the experimental aneroid barometer of Buckmaster and Mears [58173] which has already been described. Either the Graf design was overlooked by Buckmaster and Mears, or Askania did not go through with its manufacture. In detail, Graf used an evacuated Bourdon helix instead of diaphragm capsules for the pressure sensor, and an autocollimator instead of a microscope for amplifying and measuring the deflection of the Bourdon tube. The light beam passes through a transparent scale, is reflected from a mirror attached to the free end of the Bourdon tube, and then through an index to an eyepiece. Each scale division is equivalent to a pressure change of 0.1 torr. The sensitivity is about 0.01 torr. The scale is visible for a pressure range of 10 torr. To cover the range 300 to 900 torr, the Bourdon tube as a whole is angularly deflectable by means of a micrometer screw, with provision for equating the pressure to the angular motion.

4.4.2. Interferometric

Scheel and Heuse [0902] describe in considerable detail the design and calibration of a micromanometer used in measuring the vapor pressure of water at pressures below 0.001 torr. Simply, a small glass optical flat was fastened centrally to a very thin, flat copper diaphragm which was under radial tension. Another glass optical flat was installed just above the one on the diaphragm. To secure interference fringes, a monochromatic light beam (helium 5876-angstrom line) impinged on the optical flats. One fringe passed for a pressure difference across the diaphragm of 3×10^{-4} torr. Calibration was obtained by using a U-tube mercury manometer using two index points controlled by micrometers, and also by volumetric division.

Kenty [4008] describes an instrument based on Newton's rings, using a diaphragm and an optical flat both of quartz. His measurements extended to 54 atm and to temperatures up to 820 °C. At the lower pressures the sensitivity obtained was 0.5 torr.

Perhaps of interest is a method of recording the interference fringes developed by Buck [5282]. A high-speed motion-picture camera was used, together with a tailored optical system, for recording dynamic pressures using a quartz diaphragm as a sensor.

Bogatyrev, Kosov, and Kurlapov [6728] used a Rayleigh type interferometer to measure gas pressures in the range 0 to 800 N/m² (6 torr). Two parallel tubes, 1 m long, were filled with a gas of high molecular weight to increase the number of the interference fringes. One tube was connected to the system with a liquid bubble intervening and, similarly, the other tube to the reference pressure. Thus the pressure measurement was made independent of the composition of the gas. Collimated light passed through both tubes and a lens to the eye of the observer. The light paths were equalized by angularly deflecting an optical flat in the reference pressure path. The amount of this angular motion was a measure of the pressure difference in the two tubes.

4.4.3. Photoelectric

Heiland [5172] incompletely describes a barograph, in which photocells detect the deflection of the Bourdon tube, their output being recorded by a microampere recorder.

Boschi and Garcia [6726] detect the deflection of a glass bellows by a photocell. A shutter which is immersed in a liquid is attached to the free end of the bellows. The amount of a light beam passing through the liquid was controlled by the shutter and was received by a photocell. The output of the latter is fed to a Wheatstone bridge and indicated on a potentiometer. The pressure range of the constructed instrument was 1 to 700 torr with an estimated sensitivity of 0.1 torr.

4.5. Capacitance Transducer

The relatively great sensitivity of the capacitance transducer coupled to a diaphragm has resulted in the development of many forms of instrumentation and in a wide variety of applications. The large number of technical papers on the capacitance gage in recent years, far greater than for any other type relying on an elastic element, testifies to its importance. A somewhat extended treatment is therefore justified.

The principle is simple. An elastic element, usually a flat diaphragm, sometimes a corrugated diaphragm, and, rarely, a metal bellows, separates two chambers, the difference in pressure in which is to be measured. An insulated metal disk and the grounded diaphragm, mounted parallel and close to each other, form an electrical capacitance (see fig. 29). Or, two capacitances may be formed by using two disks with the diaphragm between them (see fig. 30). The change in the capacitance(s) as the diaphragm deflects is a function of the pressure. The diaphragm capacitance usually forms part of a capacitance bridge, the output of which may be measured in various ways, or it may be used to indicate the null position of the diaphragm while the restoring force is measured, all as discussed later.

4.5.1. Theory

The theoretical analysis published to date covers only the diaphragm sensing element. Bellows-capacitance instruments have been little used; Bourdon tubes apparently not at all, although attempted by Yasumori [6712]. The theory presented here for single-electrode elements can be applied with minor modifications to the bellows-capacitance gage.

The change in the electrical capacitance, as a differential pressure causes the diaphragm to deflect, can merely be measured; this is the open-loop case. In a closed-loop situation, the electrostatic force required to maintain the diaphragm in the null position can be applied by feedback from the primary capacitor. This electrostatic force is proportional to the applied differential pressure.

Theory covering both the open- and closed-loop instruments has been developed by Drawin [58110],

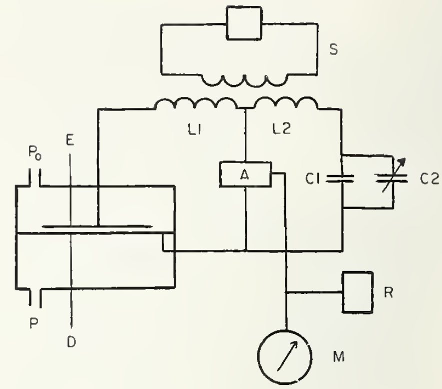

FIGURE 29. *Single capacitance micromanometer.*
A, amplifier; *C1* and *C2*, capacitances; *D*, diaphragm; *E*, metal disk; *L1* and *L2*, inductances; *M*, microammeter; *P—P₀*, differential pressure; *R*, recorder; *S*, radio frequency power supply.

Cope [6217], and Rony [64265]; for the open-loop instrument only by Lilly, Legallais, and Cherry [4701]; and for the closed loop only by Drawin [6081].

The theory developed by Drawin [6081] for the closed loop will be presented first. For one electrode and a flat (or corrugated) diaphragm, figure 29, with all quantities in consistent SI or cgs units:

$$\Delta P \pi R^2 = \frac{\epsilon \pi r^2}{8\pi d_0^2} U^2, \text{ or} \tag{2}$$

$$\Delta P = B_0 U^2, \tag{3}$$

where

$$B_0 = \frac{\epsilon}{8\pi d_0^2} \left(\frac{r}{R}\right)^2. \tag{4}$$

Here $\Delta P = P - P_0 =$ pressure differential across the diaphragm (P exceeds P_0)

$R, r =$ diaphragm and electrode radius, respectively

$d_0 =$ gap between electrode and diaphragm

$\epsilon =$ dielectric constant of gas (with reference to vacuum)

$U =$ electric potential applied to electrode and diaphragm to maintain diaphragm in null position

It is assumed (a) that the electrode and diaphragm surfaces are parallel, (b) that stray capacitances are negligible, and (c) that the null position of the diaphragm does not significantly vary with the differential pressure $P - P_0$. The effect of the expected variations in the dielectric constant with pressure and with possible arcing of the gas will be discussed in section 4.5.4.

As shown by eq (3), the square of the measured potential is proportional to the differential pressure.

If ΔP is in torr and U is in volts, eq (3) becomes

$$\Delta P = 3.333 \times 10^{-10} \epsilon \left(\frac{r}{R d_0}\right)^2 U^2. \tag{3a}$$

In practical designs U will be less than 100 V for ΔP at 0.01 torr, and still smaller as ΔP decreases.

In making calculations with eq (3a), d_o is not easily determined; substituting $d_o = \pi\epsilon_o r^2/(C_o - C_1)$, and adjusting the constant to use $C_o - C_1$ in picofarads, eq (3a) becomes

$$\Delta P = 4.30 \times 10^{-8}\,\epsilon\left(\frac{C_o - C_1}{Rr}\right)^2 U^2. \qquad (3b)$$

Here C_o and C_1 are respectively the diaphragm-to-electrode capacitance and the stray capacitance.

Drawin [6081] further presents a calculation for the case when the diaphragm surface is slightly curved, resulting in a slight increase in the capacitance C_o in eq (3b). This calculation appears of little practical use in a closed-loop instrument, since information on the curvature of the diaphragm is difficult to obtain, and is not really needed in a closed-loop force-balanced instrument.

The above theory holds for one electrode. The varying cases for two electrodes can be considered by applying eq (3). If, as shown in figure 36, one electrode is grounded, the other at a constant voltage U, and the diaphragm subjected to an adjustable voltage $U1$, eq (3) becomes

$$\begin{aligned}\Delta P &= B_o\,[(U - U1)^2 - U1^2] \\ \Delta P &= B_o\,(U - 2\,U \cdot U1).\end{aligned} \qquad (5)$$

Thus ΔP is proportional to the voltage change $U1$; when $U1 = \frac{1}{2}\,U$, $\Delta P = 0$.

If the circuit now has the diaphragm grounded and the two electrodes initially at voltage U, and the voltage on one electrode adjusted to null the diaphragm position,

$$\Delta P = B_o\,(U^2 - U1^2). \qquad (5a)$$

Here ΔP is proportional to the square of the adjustable voltage $U1$.

Again let the diaphragm be grounded with both electrodes initially at voltage U (see fig. 36). To null the diaphragm, the voltage on one electrode is increased and on the other decreased equally by a voltage $U1$. Then

$$\begin{aligned}\Delta P &= B_o\,[(U + U1)^2 - (U - U1)^2] \qquad (5b) \\ &= B_o\,(4\,U\,U1).\end{aligned}$$

Here ΔP is proportional to the voltage change $U1$.

Cope [6217] and Rony [64265] present the theory in more detail.

In the open-loop case, where the diaphragm is allowed to deflect freely, the theory is complicated by the various relations which exist between pressure change and diaphragm deflection for various diaphragm designs. For a radially stretched flat diaphragm three regimes exist: (a) the deflection large compared with the diaphragm thickness, (b) both of the same order, and (c) the deflection comparatively small. Probably case (a) is most applicable to micromanometers. If a corrugated diaphragm is used, it is probably advantageous to have a single corrugation at the rim and have a stiff circular central plate which is electrically coupled to a parallel circular electrode. In the latter design, the capacitor gap varies very little radially, and the diaphragm deflection can be made to be linear with the pressure change, an advantage for micromanometers.

In open-loop designs, theoretical diaphragm deflection-pressure relations are not sufficiently exact to permit reliable calculation of the micromanometer performance, and the micromanometer must be calibrated against a standard. The chief value of the various theoretical relations between diaphragm deflection and pressure is in selecting and designing the diaphragm. Theory which includes diaphragm performance is given by Lilly, Legallais, and Cherry [4701], Drawin [58110], Cope [6217], and Rony [64265].

The simplest case is where the deflection of the diaphragm is linear with pressure and the electrical capacity varies linearly with the reciprocal of the gap between the electrode and diaphragm. Then for a single electrode, figure 29:

$$P - P_o = \Delta P = Kd \qquad (6)$$

and assuming the diaphragm deflection d is constant radially,

$$C - C_o = \Delta C = \frac{K_1}{d_o - d} - \frac{K_1}{d_o} \qquad (7)$$

and

$$\Delta P = \frac{Kd_o\Delta C}{\Delta C + K_1/d_o} \qquad (8)$$

$$K_1 = \frac{\epsilon A}{4\pi}.$$

Here d_o is the diaphragm-electrode gap at zero differential pressure,

d is the diaphragm deflection at differential pressure ΔP,

ΔC is the change in electrical capacitance at ΔP,

ϵ is the dielectric constant of the fluid in the gap, and

A is the area of the capacitor.

K_1/d_o is large compared to ΔC, so that in the practical case ΔP is directly proportional to ΔC.

If two electrodes are used, figure 30, assuming the diaphragm-electrode gaps initially identical ($= d_o$)

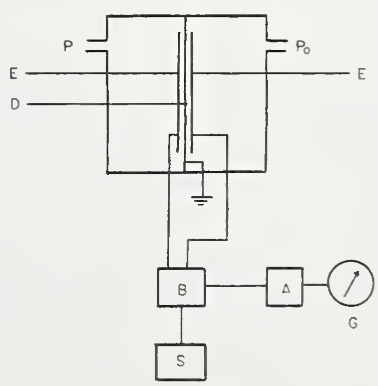

FIGURE 30. *Double capacitance micromanometer.*
A, amplifier; *B*, capacitance bridge; *D*, diaphragm; *E*, metal disks; *G*, galvanometer; *P—P₀*, differential pressure; *S*, power supply.

and the two capacitors forming two arms of a bridge circuit:

$$C - C_o = \Delta C_1 = \frac{K_1}{d_o - d} - \frac{K_1}{d_o} \qquad (9)$$

$$C_o - C = \Delta C_2 = \frac{K_1}{d_o} - \frac{K_1}{d_o + d}. \qquad (10)$$

Then in a two-capacitor bridge circuit, where E_2 is the electrical output,

$$\frac{C_o + \Delta C_1}{C_o - \Delta C_2} = K_3 E_2. \qquad (11)$$

For the single-capacity bridge circuit, where E_1 is the electrical output,

$$\frac{C_o + \Delta C_1}{C_o} = K_3 E_1. \qquad (12)$$

The relation of their outputs is

$$\frac{E_2}{E_1} = \frac{C_o}{C_o - \Delta C_2}. \qquad (13)$$

The relative gain in bridge output by using two electrodes is given by eq (13); since d cannot exceed d_o, the gain varies between the limits of 1 and 2.

Drawin [6081] considers theoretically several sources of error for the closed-loop case. However, his conclusions are largely applicable to the open-loop case; for the range of pressures measured by micromanometers they are:

(a) the effect of pressure on the dielectric constant ϵ (present as a factor in K_1, eqs (7) and (9)) at pressures below 10 torr is insignificant;

(b) the effect of moderate temperature changes on the value of ϵ is likewise insignificant, even for gas molecules with a dipole moment;

(c) the influence of adsorbed gases in altering the contact potential, and thus of the nulling voltage, is not significant;

(d) the effect of temperature changes on the diaphragm dimensions and stiffness, and hence on the gap, is significant, and will be discussed in section 4.5.4. See Pressey [5307].

4.5.2. Electrodes and Pressure-Sensitive Elements

Usually the pressure-sensitive element is a flat metal diaphragm. Some experimenters have used metal diaphragms with a single corrugation, notably Cook and Danby [5302], and Perls, Kaechle, and Goalwin [5305]. To obtain additional sensitivity Beynon and Cairns [6446] used a plastic diaphragm (Terylene), aluminized on one side to obtain an electrical conducting surface.

Either one or two metal disks have usually been used as electrodes to form a capacitor with a diaphragm. If one electrode is used, and electrostatic nulling is used, the differential pressure is of necessity always applied so that the capacitance decreases.

Two variations in design are of interest. In one, shown in figure 31, due to Lovejoy [6108] and Mitsui [64180], a beryllium copper diaphragm D is clamped between pyrex glass blocks A and B. A metal film is deposited on the pyrex surfaces L to secure the two capacitances. Holes in the pyrex admit the gas and permit leads to be brought out from the metal surfaces. In another, figure 33, developed by Suetin and Volobuev [6485], two nesting, corrugated diaphragms are used. See section 4.5.3.3.3 for a description.

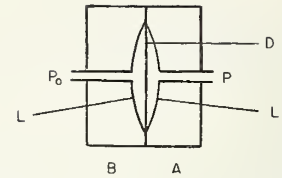

FIGURE 31. *Lovejoy capacitance element.*
A and *B*, glass blocks; *D*, metal diaphragm; *L*, evaporated metal film; *P—P*$_o$, differential pressure.

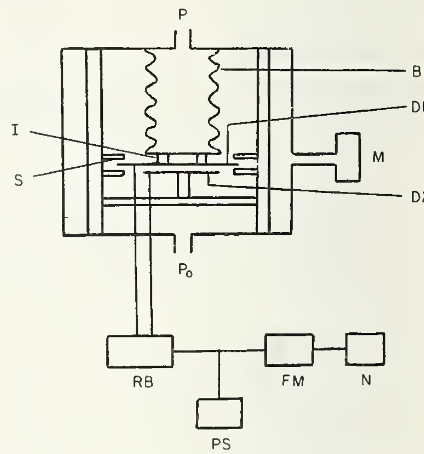

FIGURE 32. *Bellows-capacitance micromanometer.*
B, metal bellows; *D1* and *D2*, metal disks; *FM*, mixer; *I*, insulator; *M*, McLeod gage; *N*, frequency indicator; *P*, system pressure; *P*$_o$, reference or balancing pressure; *PS*, power supply; *RB*, resonant frequency bridge; *S*, glass stops.

Figure 32 illustrates the electrode design with a metal bellows as the sensitive element. All designs [60104, 6344, 6594] have means for initial setting of the gap between the electrode and bellows, by moving either the electrode or bellows.

4.5.3. Measurement Circuits

The major methods of measurement will be outlined. These are in general equally applicable devices using either one or two electrodes. A number of instrument companies manufacture some form of capacitance pressure gages; these have been discussed as of 1965 by Rony [64265]. Probably their circuits will not be novel except in details. The fundamental development work to achieve a precise and accurate instrument has been done by five groups: Lilly, Legallais, and Cherry [4701], Opstelten and Warmoltz [5562, 5616, 58117], Becker and Stehl [5212], Drawin [58106, 58110, 6081], and Lamers and Rony [64265]. The performance of precise commercial instruments has been given by Mueller [60112] and by Utterback and Griffith [6601].

Undoubtedly, circuit variations from those to be described are possible, and have merit. Only those described in the literature as applied to the capacitance pressure gage are presented.

4.5.3.1. Capacity Bridge Balanced, Change in Capacitance Measured

Heylen [60104, 6344] designed a pressure sensing element which could be baked out at 430 °C. Only the pressure element design, not the measuring circuit, is indicated in figure 32. This design consisted of stainless steel bellows B, to which a metal disk $D1$ was fastened at one end with an intervening insulator I. A disk $D2$ parallel to the first, formed the capacitance which varied with change in deflection of the bellows. The inside of the bellows was connected to the pressure to be measured, while the outside was maintained at a high vacuum (not as indicated in fig. 32). A commercial proximity meter (British term for a form of capacitance bridge) was used to measure the change of capacitance with pressure. In figure 29, capacitance $C2$ (and $C1$) would be adjusted to secure a null reading on milliammeter M; the change in capacitance is a function of the change in pressure. In Heylen's design the initial clearance between disks $D1$ and $D2$ is adjustable by raising or lowering disk $D2$, figure 32, permitting adjustment to any pressure range up to 25 torr. The best sensitivity obtained by Heylen was 0.02 torr.

Beynon and Cairns [6446] also measured the change in capacitance as a function of pressure, using a commercial capacity bridge, as did Heylen. Their contribution is in the design of the pressure sensitive element. Instead of a metal diaphragm (fig. 29), one of plastic (Terylene) was used to increase the sensitivity. One side was aluminized. The calibration curve for the range 0 to 50 $\times$ 10^{-3} torr is nonlinear; the change in capacitance for this range was 12 pF. The sensitivity obtained was 4 $\times$ 10^{-5} torr.

4.5.3.2. Capacity Bridge Unbalanced

Two means of measurement are used, (a) most common, the current due to the unbalance is measured, and (b) the unbalanced voltage is measured by a potentiometer. The discussion will be in broad outline; consult the references for details.

A nonlinear twin T network for capacitive transducers was described by Lion [64271].

4.5.3.2.1. Current Measured. Becker and Stehl, and Drawin appear to have made the major contributions to the design of accurate and stable instruments of this type. Their circuits will be described first.

The Becker and Stehl [5212] design is shown schematically in figure 30. An aluminum flat diaphragm is installed between two metal disks E, forming two capacitances. The latter are connected to high-frequency capacitance bridge B; the unbalanced bridge current is fed to amplifier A; and the rectified current indicated on galvanometer G. Their main contribution was meticulous attention to details. The construction was sturdy. The stability in performance was checked and was believed good enough to warrant the use of the instrument as a secondary standard. The only drawback according to Rony [64265] is the difficulty in constructing the pressure transducer. The galvanometer used had a sensitivity of 1 $\times$ 10^{-6} A per scale division; this corresponded to a pressure of 2 $\times$ 10^{-6} torr.

A typical capacitance bridge circuit for the single-electrode instrument due to Drawin [58106, 58110] is shown in figure 29. Here electrode E and diaphragm D form one capacitance in the bridge formed by capacitances $C1$ and $C2$ and inductances $L1$ and $L2$. The radiofrequency power supply S supplies a-c at a constant frequency. Deflection of the diaphragm unbalances the bridge; the voltage due to the unbalance is fed to amplifier A. The resulting direct current can be read on microammeter M or fed to recorder R. Drawin developed this design for use in the range 2 $\times$ 10^{-2} to 30 torr, and also a null type for measurements down to 10^{-5} torr. An output linear with pressure was obtained. A diagram of a similar circuit is given by Opstelten and Warmoltz [58117] for measurements above 1 torr.

Extensive experimental and theoretical work was carried out by Lilly, Legallais, and R. Cherry [4701] on the capacitance transducer-diaphragm gage for dynamic measurement, particularly that of explosive decompression occurring in pressurized airplanes. Circuit details were not given but figure 29 applies essentially, except that the output was displayed on an oscilloscope.

Mueller [60112] describes a commercially available instrument which had a double-capacitance formed by a stainless steel diaphragm between two disks. The circuit is essentially as shown in figure 30. However, two additions were made. First, an ac output can also be obtained, useful when dynamic measurements need to be made. Second, the output of the bridge is balanced by an ac bucking voltage from the power supply (2500 Hz) which is measured by a series of resistances calibrated directly in pressure units. For the dc output, eight pressure ranges from 0.01 to 30 torr are obtainable, with an accuracy of $\pm$ 3 percent, and a maximum sensitivity of 10^{-4} torr. For the ac output, the pressure range is from 1 to 30 torr with a maximum sensitivity of 0.01 torr. The accuracy when the bridge output is manually balanced is $\pm$ 1 percent of the balancing resistance dial reading.

The electrical circuits used by Lovejoy [6108] and Mitsui [64180], figure 31, do not essentially differ from that shown in figure 30. The sensitivity obtained was 10^{-3} torr, which practically fixes the lower end of the range at 10^{-2} torr.

Three applications of the single-capacitance pressure sensor should be mentioned. Baird and Banwell [4019], Johnson and Chiles [5784], and Jones and Forbes [6230] each developed a microbarograph to record atmospheric pressure oscillations. These are described in section 8.2.1.

4.5.3.2.2. Voltage Measured. Two commercially available instruments, one described by Mueller [60112] and one described by Rony [64265], provide a voltage output. As mentioned in section 4.5.3.2.1, voltage from the ac supply nulls the ac output of the capacitance bridge. The variable resistors controlling this voltage are calibrated in pressure units.

Utterback and Griffith [6601] state that a commercial instrument of similar design had a sensitivity of 10^{-5} torr.

4.5.3.3. Resonant Capacity Circuit, Resonance Maintained

4.5.3.3.1. Capacitance Measured. The capacitance gage was first developed by Olsen and Hirst [2902]. Their measurement circuit is now of historical interest only. A glass diaphragm was used, to which a single metal electrode was attached. A circuit was formed by the sensitive element capacitance, a variable capacitance, and an inductance. A quartz crystal oscillator was inductively coupled to the sensitive element circuit. As the diaphragm deflected, the variable capacitor was adjusted to maintain resonance with the quartz oscillator. Resonance was indicated by a milliammeter in the quartz oscillator circuit. The change in capacitance to maintain resonance was indicative of the pressure change. The sensitivity reported was 3×10^{-4} torr.

4.5.3.3.2. Frequency Change Measured. Cook and Danby [5302] set up a capacitance-inductance bridge circuit of which the single capacitance pressure sensor formed one arm. This was maintained in resonant vibration with the aid of a pentode electron tube. The change in the natural frequency of this bridge as the diaphragm deflected under pressure changes was measured by a wave meter. Resonance was indicated by auxillary circuits incorporating two milliammeters, one for coarse and the other for fine indications. For a pressure range from 5×10^{-3} to 120×10^{-3} torr the resonant frequency shifted from about 5.8 to 6.6 MHz. The resonant frequency-pressure curve was very nearly linear. The instrument was used to measure rough vacuum in connection with the operation of a mass spectrometer.

Chester, Choudhery, Jones, and Williams [6815] designed a single electrode capacitance-diaphragm gage to measure liquid helium pressure. The novelty here was the low temperature of the liquid helium in which the gage was immersed. A stainless steel diaphragm, 3 cm in diameter, was used. The electrical circuit was arranged to measure changes in resonant frequency. The frequency was measured by an electronic counter and displayed as a voltage by means of a digital-analog converter. The sensitivity was 87 Hz per millimeter change in the liquid helium level.

4.5.3.3.3. Beat Frequency Measured. The design of the instrument developed by Suetin and Volobuev [6485] is shown in figure 33. The nesting diaphragms, $D1$ and $D2$, form a capacitor and were connected into an oscillating circuit RB. The interior of the capsule is connected to the reference pressure P_0 and the position of $D2$ is adjustable by screw S. The power supply PS is a 1000-kHz crystal-stabilized oscillator. As the diaphragm deflects, the resonant frequency of oscillation in RB changes. The outputs from RB and PS are fed into a mixer M and then into a frequency meter FM, where the beat frequency is measured. In the range 1 to 30×10^{-3} torr, the output, 20 to 450 Hz, was linear. It follows that the sensitivity was 6.75×10^{-5} torr/Hz.

4.5.3.4. Resonant Capacity Circuit; Unbalanced Current Measured

Perls, Kaechle, and Goalwin [5305] used the circuit devised by Cook [5383] in their micromanometer. The circuit is shown schematically in figure 34. Capacitances $C1$, $C2$, and $C3$ plus the diaphragm D and electrode disk form the resonant bridge, excited by the crystal oscillator CO. The output of the bridge changes with a change in pressure, $P - P_0$, is amplified by $A1$, and passes to discriminator DI of the direction of unbalance of the bridge. From amplifier $A2$, the output passes to an oscilloscope O or other means of indication. The null output, when the pressure $P - P_0 = 0$ and the bridge is balanced, is indicated by the detector N. The frequency of oscillation of CO was 500 kHz. Leads as long as 20 ft connected the bridge to amplifier $A1$. The authors point out the need for good shielding and firm construction of the bridge parts. The diaphragm had a single corrugation near its rim so that the electrode disk was faced by a flat portion. The sensitivity was 10^{-6} torr and the range 10^{-6} to 10^{-3} torr.

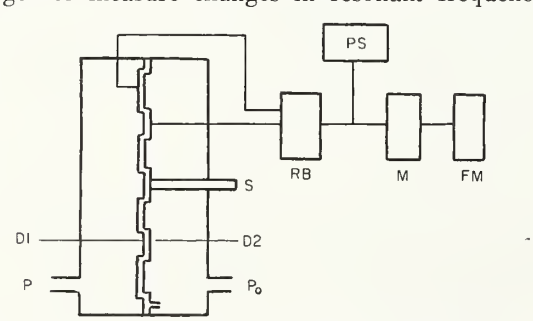

FIGURE 33. *Nesting diaphragms—capacitance micromanometer.* *D1* and *D2*, nesting diaphragms; *FM*, frequency meter; *M*, mixer; *P* and P_0, pressure and reference pressure; *PS*, power supply; *RB*, oscillator; *S*, adjusting screw.

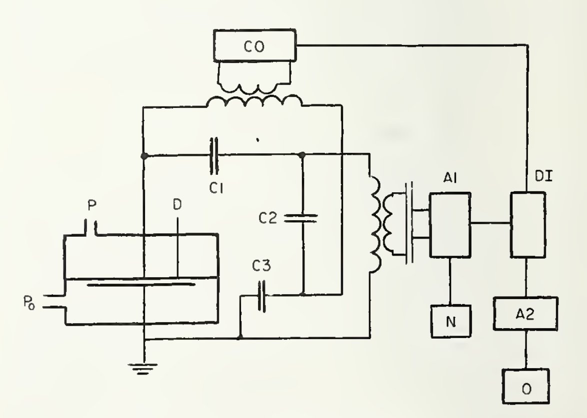

FIGURE 34. *Cook resonant capacitance circuit.* *A1* and *A2*, amplifiers; *C1*, *C2*, and *C3*, capacitances; *CO*, crystal controlled oscillator; *D*, diaphragm; *DI*, discriminator; *N*, detector; *O*, oscilloscope; *P* and P_0, pressure and reference pressure.

Rideal and Robertson [5570] also used a resonant bridge circuit that was operated at 0.8 Hz off resonance. The power supply was a crystal-controlled oscillator of radio frequency 3.505 MHz. The bridge output was fed to a detector, through an amplifier, and then to an oscilloscope, since the application was to investigate gas-phase reactions. The sensitivity was 10^{-4} torr, the range 0 to 2.20 torr, and the deviation from linearity was 2 percent at the highest pressure. The frequency response extended to 10^4 Hz.

4.5.3.5. Elastic Element Null Restored

While subjected to a differential pressure, the elastic element has been restored to its null position by an electrostatic voltage, by applying a balancing pressure, or by a helical spring. These procedures are discussed below. Of these, only the first two merit serious attention. Complete restoration of the null position is achieved only by a balancing pressure. The restoring electrostatic force acts on a central portion of the diaphragm with its outer periphery left under some stress as the capacitance is brought to its initial value. Any effect of this residual distortion can, of course, be eliminated in the calibration of the instrument. This distortion of the diaphragm may become serious if a central force is applied to null the diaphragm, in that the resultant elastic hysteresis and drift can limit the accuracy.

4.5.3.5.1. Electrostatic Voltage Restores Null. Based on a single capacitance formed by diaphragm D and a metal disk, Drawin [58110] developed the circuit shown in figure 35. The bridge is formed essentially by capacitances $C1$, $C2$, $C3$, and $C4$. The temperature of the pressure-sensor unit is controlled at 40 °C above ambient temperature. The output amplified by A is fed to a phase discriminator DI and null indicator N.

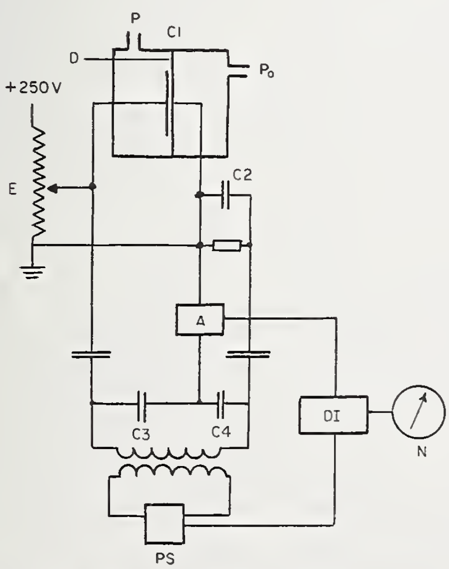

FIGURE 35. *Drawin electrostatic null micromanometer.*
A, amplifier; *C1, C2, C3*, and *C4*, capacitances; *D*, diaphragm; *DI*, phase discriminator; *N*, null indicator; *E*, potentiometer; *P* and P_0, pressure and reference pressure; *PS*, power supply.

The power supply PS had a frequency of 20 kHz. To restore the null when the diaphragm deflects, potentiometer E is adjusted to apply a voltage to the sensor electrode of $C1$. The square of the measured voltage is directly proportional to the differential pressure $P - P_0$. Note that any voltage difference between the diaphragm and the electrode results in their mutual attraction, so that it is necessary for the diaphragm to deflect away from the electrode with increasing differential pressure. The pressure range [6081] was 10^{-5} to 1 torr, with a 1 to ½ percent uncertainty in the measurements. While manual adjustment of the potentiometer is here indicated, feedback circuits have been developed [58117, 6217, 64265] for making the adjustment automatically.

Improvements in Drawin's single-capacitance design were made by Ryzhov [63345], and used by him as a standard in the pressure range from 0.001 to 0.1 torr.

Drawin [6081] developed theory (eqs (2) to (4), sect. 4.5.1) to compute the sensitivity of his micromanometer. This was reviewed by Ryzhov [63345]. For a variety of gases, including some hydrocarbons, all at 52°C, Drawin obtains differences well within 2 percent on the average (maximum 3 percent) for the computed value of B_0 (eq 4) and the experimental value, using a McLeod gage as a standard. He considers sources of error also, details of which are presented later, and concludes with good reason that the micromanometer has application as a secondary standard.

Two designs of electrostatic nulling have been developed using a diaphragm between two disks to form two capacitors. The first to be discussed is that developed by Opstelten and Warmoltz [5562, 5616, 58117], in which one electrode is manually maintained at a constant voltage $U + U1$ and the other at $U - U1$, and the diaphragm is grounded. The circuit diagram is shown in figure 36. The two capacitors formed by the diaphragm D and two disks are part of bridge B, which is activated by an ac power supply PS having a frequency of about ½ MHz. Any deflection of the diaphragm unbalances the bridge, the output of which is amplified by A and fed to null detector N. The dc voltage restoring the diaphragm to the null position as indicated by null detector N is obtained from potentiometer circuit R. The measured restoring voltage $U1$

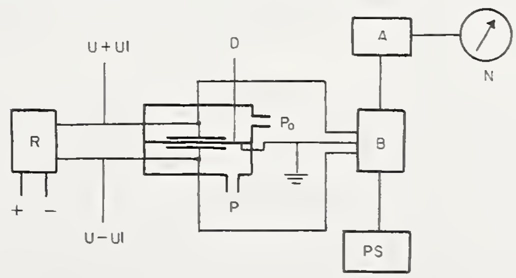

FIGURE 36. *Opstelten-Warmoltz electrostatic null micromanometer.*
A, amplifier; *B*, bridge; *D*, diaphragm; *N*, null detector; *P* and P_0, pressure and reference pressure; *PS*, power supply; *R*, potentiometer; *U* and *U1*, electrostatic voltages.

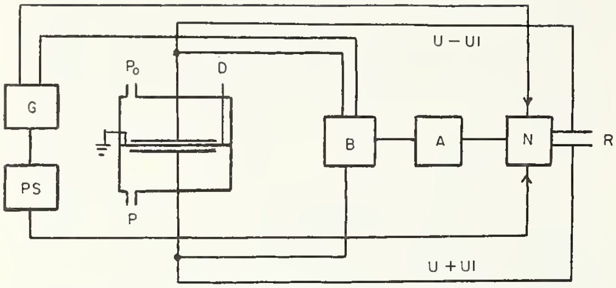

FIGURE 37. *Automatic electrostatic null micromanometer.*
A, amplifier; *B*, bridge; *D*, diaphragm; *G*, crystal oscillator; *N*, null detector and feedback; *P* and P_o, pressure and reference pressure; *PS*, power supply; *R*, to recorder; *U* and *U1*, electrostatic voltages.

is directly proportional to the pressure change (eq (5.2)). At absolute pressures above 1 torr, the dc voltage causes a glow discharge so that the pressure range is limited to below about one torr. However, for differential pressures at absolute pressures of 1 atm, the design might be usable. The range of the instrument is from 10^{-5} to 1 torr. The accuracy [5562] above 10^{-2} torr is 0.1 percent, at 10^{-5} torr, 10 percent. This indicates a sensitivity of 10^{-6} torr.

The other design, for which a circuit was given by Opstelten and Warmoltz [58117], described in detail by Rony [64265] and by Cope [6217], adds a feedback to the circuit of figure 36 to apply the restoring voltage automatically. The circuit is shown schematically in figure 37. The diaphragm capacitances form part of bridge *B*. When the diaphragm deflects, the resulting unbalance of the bridge is fed through amplifier *A* to null detector *N*. The latter contains a phase discriminator and the feedback, whereby the initial voltage *U* on the two electrodes is reduced in one case to $U - U1$, and increased in the other to $U + U1$, to restore the diaphragm to a position where the two capacitances are equal. The diaphragm is grounded. The voltage *U*1 is indicated at *R*, or may be recorded. The power supply *PS* operates a crystal oscillator *G*, the output of which is fed to bridge *B* and to null detector *N*. The voltage *U*1 is directly proportional to the differential pressure. Rony gives the range of his instrument as 10^{-4} torr. Its use was abandoned for his particular application in favor of a deflecting instrument (see sect. 4.5.3.2.1, fig. 30) because of inferior stability and inferior pressure ranges. Undoubtedly, further development work would rectify these shortcomings measurably.

A variation from the circuit diagram given in figure 36 was used by Sharpless, Clark, and Young [61235]. Here the nulling voltage was applied only to one electrode. The diaphragm was grounded. Two capacitances, formed by the diaphragm, and two electrodes were connected to the bridge. The nulling voltage was applied automatically by means of a servomotor which controlled the applied dc voltage. The differential pressure *P* for their sensor was given by $P = 2.30 \times 10^{-5}\, U^2$, where *U* is the applied voltage. The sensitivity was 3×10^{-6} torr, equivalent to the effect of a change in sensor temperature of 0.002 °C.

4.5.3.5.2. Pressure Restores Null. The reason given for the development of this class of instrument was to isolate the system from contamination, but the construction is also essential in gas thermometry to maintain a constant amount of gas in the system. While perhaps more expensive, the purpose could be achieved by evacuating an enclosed space surrounding the pressure-sensitive element and using a capacitor to measure the deflection of the sensitive element, and thus the pressure directly. However, in current designs, the pressure external to the sensitive element is controlled to restore the pressure sensor to the null position as indicated by restoration of the initial capacitance value, and this balancing pressure measured.

Figure 32 is a diagram of the instrument developed by Hackam, Austin, and Thomas [6594]. The bellows *B* is connected to the system pressure. A metal disk *D*1 is rigidly connected to the free end of the bellows but insulated from the bellows by a glass ring *I*. A fixed disk *D*2 and disk *D*1 form the capacitance. The system pressure is balanced by pressure applied at P_o. The capacitor $D1 - D2$ forms part of a bridge *RB* in resonance with a 1 MHz oscillator *PS*. Any difference in the frequency of *PS* and *RB* is fed to the mixed *FM* and to an indicator *N*, which is used to determine the equivalence of the two pressures. The balancing pressure is measured by McLeod gage *M* or other absolute type, depending on the range. The circuit is similar to that shown in figure 33 except for the null feature. The pressure, in the desired range, 0.1 to 760 torr, could be nulled to an accuracy of $\pm 5 \times 10^{-3}$ torr. Full scale on the frequency meter *N* in pressure units was 20×10^{-3} torr.

The null-reading gage developed by Alpert, Matland, and McCoubrey [5101] is now of more historical than technical interest. A corrugated diaphragm and disk formed a capacitance in a bridge powered by a 10-kHz generator. The output of the bridge was fed to a voltmeter which indicates the null position of the diaphragm, as the system pressure on one side of the diaphragm was balanced by a pressure applied on its other side. An oil U-tube manometer measured the applied pressure. The accuracy of the nulling system was $\pm 10^{-2}$ torr, equivalent to $\pm$ 0.1 V. A diaphragm motion of 5×10^{-6} mm was detectable. The gage was designed primarily to make rather coarse vacuum measurements, as simply as possible.

4.5.3.5.3. Spring Force Restores Null Flauraud, Mears, et al. [5490], investigated microbarometric oscillations using an automated version of the Paulin barometer (fig. 24). In this recorder, shown in figure 38, capacitance disk *C*1 is attached to the corrugated, evacuated diaphragm capsules *D*. Disks *C*2, attached to the case through insulators, form two capacitances with *C*1. When the diaphragm capsules deflect from the null position, capacitance bridge *B* becomes unbalanced, the output, amplified by *A*, activates servomotor *SM*, turning micrometer screw *MS* to adjust the force on spring *S*, to return disk *C*1 to the null position. The angular motion of *MS* is recorded on recorder *R*. A setting mechanism is provided to adjust the recorder

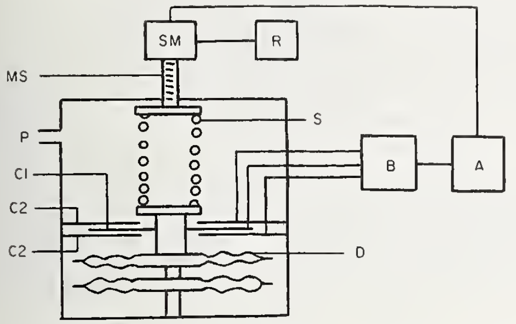

FIGURE 38. *Barograph, spring force restores null.*
A, amplifier; *B*, bridge; *C1* and *C2*, capacitance disks; *D*, diaphragm capsules; *MS*, micrometer screp; *P*, pressure; *R*, recorder; *S*, spring; *SM*, servomotor.

to any desired 35 mbar (26 torr) range of pressure. The pressure range was 990 to 1045 mbar (742 to 784 torr). The sensitivity was of the order of 0.035 mbar (0.026 torr) per scale division (about 0.6 cm) on the recorder chart. The speed of response was 0.5 mbar (0.37 torr) per minute. The instrument was designed for field use; therefore, the pressure-sensitive unit was thermostated and the electronics, battery-powered.

4.5.4. Performance Factors

Rony [64265] lists about a dozen performance factors for capacitance gages. Of these a number will be considered here as being fundamental. Only the best obtained performance will be presented, which will limit the number designs discussed. Dynamic response will be considered in section 8.1. See also section 4.14.

4.5.4.1. Sensitivity, Linearity, and Stability

It is desirable in a precision instrument that the sensitivity or resolution at the worst be 1 percent of the measured pressure. Instruments have been developed which have a sensitivity of 10^{-6} torr at pressures in the range from 10^{-5} to 10^{-4} torr; bettering this sensitivity may be possible, but will not be easy. Instruments in the 10^{-6} torr range of sensitivity are reported in [5212, 5305, 5562, 6081, 61235, 6601]; this sensitivity was achieved with either a deflecting diaphragm or a diaphragm returned to the null position.

As regards pressure range which can be covered, the null type of instrument has a substantial advantage over the deflecting type. When the diaphragm is maintained near its initial position, the range is limited only by the range of the nulling voltage, and if the system pressure is proportional to the square of this voltage, a further advantage ensues. Drawin [6081] indicates a possible range from 10^{-5} to 1 torr.

In most designs where the diaphragm deflects freely, the range is limited to about two or three decades of pressure, owing to the inherently small value of the capacitance and the limited range of the measurable capacitance. Although the maximum deflection of the diaphragm is fixed with narrow limits, the pressure range can be selected by using a diaphragm of appropriate stiffness. In the designs where the output of the bridge is nulled by a voltage [60112, 6601], the pressure range can extend over four decades. The sensitivity of the type using a null detector voltmeter is controlled by modifying the input signal in eight steps.

Linearity within 1 percent has been achieved without difficulty in deflection-type instruments, as is predicted by eq (8). In nulling instruments, the differential pressure may either vary linearly within close limits with the square, eq (3), or with the first power of the nulling voltage, eqs (5), (5.2), depending upon the manner of its application.

As regards stability, Rony [64265] has obtained data on both short-term (30 seconds) and long-term effects. For a commercial instrument his values are respectively 10^{-5} torr and 2×10^{-5} torr per hour; for his own best design, 10^{-6} torr and 3×10^{-5} torr per hour. These values are essentially equalled by the designs of Becker and Stehl [5212] and by Opstelten and Warmoltz [5562, 5616]. The instrument of the latter was the nulling type; that of the others, the deflecting type. Incidentally, Rony states that the superior short- and long-term stability of the Becker and Stehl instrument is due to the superb design of the diaphragm capacitance element.

4.5.4.2. Temperature Effect

The effects of temperature changes on a capacitance gage are threefold: (a) change in capacitance of the pressure sensor due to dimensional changes; (b) change in stiffness of the diaphragm, and. (c) change in the dielectric constant of the gas.

First, the change in dielectric constant with temperature was considered theoretically by Drawin [6081]. The effect is greatest for gases of molecules with the greatest electrical dipole moment, notably water vapor and hydrocarbons. He concluded that for modest temperature changes, and for low pressures, the effect was negligible.

By choice of a material for the diaphragm which has a very low temperature coefficient of elasticity, the change in stiffness with temperature can be held to a low value. There remains also the variation in stiffness as the radial tension is changed by differential expansion of various parts of the assembly, or the slight buckling of a corrugated diaphragm from the same cause.

Obviously, as the parts of a pressure sensor expand as the temperature rises, the diameter of the electrodes increases and the gap, electrode to diaphragm, changes, thus changing the capacitance.

Temperature effects have been considered theoretically by Pressey [5307] and notably by Drawin [6081]. From the practical standpoint, a gage can be calibrated at the same temperature at which it is to be used. In this case, only the degree to which the temperature can be held constant need be considered. Calibration can be made also at various temperatures so that correction can be applied for intermediate temperatures of the instrument. Fluctuating instrument temperatures will give rise to significant uncertainty.

Following Drawin [6081], with voltage U resulting from pressure change ΔP on a null-type instrument

$$\Delta P = B_o U^2 \quad (3)$$

where
$$B = B_o (1 + \alpha \Delta T) \quad (14)$$

$$\alpha = \frac{1}{B_o} \frac{\Delta B}{\Delta T},$$

and ΔT is the change in temperature.

He obtains two values for the temperature coefficient α, one where the diaphragm remains flat, and the other where the diaphragm is slightly curved. He computes α for the flat diaphragm case to be between 10^{-4} and 10^{-2} per degree Celsius.

The value of α for his instrument was measured at 50 °C intervals from 50 to 200 °C and was -1.15×10^{-3} at 50 °C, and -1.40×10^{-3} per degree Celsius at 200 °C. The theoretical calculations were within 10 percent.

For a deflecting instrument, Pressey [5307] obtained a value of α of -100 parts per million per degree Celsius for a pressure sensor especially designed to reduce the temperature error. His theory gave $\alpha =$ 144 ppm. Thus, Drawin obtains a temperature effect of about 0.11 percent per degree Celsius and Pressey reduces it to about 0.01 percent per degree Celsius, for equilibrium conditions.

Dean and Flynn [6606], in connection with a cryogenic application, presented data on the temperature effect in the range 77 to 530 °K for their instrument for pressures up to 500 psig, well above pressures of interest here.

4.5.4.3. Gas Composition

Drawin [6081] considers the effect on the instrument indication of the variation of the dielectric constant of various gases. For a very wide variation in the dielectric constant, he computes that the effect on the instrument indication is 0.0017 percent per torr. For pressures in the micromanometer range, this effect is insignificant. As stated in the preceding Section, the temperature variation of the dielectric constant also has no significant effect on the instrument indication.

Experimental data on the sensitivity of a nulling instrument for a group of gases, including a number of hydrocarbons, given by Drawin [6081], indicate no significant effect of gas composition. Utterback and Griffith [6601] present data for a deflecting instrument which likewise shows no effect; in fact, their data check substantially the change in ionization gage sensitivity with gas composition.

4.5.4.4. Gas Adsorption

Drawin [6081] discusses two effects of gas adsorption. First, a contact potential may exist between a clean metal surface and an adsorbed gas. He estimates that this contact potential will not exceed 0.25 V, and concludes that in measuring a nulling voltage the error will be about 1 percent at 10^{-5} torr. At higher pressures the error is negligible.

Second, an adsorbed gas may slightly alter the gap distance between an electrode and diaphragm. The error introduced in a measurement of pressure was computed to be insignificant, although this differs from the conclusion reached by Milazzo [5677].

If the micromanometer is used to measure absolute pressure, the chamber on one side of the diaphragm must be evacuated to a pressure at least 1/100 of the lowest pressure to be measured. Below about 10^{-6} torr, continuous evacuation is recommended by most experimenters. Bakeout may be desirable in some applications, in which case the pressure sensor design, and particularly the possible annealing effect of the high temperature on the diaphragm, require attention.

4.5.4.5. Ionization of Gases

Opstelten and Warmoltz [58117] state that at absolute pressures above 1 torr, an electrical discharge occurs between the electrode and diaphragm of micromanometers, if an electrostatic voltage is used to restore the diaphragm to the null position. Both Opstelten and Warmoltz, and Drawin [58110], propose for measuring pressures above about 0.1 torr the use of designs in which the capacity bridge is unbalanced by the pressure change and the resulting current is measured.

4.5.4.6. Variation of Null With Pressure

Invariably, when the null position of the diaphragm or bellows is restored by an electrostatic force, the null position is indicated by a constancy of the capacitance of the pressure sensor. Always, some portion of the outer area of the diaphragm remains under stress and, to this extent, the null position for zero differential pressure is not restored. See also Drawin, section 4.5.1. The effect increases with increase in the differential pressure. No quantitative data appear to be available, but the effect in good diaphragm-electrode designs is believed to be small. If a bellows is used, the effect may become significant. In both cases, the effect is wiped out by calibration of the instrument. This failure becomes much more significant if the center of the diaphragm is restored to null by a central force. Here most of the advantage of nulling, in minimizing elastic defects such as drift and hysteresis, is lost.

While of limited application, perfect nulling is obtained by using a balancing pressure; unfortunately, measuring the balancing pressure still remains a problem.

4.5.4.7. Stray Capacitances

Stray capacitances within the bridge circuit of the instrument, if constant in value, lower the sensitivity of response and, if variable with pressure, introduce an error. Since the capacitance of the sensor is small, in the range 20 to 400 pF (10^{-12} F), designers have made efforts to reduce the extraneous capacitance to a minimum. Good insulation between the electrodes and pressure element (diaphragm or bellows), and shielded, short lines for the bridge circuit, are provided. A high-frequency power supply is used. Suitable guard rings or shields would improve many designs.

4.5.4.8. Overpressure

Since the gap between a single electrode and a diaphragm in deflecting instruments is largest (within the maximum permissible deflection of the diaphragm) at zero differential pressure, system overpressure brings the two into contact, thus supporting the diaphragm. Permissible system overpressures of at least one atmosphere have been obtained. In nulling instruments, overpressure deflects the diaphragm away from the electrode if the nulling electrostatic voltage is not applied.

If two electrodes are used, protection against overpressure, either side, is obtained. The use of nesting diaphragms, one being the electrode (Suetin and Volobuev [6485], fig. 33), should be mentioned as another method of protection against overpressure, but constructional difficulties are a bar to its general use.

4.6. Inductance Transducers

Three variations of inductance transducers exist: the differential transformer, the variable reluctance (two coils magnetically linked by a metal armature), and the mutual inductance (two concentric coils on a ceramic form). All are highly sensitive to small displacements.

4.6.1. Differential Transformer Transducer

The instrument developed by Sancier and Richeson [5617] is shown in figure 39. As bellows $B1$ moves, it deflects an iron core C in the field of two transformer coils $T1$ and $T2$. Power is supplied to coil $T1$ by PS; the change in induced voltage in $T2$ is measured by a sensitive voltmeter VM. An additional bellows $B2$ is rigidly connected to $B1$ and is vented to the reference pressure P_0. This bellows compensates for thermal expansion of $B1$, but not for the change in the elastic modulus with temperature. The stiffness (pressure change per unit deflection) is the sum of the stiffnesses of the two bellows. This application was for measuring the pressure of corrosive fluids, so monel bellows were used. The frequency of the 3-A power supply was variable in the range 1000 to 10,000 Hz. On the voltmeter 0.005 mV was detectable; on this basis the sensitivity was 0.05 torr at 1000 Hz, 0.02 torr at 2000 Hz, and 0.005 torr at 10,000 Hz.

The gage designed by Tsujimura, Takahashi, and Fujisawa [6821] for measuring the differential pressure of fluorine is essentially the same as that of Sancier and Richeson shown in figure 39. Their gage had a linear range of ± 150 torr and sensitivity of 1.7 mV per torr.

Hooley [5797] hung the iron core of the linear differential transformer from the free end of a glass spoon-shaped Bourdon tube. The output of the transformer was amplified, converted to direct current and recorded on a millivolt recorder. The accuracy was estimated to be 0.1 to 0.2 torr. The pressure range of the constructed instrument, —100 to 650 torr, is outside the range of interest here, but could be made so by using a more sensitive Bourdon tube. However, attention would have to be given to reducing the zero drift caused by the weight of the iron core, as pointed out by Hooley.

Sheft [6602] measured the deflection of a flat diaphragm with a linear differential transformer. The electrical circuit was as shown in figure 39. A vacuum tube voltmeter was used to measure the output. The linear range of the transducer was ± 1.52 mm and the output 1.02 mV per 0.1 torr. It was used to secure distant indication of the pressure of corrosive gases. While the pressure range of Sheft's instrument was about 1 atm, the same design with a more sensitive diaphragm would bring the instrument sensitivity into the micromanometer range.

4.6.2. Mutual Inductance Transducer

Dibeler and Cordero [5102] depended on the variation in mutual induction with the proximity of a metal diaphragm. Eddy currents generated in the diaphragm increases the coupling between the coils as the diaphragm recedes from the coils. The design is shown schematically in figure 40. The corrugated diaphragm D is part of a capsule which is connected to the pressure P. The instrument case is kept evacuated at a pressure P_0, preferably much below P. The two induction coils $C1$ and $C2$, wound on a ceramic form, are mounted above the center of the diaphragm. One coil, $C2$, is activated by the radiofrequency power supply PS; the voltage induced in coil $C1$ is amplified by A, rectified by R, and the resultant current is indicated on dc microammeter I. For a pressure range from 100×10^{-3} to 1 torr, the sensitivity was 10^{-4} torr. The gain was adjustable to give an output of 50μA for a pressure of 25×10^{-4} torr. It is of interest to note

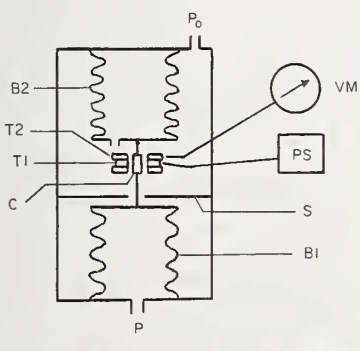

FIGURE 39. *Bellows–differential transformer micromanometer.*
B1 and *B2*, metal bellows; *C*, iron core; *P* and P_0, pressure and reference pressure; *PS*, ac power supply; *S*, a stop; *T1* and *T2*, primary and secondary transformer coils; *VM*, sensitive voltmeter.

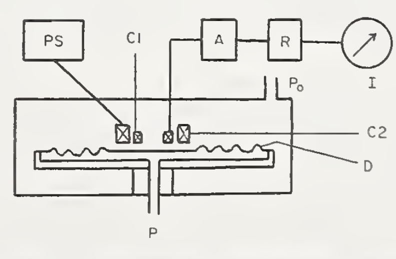

FIGURE 40. *Mutual inductance vacuum gage.*
A, amplifier; *C1* and *C2*, inductance coils; *D*, diaphragm; *I*, microammeter; *P* and P_0, pressure and reference pressure; *PS*, power supply; *R*, rectifier.

that the diaphragm was made of brass 0.001 in thick and had 26 corrugations. It had a central deflection of about 2×10^{-5} in (5×10^{-4} mm) per 10^{-3} torr. The micromanometer application was for measuring the pressure of gas samples being admitted to mass spectrometers.

4.6.3. Variable Reluctance Transducer

Halliday [4801] designed a micromanometer with electrical transmission in order to eliminate the lag introduced by pressure transmission through tubing. In figure 41, two bellows, *B*1 and *B*2, have interior pressures of *P*1 and *P*2 respectively. These are rigidly connected to lever arm *A* with a fulcrum of crossed strips at *F*. Soft iron strips, *S*1 and *S*2, one attached to one end of the arm *A*, control the inductance of two coils, *C*1 and *C*2. The output from coil C1 and from the similar coil *C*2 goes to bridge circuit *B*. The unbalance, caused by a bellows deflection, is fed to servomotor *M*, which, through gear box *G*, moves the second soft iron strip *S*2 until the bridge is balanced. The gear rotation is indicated by a counter *CO* and is a measure of the pressure *P*2 — *P*1. A power supply *PS* actuates the

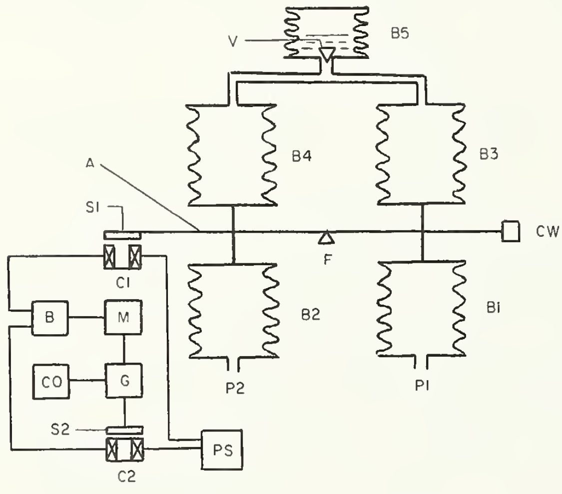

FIGURE 41. *Variable reluctance micromanometer.*
A, lever arm; *B*, inductance bridge; *B1-B5*, metal bellows; *C1*, *C2*, inductance coils; *CO*, counter; *CW*, counterweight; *F*, fulcrum; *G*, gear box; *M*, servomotor; *P1*, *P2*, pressures; *PS*, power supply; *S1*, *S2*, soft iron strips; *V*, check valve.

inductance coils. The lever arm has a counterweight *CW*. For damping, two oil-filled bellows *B*3 and *B*4 are connected as shown. Oil flows from one bellows to the other as *B*1 or *B*2 deflects. An additional bellows *B*5 is connected to *B*3 and *B*4 through a check valve in order to compensate for volume changes in *B*3 and *B*4. The range was 3 in of water (5.6 torr) with a sensitivity as good as that of a 26-in Chattock gage (sect. 2.9) (0.001 torr).

Cox, Atanasoff, et al. [4902] describe a microbarograph used to detect infrasonic waves in the atmosphere caused by severe explosions. Schematically in figure 42, the flat diaphragm *D* encloses a chamber in which, by means of a selected restriction *L*1, low-frequency pressure waves are not transmitted into the chamber and a reference pressure P_o is obtained. Restriction *L*2 connects the main chamber with the atmosphere to suppress high-frequency oscillations. Pressure oscillations having a frequency above 10 Hz were eliminated from the chamber; at 4 Hz their amplitude was reduced 50 percent. A variable reluctance transducer *VR*1 consists of a soft iron pole piece fastened to the diaphragm, and of two induction coils. A similar second transducer *VR*2 is fixed in position and is the reference. The primary coil of both *VR*1 and *VR*2 is fed by an ac (10 kHz) power supply *PS*. The output of the secondary coils, one with constant induced current and the other with induced current controlled by the diaphragm deflection, is fed to a bridge circuit *B* and amplified by several amplifiers *A*. The amplified output is rectified by *C* and recorded on milliampere recorder *R*. The best sensitivity obtained was a recorder deflection of 0.1 mm per microbar (7×10^{-4} torr). Means for compressing the deflection at high pressures were incorporated so that any expected pressure range could be recorded. Very approximately, the recorder deflection was proportional to the logarithm of the pressure.

Yasumori, Ohno, and Miyazaki [6712] attached an inductance transducer to a Bourdon tube, in contrast to the many variations of mechanical and optical transducers devised by experimenters in the past for this type of sensor. In figure 43, *T* is the spoon-shaped Bourdon tube to which is attached an aluminum disk

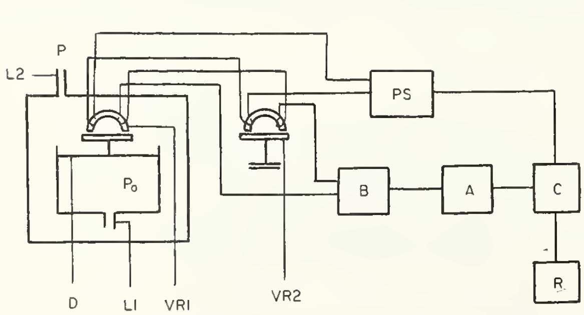

FIGURE 42. *Variable reluctance microbarograph.*
A, amplifier; *B*, inductance bridge; *C*, rectifier; *D*, diaphragm; *L1*, *L2*, restrictions; *PS*, power supply; *P*, atmospheric pressure; P_o, reference pressure; *R*, recorder; *VR1*, *VR2*, variable reluctances.

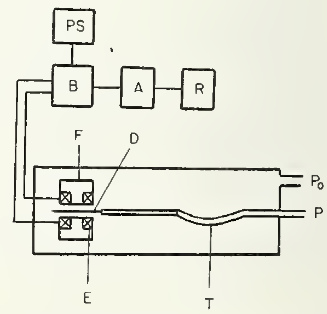

FIGURE 43. *Variable reluctance Bourdon gage.*
A, amplifier; *B*, ac bridge; *D*, aluminum disk; *E*, detecting coils; *F*, ferrite cores; *P*, P_o, pressure and reference pressure; *PS*, power supply; *R*, recorder; *T*, Bourdon tube.

D. Detecting coils E are imbedded in ferrite cores F. The output of E is fed to an ac bridge B, amplified by A, and recorded by voltage recorder R. The pressure P in slow gaseous reactions was measured; P_0 was the reference pressure. The pressure range was 20 torr, with 7×10^{-2} torr detectable. The response time was 0.6 s at atmospheric pressure P_0 and 4 s at $P_0 = 10^{-3}$ torr, the difference probably due entirely to tubing lag.

4.7. Strain Gage Transducers

Until quite recently only resistance wire strain gages have been used as strain transducers. These have been either bonded to the elastic element or unbonded. Recently, strips cut from single-crystal semiconductors, either of silicon or germanium, have come into use as strain-measuring elements. Their electrical resistance also varies with imposed strain. Sion [65345] states that the semiconductor strain gage, also called piezoresistive, is 70 to 80 times more sensitive than the resistance wire types. Incidentally, he includes a theory of typical measurement circuits in his review on the semiconductor type. A transistor is installed in the circuit for temperature compensation; otherwise the temperature effect would be 0.4 percent per degree Celsius for a silicon transducer. See also Tufte and Long [63344].

The principal advantage of the strain gage transducer is its inherently greater speed of response, compared to that of the inductive or capacitance types where the electrical circuitry is a limiting factor. The strain gage instrumentation described in the literature for measuring dynamic pressures usually is not designed to measure pressures in the micromanometer range and, therefore, is not discussed here.

4.7.1. Unbonded Strain Gage Micromanometers

Matheson and Eden [4803], in an instrument now largely of historical interest, used unbonded resistance wires to measure the deflection of a diaphragm capsule. As shown in figure 44, nesting diaphragm capsule D is connected to a commercial wire strain gage S so that as the capsule deflects, the stress in two wires increases and in two, decreases. These four resistances form Wheatstone bridge B, the output of which is indicated by galvanometer G. The diaphragms were of beryllium copper 0.0022 in (0.055 mm) thick. Excess pressure of 1 atm external to the capsule, and 0.2 atm internal, was safely withstood. Differential pressures were measurable to 0.001 torr in the range $\pm$ 0.5 torr. The diaphragm capsule was stiffer by about 12 percent when the lower pressure was inside the capsule.

Keenan and McIntosh [4830] also used an unbonded wire strain gage. Eighteen strands of "Advance" wire were connected to a brass metal bellows and a support. The change in resistance was measured by balancing a Wheatstone bridge. In the range from 0 to 12 torr the sensitivity was 0.003 torr, but the poor elastic properties of the resistance wires used increased the measurement uncertainty to 0.04 torr.

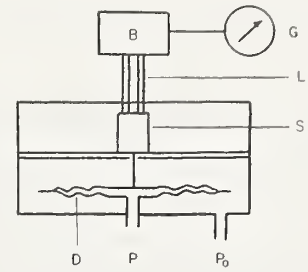

FIGURE 44. *Unbonded strain gage micromanometer.*
B, bridge; *D*, diaphragm capsule; *G*, galvanometer; *L*, leads; *P*, P_0, pressures; *S*, strain gage unit.

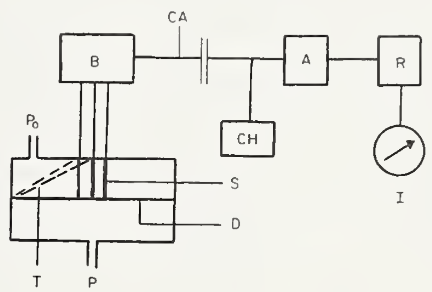

FIGURE 45. *Semiconductor strain gage micromanometer.*
A, amplifier; *B*, bridge; *CA*, long cable; *CH*, chopper; *D*, diaphragm; *I*, milliammeter; *P*, P_0, pressure and reference pressure; *R*, rectifier; *S*, *T*, single silicon crystal strips.

Hayashi and Tsukakoshi [64119, 64276] designed a gage using an unbonded semiconductor strain gage. In the diagram, figure 45, a thin invar diaphragm D compresses three silicon strips S, cut from a single crystal, as pressure P rises. Two auxiliary silicon strips T are added to obtain temperature compensation. The strips S and T form part of Wheatstone bridge B, the output of which was converted to alternating current by chopper CH and fed to amplifier A. The amplifier output is rectified by R and indicated by milliammeter I. Distant indication of the pressure was desired; it was found that a cable CA from 2 to 300 m long carrying the dc output from the bridge had no effect on the indication. The pressure range was 1 to 760 torr; the sensitivity, 0.1 torr per 0.01 mA indication on I. The pressure range could be reduced and the sensitivity improved by using a less stiff diaphragm of a better material than invar, such as Ni-Span-C or beryllium copper.

A recent development, described in an insert in a paper by Moore [6801], is the application of a piezoelectric transistor to pressure measurement. A silicon npn junction planar crystal changes its output voltage upon application of small forces. By mechanically coupling the crystal to a diaphragm, pressures can be measured. Data presented for one design show that a linear response was obtained for a pressure change from -4 to $+4$ in of water (-7.5 to $+7.5$ torr), for which the output change was 2 V; this is a sensitivity of 0.13 V per torr.

4.7.2. Bonded Strain Gage Micromanometers

The strain gages may consist of either a loop of wire or a foil patterned to be equivalent to a wire loop. The literature on the wire loop is extensive and available; and the strain elements are commercially available. The foil strain gages are considered in some detail by Mukhin [65353] and Sinev and Etingof [6632]. The latter discuss their application as pressure transducers.

A transitorized circuit for strain gage pressure transducers is described in detail by Ayling [6812]. He states that the resolution obtained was as small as 0.02 percent of the pressure range of the transducer.

Thureau and Lemière [62123] were interested in measuring feeble oscillatory pressures developed in a micro Pitot tube. A rectangular mylar diaphragm, 9 × 34 mm, had four strips of bismuth evaporated on its surface. These formed four resistances of a Wheatstone bridge. Deflection of the diaphragm altered the electrical resistance and the output of the bridge, which was measured by an oscilloscope. The natural frequency of the diaphragm was 16,500 Hz. Incidentally, Koike and Kurokawa [6624] have investigated the elastoresistance performance of evaporated bismuth films. The deflections of the diaphragm were linear with pressure up to ± 2 mbar (1.5 torr), at which the bridge output was about 200 μV.

Although not useful as designed for measuring low pressures, the design developed by Carter, Ghosh, et al. [4927] could be adapted to do so. They bonded a resistance wire strain gage to a flat metal diaphragm, thus differing from the Thureau design. The change in curvature of the diaphragm with pressure changed the strain and, therefore, the resistance of the strain gage.

Similarly, Wenk [5173] bonded two resistance wire strain gages to an aluminum alloy diaphragm ¾ in in diameter and 0.01 in thick. One, in tension as the diaphragm deflected, was placed in the center of the diaphragm; the other, in compression, was placed at the periphery. At 1 psi (50 torr) the best resolution was 0.025 psi (1.25 torr). Obviously, if desired, indication in the micromanometer range is possible if the diaphragm diameter is increased and its thickness decreased.

Three recent designs merit mention. Styburski [6820], who bonded a strain gage on a flat diaphragm, had the more sensitive instrument; differential pressures as low as 1 mm of water (0.07 torr) were measured. Parameswaraiah and Sankaranarayanan [6823] described a similar design. The pressure range was ± 5 psi (260 torr); the natural frequency was 3000 Hz.

Kimura, Sakurai, and Kondo [6822] combined a diaphragm and cantilever spring with the strain gage on the spring. They present both theory and performance data on their instrument. Its natural frequency was 130 Hz.

4.8. Electrical Conductance Manometer

Pappenheimer [5456] developed an instrument for physiological research, based on a design proposed over 40 years earlier and then neglected. It is based on the variation in conductance of an electrolyte, a sodium chloride solution, controlled by pressure change. In figure 46, *D* is a quartz diaphragm clamped between quartz blocks *Q*. Two chambers in *Q* on each side of *D* are connected by a conduit *G*, with the gap between *D* and *Q* about 20 to 25 μm. Any deflection of the diaphragm causes the gap *G* to increase on one side of *D* and decrease on the other side, changing the cross-sectional area of the electrolyte which fills the instrument and, thus, the electrical current in the two arms of *G*. Silver electrodes *A*1 and *A*2 are connected to form one arm of an ac bridge *B*, and *A*3 and *A*4 to form another. An oscilloscope *I* measures the bridge output. *A*1 and *A*2 are tubes so that pressures P_0 and *P* can be transmitted to the diaphragm. *A*3 and *A*4 also are tubes connected to electrolyte reservoirs. The greatest sensitivity obtained was 0.41 mV per torr. When the system was critically damped, 95 percent of the final output was obtained in 12 ms when the instrument had the above given sensitivity.

Massey and Kavrak [6604] describe an instrument of the electrical conductance type, which is discussed in section 8.8.

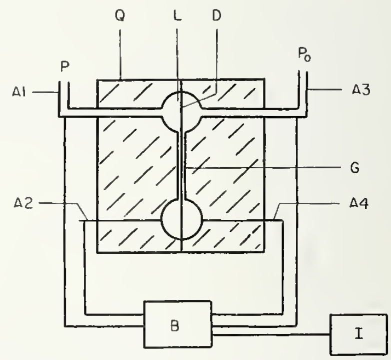

FIGURE 46. *Electrical conductance manometer.*
A1, A2, A3, A4, silver electrodes; *B,* ac bridge; *D,* diaphragm; *G,* conduit; *L.* electrolyte; *I,* oscilloscope; *P, P₀,* pressure and reference pressure; *Q,* quartz blocks.

4.9. Microwave Null Detector

Kramer and Platzman [5841] desired to isolate a system from the liquid type manometer used to measure the system pressure. The solution adopted is unique but probably of limited interest. Essentially, a steel diaphragm 0.004 in thick isolates the primary system from the measuring system. Microwaves (8650 MHz) are produced and transmitted to the resonant cavity bounded by the diaphragm. The reference resonant frequency was measured with no differential pressure across the diaphragm. When a differential pressure deflected the diaphragm, its null position was restored as indicated by the reference frequency by controlling the pressure in the measuring system.

This pressure was measured by the U-tube manometer. The pressure range of the instrument was about 1 atm with a sensitivity of 2.4 MHz per torr. A change in the null pressure of 0.1 torr was easily detectable. The authors state that with added electronic apparatus the microwave sensitivity could be improved.

4.10. Vacuum Tube Transducer

Essentially, the design consists of a diaphragm which is rigidly connected to the anode or grid of a vacuum tube. The output of the latter is dependent on the deflection of the diaphragm and hence, on the pressure. The vacuum tube and one side of the diaphragm must normally withstand atmospheric pressure. This limitation on the sensitivity of the diaphragm makes this transducer normally too insensitive for use as a micromanometer.

The design and performance of the various types of diode and triode vacuum tube transducers are given by Olson [4729]. Day [4928] described a diode type for use as an aviation altimeter, where the position of an anode pair (one on either side of the cathode) mechanically connected by an insulator was controlled by a diaphragm. For recording blood pressure, Pettersson and Clemedson [5059] had the diaphragm control the position of the anode in a triode tube, the whole small in size (8 mm in diameter and 20 mm long).

Sinclair [65351] designed an instrument for dust-devil measurement, in which a diaphragm capsule was connected to the anode of a vacuum tube through a flexible joint. The inside of the capsule was connected to the atmosphere and the enclosing chamber also, but through a restriction. Thus, the rate-of-change of pressure was measured as in a microbarograph. See section 8.2. The output of the vacuum tube was fed to a bridge, the unbalanced current of which was measured. The sensitivity was 0.1 mbar (0.07 torr).

4.11. Microphone Micromanometers

The three instruments to be described are, for want of a better term, called microphone micromanometers, since the heart of the instruments is a diaphragm maintained in vibration.

Dimeff, Lane, and Coon [6215] developed their instrument for making dynamic measurements in wind tunnels. The need for long connecting tubing was eliminated; also the transducer element could be small; for example, one 0.28 in in diameter was constructed. A schematic diagram is shown in figure 47, where *D* is a flat diaphragm of high natural frequency (about 1000 Hz); *DE*, the driving electrode; *PE*, the pick-up electrode; *DO*, a variable-frequency oscillator tuned to the natural frequency of the diaphragm. If the pressure *P* changes, the amplitude of vibration of the diaphragm, driven by *DO*, also changes due to viscous drag. The capacitance formed by *PE* and *D* changes, is picked up by the displacement indicator *DI*. The energy input by *DO* is adjusted to return the capacitance *D* — *PE* to its original value. This change in energy is measured

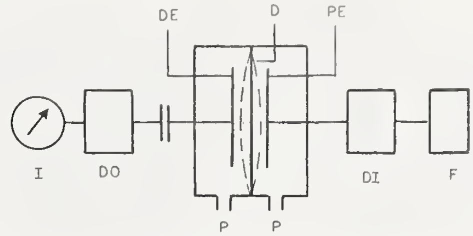

FIGURE 47. *Vibrating diaphragm manometer.*
D, diaphragm; *DE*, driving electrode; *DI*, displacement indicator; *DO*, oscillator; *F*, frequency indicator; *I*, indicator of energy input; *P*, pressure; *PE*, pickup electrode.

by *I* and is a function of the pressure *P*. A frequency indicator *F* is useful for checking performance. The instrument actually constructed was automatic in operation. Feedback, controlled by a servomotor, maintained constant the amplitude of diaphragm vibration. The angular deflection of the servomotor was proportional to the cube root of the absolute pressure. The range was approximately 10^{-4} to 10^3 torr. Applicable theory is given, together with data on the effect of changing such parameters as electrode-diaphragm clearance, natural frequency, electrode curvature to match vibrating diaphragm, and gas composition.

Schwarz [5663] did some preliminary work on measuring pressure with a resonant diaphragm. He kept the diaphragm vibrating at resonance frequency, and found the ac current driving force to vary with pressure in about the same pressure range obtained by Dimeff.

Noiseux and Maidanik [6711] had a driver *DO* to keep the diaphragm vibrating at a constant amplitude, as indicated in figure 47. However, their transducer was a microphone which was used to pick up the energy of the sound in the air chamber between the diaphragm and microphone. The microphone output was amplified by an electronic circuit. This output in decibels was directly proportional to the logarithm of the pressure over the pressure range from 10^{-4} to 760 torr, except for a transition region 0.03 to 0.3 torr, unfortunately in the micromanometer range. Above and below the transition region the slopes of the curves were the same. A theory was presented.

Antal and Koenig [5773] had a design which essentially anticipated Noiseux and Maidanik. A loudspeaker was at one end of a chamber, closed except for a pressure connection, and a receiver microphone at the other end. The measured output of the microphone was a measure of the chamber pressure in the range from 1 atm to 0.05 torr.

4.12. Vibrating Wire Gage

The vibrating wire gage* has distant indication as its principal utility. Prast, Calhoun, et al. [5585] describe a vibrotron for use in measuring atmospheric pressure on guided missiles. In figure 48, *W* is a vibrating wire connected to diaphragm *D*. Deflections of the

* Known as the Vibrotron.

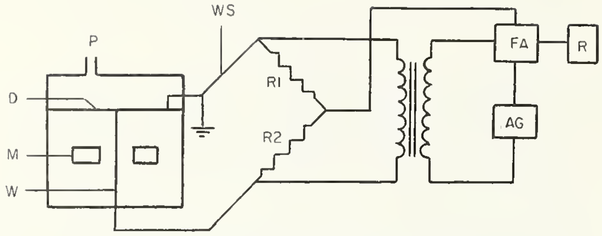

FIGURE 48. *Vibrotron micromanometer.*
AG, autogain amplifier; *D*, diaphragm; *FA*, feedback amplifier; *M*, electromagnet; *P*, pressure inlet; *R*, recorder; *R1*, *R2*, resistances; *W*, vibrating wire; *WS*, static wire.

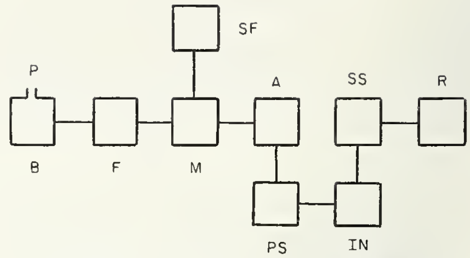

FIGURE 49. *Vibrotron microbarograph.*
A, amplifier; *B*, Wheatstone bridge; *F*, frequency multiplier; *IN*, integrator; *M*, mixer; *P*, pressure inlet; *PS*, pulse shaper; *R*, recorder; *SF*, 100 kHz reference frequency; *SS*, scale selector.

diaphragm due to changes in pressure *P* cause the tension on the wire to change, which changes its natural frequency. An alnico magnet *M* causes a voltage to develop in the vibrating wire. This voltage is fed to a Wheatstone bridge composed of *W*, resistances *R*1 and *R*2, and to a duplicate, but not vibrating, wire, *WS*, which is for temperature compensation. The bridge output is fed to feedback amplifier FA and to an audio gain amplifier *AG*. The output is telemetered in this application, and in other applications, transmitted long distances over telephone lines to a recorder. Part of the output is fed back to wire *W* to keep it vibrating. Wire *W* is under stress and may have a frequency of vibration within the limits of 400 and 70,000 Hz. The square of the vibration frequency is proportional to the differential pressure (Morris [6706]). The design is such that the wire frequency decreases with increase in differential pressure. The frequency which is finally recorded is precisely the natural frequency, or a multiple thereof, of vibration of the wire. The dynamic response of this pressure-sensitive unit is very fast; Poindexter [5281], for one design, quotes perfect response at 5000 Hz. However, other elements of the system slow down the overall response. The telemetering system described by Prast et al. at best had a pressure sampling rate of 14 per second. Prast gives no sensitivity data; Ohman [5584] for a microbarograph design gives a sensitivity of 3×10^{-6} atm (2.3×10^{-3} torr). Performance data and possible applications are discussed by both Ohman and Poindexter.

Recently, Morris [6706] has described the circuit of a microbarograph measuring absolute pressure in which the vibrotron unit is the pressure-sensing element. A block diagram is shown in figure 49. Here *B* is a bridge containing the vibrating wire unit, shown in more detail in figure 48, but not described by Morris. The output frequency from *B* is increased ten times by multiplier *F*; *M* is a mixer of the output from *F*, and from a stable 100-kHz reference frequency *SF*. Successively, the output from *M* is amplified by *A*, passes through pulse shaper *PS*, integrator *IN*, scale selector *SS*, and finally to electrical recorder *R*. Means for eliminating temperature errors are described. The response time of the instrument is adjustable in the range from 0.3 to 10 s. The scale selector *SS* permits variation in full-scale output of the recorder for differential pressures from 0.5 to 40 μbar (0.4 to 30 torr). The best sensitivity is 0.01 μbar (0.0075 torr). For the pressure range from 0 to 1050 μbar, the frequency of the vibrating wire varied from 11,000 to 9900 Hz.

The technology and application of the vibrotron have been reviewed by Lefcourt [6817]. The electronics with special application to underwater pressure measurement are discussed by Rolfe [6818].

5. Piston Gages

Piston gages have long been used to measure high pressures but only recently to measure pressures in the micromanometer range.

5.1. Tilted, Air-Lubricated Piston Gages

The tilting air-lubricated piston gage for measuring differential pressures up to about 12 torr was developed by Hutton [5910]. In figure 50, *C* is the cylinder of 1¼-in precision-bore glass tubing, and *PI* is the piston. To avoid friction between the piston and cylinder, the cylinder is mounted in bearings and provision is made to rotate it by means of a fan motor. To prevent oscillation and rotation of the piston, it is eccentrically loaded with small shot, indicated by *W*1. To obtain various pressure ranges, weights *W*2 are added. The reference pressure P_0 could be controlled by placing the entire instrument in a chamber in which the pressure is controlled. The variable pressure *P* was applied to the bottom of the cylinder as indicated. To compensate for gas leakage past the piston, a small flow of air is maintained through nipple *F*. For any one loading of the piston and pressure *P* within the measurable range, the piston assembly was tilted until the piston weight balanced the differential pressure. The height *h* was measured principally by gage blocks *G*, and within

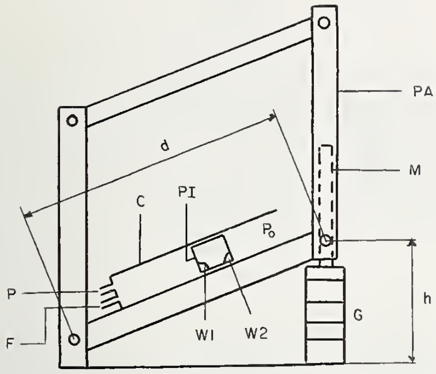

FIGURE 50. *Tilted, air-lubricated piston gage.*
C, cylinder; *F*, nipple; *G*, gage blocks; *M*, micrometer; *P*, P_0, pressure and reference pressure; *PI*, piston; *PA*, parallelogram structure; *W1*, *W2*, shot weights.

1 in by micrometer M. The micrometer was supported by a horizontal bar forming part of parallelogram PA, which maintained M in a vertical position. A level on the base plate and adjusting screws were used to keep the base plate horizontal.

The pressure P is given by

$$P = \frac{mgh}{ad} = Kh \tag{15}$$

where m is the mass of the piston; d is the length of the hypotenuse; a, the effective area of the piston; h, the altitude (fig. 50), and g the acceleration of gravity. When the constants m, a, d, and g are determined, measurement of pressures $P - P_0$ require only measurements of h.

Various performance factors were considered and test results given by Hutton. At an inclination based on a height h of 5 in, corresponding to a differential pressure of about 10 torr, the maximum predicted error in an absolute measurement was 2×10^{-3} torr, and for a relative measurement, 1×10^{-3} torr.

Operation at low absolute pressures was considered only on an experimental basis. Electrical charges on the piston, and inadequate lubrication if dependent on air, were outstanding limitations. Operation down to a few torr was achieved, with extension to below 0.1 torr believed ultimately possible.

Douslin and Osborn [6596] modified Hutton's design in order to measure vapor pressures in the range 0.01 to 30 torr. The top of the piston was subjected to a vacuum maintained by a pump and the bottom to the vapor pressure. As in Hutton's design, the cylinder was rotated while making a measurement, but the eccentric weight on the piston permitted the piston to oscillate, thus minimizing piston-cylinder adherence. The cylinder was tilted to obtain a balance; the tilt angle was measured on circular scale using a microscope to a precision of 1″ of arc. As expected, outgassing on the vacuum side of the piston gave trouble at low pressures. The piston was lubricated with the vapor, the pressure of which was being measured. At 0.01 torr, the accuracy was ± 0.001 torr; at 40 torr, ± 0.012 torr.

5.2. Vertical Piston Gages

Gramentskii and Khansuvorov [64277] (32 references) cover briefly the various designs of packless piston gages, chiefly Russian developments. Apparently none of the designs discussed are capable of measuring absolute pressures extending down to the micromanometer pressure range. Several of the designs are substitutes for a mercury barometer.

One feature of interest [64277] is the use of buoyant force to balance the weight of the piston, thus making possible the measurement to lower differential or absolute pressures with vertical piston gages. Here a pivot at the end of the piston rests on the central part of a member having the shape of a hollow donut which is immersed in a liquid. There are other alternatives for measuring low absolute pressures. One is the tilting air-lubricated piston gage described above. Another is to use two piston gages as described below, or finally a controlled pressure and one piston gage, where a high absolute pressure is the reference pressure fed to the primary piston gage. See Lloyd [6703].

The design illustrated in figure 51, described by Desgranges and Huot [61237], and Gramentskii [64277], provides a means for making absolute pressure measurements conveniently. The compensating piston gage A contains piston $PI1$, and the primary gage B, piston $PI2$. These differential pistons must be geometrically the same. The lower end of $PI1$ is maintained at a pressure P_0, significantly below pressure P which is to be measured. Gages A and B each have an auxiliary chamber connected to each other, filled with a liquid L and sealed off. The liquid pressure $P1$, with weight $W1$ constant, will vary with atmospheric pressure by the same amount in both A and B. Thus, the change in $P1$ compensates for the change in atmospheric pressure acting upon the outside of piston $PI2$, but correction must be made for any difference in liquid head acting on the two pistons. The absolute pressure is measured by the applied weights $W2$. Means R are provided for adjusting pressure $P1$ and, not shown, means for adding liquid to the system. One design had a range from 6 to 780 torr, with an accuracy of 0.03 percent.

Dadson and Greig [65347] used a piston design in which the area in contact with the cylinder was reduced

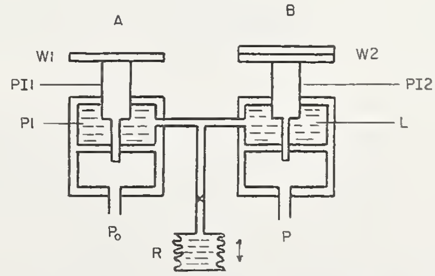

FIGURE 51. *Absolute pressure piston gage.*
A, compensating piston gage; *B*, primary piston gage; *L*, liquid; P_0, reference vacuum; *P*, pressure; *P1*, pressure on liquid; *PI1*, *PI2*, pistons identical in dimensions; *R*, adjustment for *P1*; *W1*, *W2*, weights.

by reductions in its diameter at intervals along its length. This reduced friction during piston rotation.

5.3. Piston-Type Pressure Amplifier

Ludwieg [5174] describes a piston-gage pressure amplifier for use in measuring pitot-static pressures below about 1.25 mm of water (0.09 torr). The primary piston *PI*1, figure 52, is attached to rod *R*, at the ends of which are secondary pistons *PI*2 and *PI*3. The piston axis is maintained horizontal by an adjustment and bubble level. The differential pressure *P*2 — *P*1 to be measured is amplified, to secure *P*4 — *P*3 in the ratio of the cross-sectional area of *PI*1 to *PI*2. In Ludwieg's design the amplification is about 105. Pressure *P*4 — *P*3 is measured by a U-tube manometer or other instrument. To balance the piston gage automatically, a constant air pressure is applied at *A*, with leaks at *B* and *C* controlled by the horizontal motion of the piston. For example, if *P*2 increases, the piston assembly moves horizontally to the right, increasing the leak through *B*, decreasing the leak through *C*, and permitting *P*3 to decrease and *P*4 to increase until the piston is in balance.

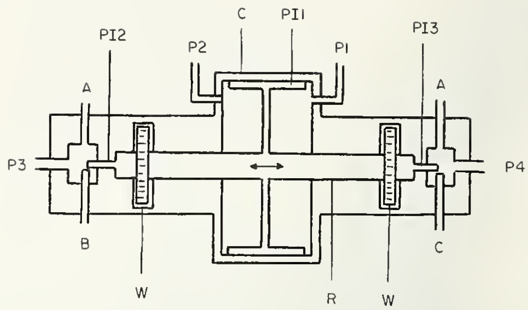

FIGURE 52. *Piston gage pressure amplifier.*
A-C and *A-B*, air pressure to maintain pistions *PI2* and *PI3* balanced; *PI1*, amplifying piston; *P2—P1*, primary pressure; *P3—P4*, amplified pressure; *R*, piston rod; *W*, air-driven turbine.

Auxiliary details include means to minimize piston friction by providing airflow through piston-bearing clearance, and by rotating the piston assembly by an air jet operating on the vanes of wheels *W*. A sensitivity of 0.001 mm of water (7.3×10^{-5} torr) was obtained; this required close control of the pressure supplied at *A*, and the piston axis to be horizontal.

6. Vane Gages

Vane gages are commonly of two types, one where the vane is pendulously suspended and the differential pressure across the vane is balanced by a component of its weight; the other, where the vane is free to rotate about a vertical axis and the differential pressure is balanced by the torque of the wire or filament from which it is suspended. Both types have been widely used in measuring low vapor pressures. Recently, interest has built up in developing the torque type for making absolute pressure measurements in the micromanometer range. Deflection types have been developed also; their description follows.

6.1. Deflection of Vane Measured

Green [6385] has described a simple vane instrument of the gravitational balance type, shown schematically in figure 53. A rectangular steel vane *D*, 1 by 2 in and 0.028 in thick, fits into a housing with a clearance of 0.01 in. A magnet *M* holds the vane in a socket so that it can deflect angularly about a horizontal axis, as observed on scale *S* engraved on glass. Neglecting the effect of the magnet, $P1 - P2 = \frac{W}{a} \sin \alpha$, where W is the weight of the vane, α its angular deflection from the vertical, and a its area. For a differential pressure $P1 - P2$ (or $P2 - P1$) of 0.1 in of water (0.186 torr), the vane deflection was 30°. This indicates a sensitivity of at least 0.006 torr per degree.

Weber and Plantenberg [4634] measured the impact pressure of the vapor from liquid metals which condensed on the vane. In figure 54, *L* is a liquid metal in a temperature-controlled enclosure, with an orifice above which is vane *V*. This vane is suspended from quartz spring *S*. A vacuum is maintained at P_0 by a pump. The spring deflection due to the impact force of the condensing vapor on *V* is measured by a micrometer microscope with a sensitivity of 4.20×10^{-7} g/micrometer scale division. Theoretically,

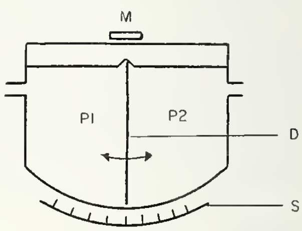

FIGURE 53. *Gravity-balanced vane gage.*
D, diaphragm; *M*, magnet; *P1*, *P2*, pressures; *S* ,scale.

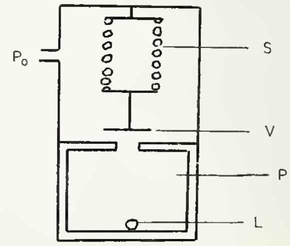

FIGURE 54. *Impact vane gage.*
L, vaporizing metal; P_0, vacuum; *S*, quartz helical spring; *V*, vane; *P*, vapor pressure being measured.

$$P = \frac{2\pi F}{dsdw} \quad (16)$$

where P = the vapor pressure; F, the impact pressure; ds, the orifice area; and dw, the solid angle of gas efflux from the orifice. If the impinging gas sticks to the vane, correcting F for the additional weight may be necessary. Only one vapor pressure measurement was reported, 0.0166 ± 0.0017 torr, for bismuth at 970 °K. Further application of this design does not appear to have been published.

6.2. Force on Vane Balanced

Hickman, Hecker, and Embree [3701], constructed a gage for measuring low vapor pressures as shown in figure 55. As the liquid L, maintained at a constant temperature, evaporated, a light, pendulously mounted vane V opened. The entire assembly was then oriented about axis A until the vane just closed. The angular deflection was measured on scale S, or a more sensitive equivalent. This process could be repeated for various controlled temperatures of the space above the liquid to secure a vapor pressure-temperature relation. A pump maintained a reference pressure P_0 well below the vapor pressure P. The pressure $P = K \sin \theta$, where θ is the measured angular deflection, and K is a constant determined by calibration. The pressure range was from 0.001 to 0.1 torr with a sensitivity at low pressures of $\pm 3 \times 10^{-4}$ torr.

Verhoek and Marshall [3906] modified the Hickman design by adding a liquid air-condensing tube to trap the effusing vapor in the space at pressure P_0, figure 55, and a heater for the vane to eliminate condensation. Measurements were made in the range from 7.4×10^{-3} to 0.8 torr.

A number of experimenters have described electrical force balances for measuring low vapor pressures. Balson's design [4727] will be described in detail. In figure 56, a vane V in the shape of a dome separates the chamber at the reference vacuum P_0 from that at the pressure P, which is maintained by the boiling liquid L in container C. The vane or lid is suspended from a spring S. An iron core A in the suspension forms part of an electromagnet, the coils of which are indicated by E. The electrical current, sufficient to cause the lid just to seat, is measured by milliammeter MA, and is proportional to the vapor pressure. Three vapor pressures were providing by three weights of the lid. The vapor pressures measured were from 0.001 to 5 torr. The instrument was calibrated against a McLeod gage.

An earlier design of the force balance by Rodebush and Coons [2706] was for measuring the vapor pressure of corrosive gases. A graphite disk replaced V in figure 56; the iron core A was enclosed in glass; and a quartz fiber cantilever spring replaced the helical spring S. The balancing electrical current was proportional to the pressure in the range from 0.01 to 0.07 torr.

Deitz [3611] used a quartz disk in place of V, figure 56, so placed that the balancing magnetic force measured by milliammeter MA had to be applied downward to break the seal. The furnace containing the sample was below the disk. A pointer, attached to the spring from which the disk was suspended, was viewed through a lens to determine the point at which the seal was broken. This instrument was used to measure the vapor pressure of salt crystals in the range from 30 ×

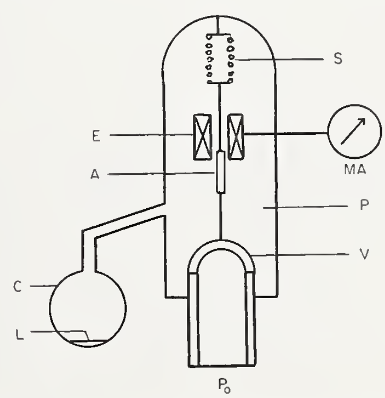

FIGURE 56. *Electromagnetic force-balanced vane gage.*
A, iron core; C, temperature-controlled chamber; E, *electromagnet;* L, vaporizing liquid; MA, milliammeter; P, vapor pressure; P_0, vacuum; S, helical spring; V, vane.

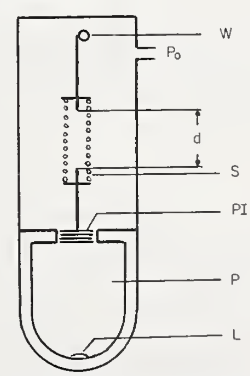

FIGURE 57. *Spring-balanced piston gage.*
L, vaporizing liquid; P, vapor pressure; P_0, vacuum; PI, mica disks, forming a piston; S, helical spring; W, windlass to keep PI in position.

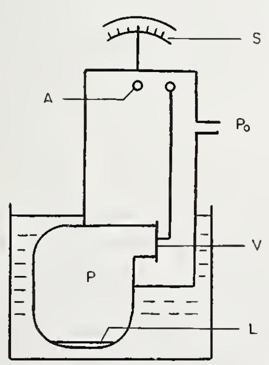

FIGURE 55. *Gravity-balanced vane gage.*
A, axis for entire apparatus; L, vaporizing liquid; P, vapor pressure; P_0, vacuum; S, scale; V, vane.

10^{-3} to 1 torr. It was calibrated by loading the disk with deadweights.

Ernsberger and Pitman [5518] designed what was essentially a spring-balanced piston gage for measuring low vapor pressures. The piston *PI*, figure 57, was formed by multiple mica disks in order to reduce leakage. It was connected to the lower end of a quartz helical spring *S* and the latter at the top of a windlass arrangement *W* by which the piston was kept in the balanced position. The spring deflection *d* was measured with a cathetometer to 0.05 mm. The liquid *L* is shown in a temperature-controlled chamber. The reference vacuum is P_0 and the vapor pressure, *P*. The mica disks were heated to prevent condensation; the piston clearance was 0.006 in. The pressure range was 20×10^{-3} to 0.5 torr. To check its performance, the vapor pressure of mercury was measured in the range 4.8×10^{-3} to 0.6 torr. The deviation from the accepted values was less than 1 percent, on the average about 0.2 percent.

6.3. Torsion Vane Gages

Reichardt [3510, 3511], for use in gas turbulence measurements, designed what was in effect a sensitive piston gage in which the pressure was balanced by the torsion of a wire. In the plane view of figure 58, *PI* is the arcuate or "curved" piston which juts through a hole in a wall dividing two chambers, and swings in the plane of the figure. The reference pressure P_0 is maintained in one chamber, and the pressure *P* to be measured in the other. The piston *PI* is suspended from a torsion wire *T* at right angles to the plane of the figure. A mirror on the anchor end of the torsion wire reflects a light beam on a scale, by which means the balancing torque can be measured. (For simplicity, pointer *PT* and scale *S* are shown in figure 58 as a substitute for the torsion wire measuring system.) Oscillations are damped by hanging a vane immersed in a liquid from the piston. Two hollow, lightweight pistons were constructed, one of light metal, the other of glass. The range with the one of light metal was 0.1 mm of water (0.007 torr), sensitivity 10^{-4} mm of water (7×10^{-6} torr), with a vibration period of 8 s. The instrument with the other had one-tenth of the range and sensitivity, and a vibration period of 25 s.

Lloyd [6703] sketches a vane manometer which is estimated to measure absolute pressures down to 10^{-9} torr where the uncertainty is 100 percent, decreasing at higher pressures. In figure 59a, the rigid unit comprising vanes *V1* and *V2* and mirror *M* was suspended from wire filament *F*. When pressures P_0 and *P* are equal the vanes close the openings to the tubing. When pressure *P* exceeds P_0, the opening of the vanes is counteracted by applying a torque at *C* to filament *F*. This torque to close the vanes is proportional to the pressure difference. The closure position of the vanes is indicated by a light beam *L* reflected from mirror *M* to photocell *PH*, the output of which could be used to maintain automatically the closed position of the vanes. Performance details are not available.

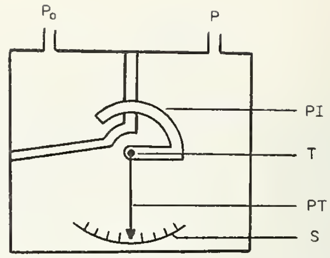

FIGURE 58. *Torsion-piston micromanometer.*
P, P_0, pressure and reference pressure; *PI*, pistion; *PT*, pointer; *S*, scale; *T*, torsion filament from which *PI* is suspended.

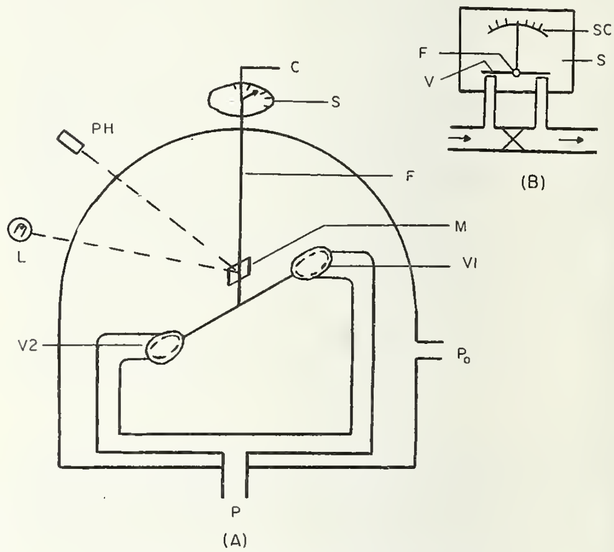

FIGURE 59A. *Torsion-vane micromanometer.*
C, balancing torque; *F*, wire filament; *L*, light source; *M*, mirror; *P*, P_0, pressure and reference pressure; *PH*, photocell; *S*, scale; *V1*, *V2*, vanes.

FIGURE 59B. *Vane flowmeter.*
F, torsion filament; *S*, chamber; *SC*, scale; *V*, vane assembly.

Measurements of low gas flow have been made by Gerlach and Mayer [2914], and for other purposes by a number of other experimenters. One arrangement proposed by Gerlach and Mayer is indicated in figure 59b. Here the measured pressure difference is a function of the flow rate and the system constants. Flow through tubing, into and out of reservoir *S* in the direction indicated, causes vane *V* to deflect clockwise. The torsion of a wire filament *F* from which the vane is suspended balances the force on the vane. Since gas flow is the desired measurement, calibration by means of known flows seems indicated. In view of the availability of other means of measuring gas flow at micromanometer pressures, the device has very limited application. The interest here is the fact that the orifice-vane combination, when the vane is positioned by an elastic pressure element, has had considerable application in controlling pressure in industrial processes.

7. Centrifugal Micromanometers

The centrifugal micromanometer may have particular application as a calibration standard and has been so applied by Kemp [5955] to measure pitot-static tube pressures in the micromanometer range. The first of two instruments to be discussed is that developed by Gross [5401]. In figure 60, *T1* and *T2* are two tubes of different diameters, closed except for outlets from the center controlled by valves *V1* and *V2*. These tubes are rotatable about their individual vertical axes by electric motors at speeds up to 1000 rpm. A diaphragm *D* with a null detector *N* can be connected to either *T1* or *T2*. The theory shows that the differential pressure $P - P_0$ is a function of the rotational speed of the tube, the change in volume of the system caused by the deflection of diaphragm before it is brought to the null (Δv in fig. 60), and other factors which are constant for each rotating system. In operation, the system and *I*, the instrument to be calibrated, are subjected to a small pressure above atmospheric, causing a deflection of *D*. Valves *V4* and *V2* are closed, *T1* is rotated to bring *D* back to the null position. Valve *V1* is now closed and *V2* opened, and the null again obtained by rotating *T2*, the speed of which will differ from that of *T1*. From these data Δv can be calculated and then $P - P_0$. Gross emphasizes the need for temperature control, and for stability in the atmospheric pressure P_0; if this is unstable, valve *V3* can be closed at the same time as *V4*. The sensitivity obtained was 10^{-6} psi (5×10^{-5} torr).

To measure low pitot-static pressures, Kemp [5955] improved a design developed by Nickel in 1951. In schematic figure 61, *S* is a thick disk with 8 radial holes, two of which are shown. It is rotated by motor *MO* about a vertical axis. The reference pressure P_0 is maintained at the axis of rotation; the output pressure developed at the periphery of rotating *S* is led to glass tube *G*, and opposed by the pressure *P* which is to be measured. The rotational speed is adjusted so that *P* and the output centrifugal pressure are equal, as determined by the absence of flow in viewing tube *G*. Atomized oil sprayed into *G* is illuminated by electric light *L*, and viewed by microscope *M* to observe when flow equilibrium exists. Two mercury seals *C* are provided. To calibrate an instrument, *I*, shown at *A* in the figure, it is merely necessary to connect it to the output side of the centrifuge and compare its indication with the centrifugal pressure. Theory is given by Kemp. The output pressure is proportional to the square of the speed of rotation. The design has a pressure range from 5×10^{-3} to 20 mm of water (3.5×10^{-4} to 1.5 torr) with an accuracy of 1 percent.

Lofquist [6221] adapted Kemp's design in order to measure water pressure. The pressure range measurable was from 5×10^{-5} to 0.1 mbar (3.7×10^{-5} to 0.075 torr).

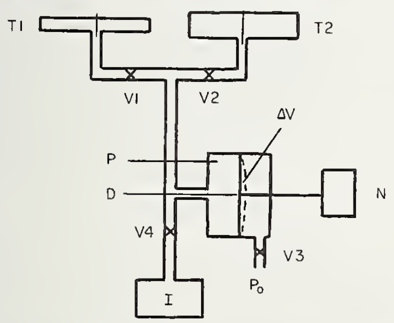

FIGURE 60. *Centrifugal micromanometer.*
D, diaphragm; *I*, instrument under test; *N*, null indicator; *P*, P_0, pressure and reference pressure; *T1, T2, rotatable tubes; V1, V2, V3, V4*, valves; Δv, a volume.

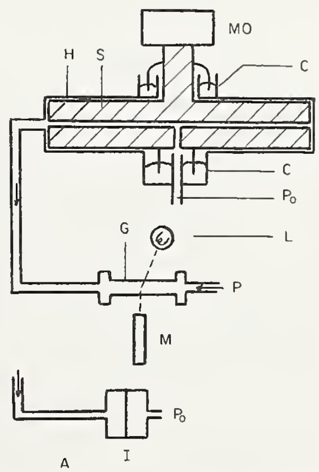

FIGURE 61. *Centrifugal microcanometer.*
A, modification when calibrating instrument *I; C*, mercury seal; *G*, glass viewing tube; *H*, housing; *L*, light source; *M*, microscope; *MO*, motor; *P*, P_0, pressure and reference pressure; *S;* rotatable disk.

8. Special-Purpose Gages

Micromanometers may be designed to be useful only for a particular application and may be of little use for other applications. Thus, some designs are uniquely useful for measuring low vapor pressures, or atmospheric pressure oscillations, or oxygen pressures, or low differential pressures at high ambient pressures. Another class of micromanometers exists for which there are additional requirements which do not impair its general use. These requirements may be the need for dynamic measurements, for measuring the pressure of corrosive gases, for distant indication, or for a small-sized gage.

Designs to meet each of these particular requirements will be considered below, noting that for some applications more than one of these requirements must be met in a particular instrument. Some of the designs have already been described; for convenience these will be mentioned again here.

8.1. Dynamic Pressure Measurement

Dynamic pressure measurement may be defined as the measurement of rapidly changing pressure such as exists in an explosion or in an internal combustion engine. The need for dynamic pressure measurement is rarely met within the pressure range of micromanometers, since rapid pressure changes are usually associated with much higher pressures. Dynamic pressures must be recorded or displayed on an oscillograph of high natural frequency. Generally, no instrument responds accurately to a pressure change having a frequency greater than the natural frequency of the instrument; in fact much less, particularly when damping is added to prevent overshoot.

U-tube liquid manometers are of little use in making dynamic measurements and will not be discussed. It should be noted that it is necessary to allow sufficient time for equilibrium to occur before making readings on a U-tube manometer. In the case of micromanometers, this time is governed by other considerations than the lag-in-response of the liquid column.

In general, neither piston nor vane gages are suitable for dynamic measurements; this fact restricts consideration to elastic element, electrical conductivity, and piezoelectric gages in the micromanometer range.

The measurement of atmospheric pressure oscillations is unique in the regime of dynamic measurement and, therefore, is discussed separately in section 8.2.

8.1.1. Theory

The lag in dynamic response of an instrument system is due to two major components: that of the instrument element, and that of the tubing connecting the instrument to the point at which the pressure measurement is desired. Considering the lag due to the connecting tubing, three principal regimes exist, one in which the flow in the tubing is viscous, one in which the flow is free molecular, and last, a transition region between viscous and free molecular flow. The transition region occurs when the mean free path of the molecules is about the same as the diameter of the tubing. Ordinarily viscous flow exists at pressures above 1 torr; free molecular flow exists at pressures below about 10^{-3} torr; transition regime flow will usually exist in the pressure range from 10^{-3} to 1 torr, exactly in the micromanometer absolute pressure range. When differential pressures are of interest at absolute ambient pressures above 1 torr, the gas flow is in the viscous regime. Generally, if pressure pulses are of a frequency such that the line lag is excessive, recourse is to electrical transmission from the pressure element.

The theory governing the line lag when the gas flow is viscous, assuming that the pressure pulse is small compared to the initial pressure, was given by Wildhack [3719], and by a number of others. A more complete theory was developed by Iberall [5058]. Theory and experimental data covering multiple tubes and gage volumes, mainly for aeronautic application, were given by Bergh and Tijdeman [65346].

The theory for line lag under free molecular flow conditions (pressures in the vacuum range) has been developed by Schaaf and Cyr [4925], Harris [5577], and Matricon [6284]. Ainsworth and LaGow [5623] considered the line lag in making ambient pressure measurements in rocket flights. See also Lyubitov [B671] on "Molecular Flow in Vessels," who presents theory for both the free molecular and transition flow regimes, and for the Knudsen effusion cell. Davis [5846] presented the theory for molecular flow, and presented data on line lag at pressures down to 0.2 torr, which included some data covering the transitional flow regime.

Hord [6725] reviewed the theory of line lag for step inputs for free molecule, transition, and continuum flow regions.

For the viscous flow region, the line lag is conveniently represented by a time constant λ, which is the time for $\frac{e-1}{e}$, or 63 percent, of the imposed pressure step to be indicated, where e is the base of natural logarithms, The indicated pressure approaches asymptotically the final value with elapsed time. For molecular free flow and the transitional flow regions, the line lag time is often defined as that when 95 percent of the imposed pressure change is indicated. The ratio of the indicated imposed pressure change to the actual imposed pressure change varies linearly with the time elapsed after imposition of the change in pressure; see [4925].

An extensive literature exists on the theory governing the dynamic response of pressure-measuring instrumentation, most of which is not pertinent in this survey. Theory covering the time lag of elastic element instruments is broadly covered by Huebner [5487]. Such theory is of limited usefulness, since other sources of lag may be significant. Huebner mainly considered instruments with electrical transducers, where most of the lag was in the elastic element. He was interested mainly in the lag for imposed pressure pulses having a definite frequency, as in measuring acoustic pressures.

8.1.2. Piezoelectric Gages

A voltage is induced in piezoelectric crystals, such as quartz, barium titanate, and others, while a force is being applied. To measure pressure, means must be used to apply the pressure directionally. Their speed of response is high, of the order of 10^{-6} s, so that they have been widely used to measure dynamic pressures; however, but rarely at the pressures as low as here of interest.

One instrument development, that by Willmarth [58151] used to measure air dynamic turbulence, will be described. Two barium titanate disks, 0.162 in in diameter and 0.04 in thick, cemented together, were mounted flush with the inner wall of a 4-in pipe. The output of the barium titanate crystals was fed to a cathode follower, an amplifier, and an oscilloscope. The sensitivity was 0.88×10^{-6} V per dyne/cm^2 (7.5×10^{-4} V per torr). A uniform sensitivity was obtained in the frequency range 5 to 50,000 Hz. Dynamic pressures as small as 12 dynes per cm^2 (0.0009 torr) were measurable.

Arlowe, Dove, and Duggin [6619] have developed an amplifier for piezoelectric crystal gages which matches the inherently fast response of the crystal. The design was particularly adapted to distant indication.

8.1.3. Frustrated Internal Reflection Gage

Ahlborn and Zuzak [6709] describe a gage which is of limited interest here because, at its present state of development, it measures only pressures well above the micromanometer range. The rise time for an indication is as low as 5×10^{-6} s. Briefly, the aluminum-coated face of a mylar diaphragm is subjected to pressure, thereby changing its area of contact with a glass prism. Light incident on the prism is reflected internally from the aluminum coat in an amount depending on the contact area and detected by a photocell. The measured voltage output of the photocell is not linear with pressure.

8.1.4. Frequency Response of Gages

The frequency response of the various designs of micromanometers is summarized in table 1.

It is seen that the best dynamic response is achieved by piezoelectric crystal gages, followed by the electrical resistance and the diaphragm-capacitance gages.

The data ascribed to Rony appear to have been obtained from the manufacturers; "M" indicates where this is established. The speed of response decreases with decrease in the stiffness of the diaphragm of the diaphragm-capacitance gage. If a decrease in the pressure range involves the use of a more sensitive diaphragm, the response time will be increased. Thus, the response time of 10×10^{-3} s given for the MKS instrument in table 1 was obtained for a 3-torr step at 760 torr; for an instrument having a lower range, say 0.03 or 0.003 torr, the response time would be substantially greater than 10×10^{-3} s.

Table 1. *Dynamic response data*

Design	References	Described in Section	Frequency or response time	% Indication		Full pressure range *Torr*
			Diaphragm-Capacitance Gages			
MKS	[64265]	----------	10×10^{-3} s	63	M	3
Barocel	[64265]	----------	5×10^{-3} s (est.)	63		10
Decker	[64265]	----------	2×10^{-3} s	63		1.9
Rony	[64265]	----------	5×10^{-3} s	63		0.035
Sharpless (Wrede)	[61235]	4.5.3.5.1	1 s	100		—
Transonics	[60112]	4.5.3.2.1	5×10^{-3} s	63	M	—
Rideal, et al.	[5570]	4.5.3.4	10^4 Hz	100		—
			Piezoelectric Gages			
Willmarth	[58151]	8.1.2	50 to 50,000 Hz	100		
Arlowe, et al.	[6619]	8.1.2	10^{-6} s	100		
		Barograph (spring force automatically restores null)				
Flauraud, et al.	[5490]	4.5.3.5.3	0.37 torr/min	100		
			Vibrating Diaphragm Gage			
Dimeff, et al.	[6215]	4.5.3.6	0.1 s (est.)	100		
			Diaphragm-Bonded Strain Gage			
Thureau, et al.	[62123]	4.7	16,400 Hz	nat. freq.		
			Conducting Liquid Manometer			
Pappenheimer	[5456]	4.8	12×10^{-3} s	95		
			Conducting Rubber Micromanometer			
Massey, et al.	[6604]	8.7	20 to 6000 Hz	100		
			Vibrating Wire (transducer only)			
Poindexter	[5281]	4.12	5000 Hz	100		

It is worth noting that the response of diaphragm gages is governed both by the speed of response of the diaphragm and by that of the amplifier, which may be either mechanical or electrical in nature.

8.2. Atmospheric Pressure Oscillations

Instruments which measure small changes in either absolute atmospheric pressure or rate of change of pressure are quite generally called microbarographs. The terms variograph and microbarovariograph have occasionally been used in practice to designate, perhaps more accurately, the recorder of the rate of change of pressure with time, in a limited frequency range. Only the latter type of recorder is described in this section. Perhaps it will clarify the concepts to add that the microbarograph records absolute pressure, and the microbarovariograph records differential pressure above or below a mean atmospheric pressure. The latter is one of the familly of variographs, of which the aircraft rate-of-climb indicator is another example. Bowing to custom, the term microbarograph will be used hereafter in place of the more descriptive term, microbarovariograph.

In very few cases is the speed of response of the pressure element and its associated means of indication an important factor in measuring atmospheric pressure oscillations. The period of the fluctuations to be measured lies in the range of one second to several minutes.

To obtain a stable reference pressure, it is necessary to introduce a restriction between the atmosphere and the chamber housing the diaphragm or bellows. This restriction is normally a capillary tube, but in coupling to the atmosphere for greatest freedom from atmospheric turbulence and high-frequency oscillations, long pipelines—up to hundreds of feet—are needed. The design of long lines with spaced holes and varying cross sections to eliminate fluctuation frequencies above 1 Hz is discussed by Daniels [59198].

The other side of the diaphragm is open to the atmospheric pressure fluctuations, except that some cutoff of high-frequency fluctuations appears often desirable. For this purpose, an adjustable orifice, usually a valve, or a short-length capillary tube, is inserted. For a more complicated arrangement see figures 42 and 65.

Thus, neither very slow or very rapid changes in atmospheric pressure are indicated by the pressure element; only fluctuations within the limits of the established frequency controls are detected.

In principle at least, microbarographs which measure absolute atmospheric pressure could be designed to measure atmospheric pressure fluctuations, but the recorded data require an inconvenient separation of the microfluctuations from the undesired major fluctuations in pressure. Actually, commercially available capacitance-diaphragm gages appear to have the necessary sensitivity and frequency response to do the job if the recorder speed were stepped up.

The literature on atmospheric pressure fluctuations is extensive; up to 1959 Thuronyi [59177] has listed 122 references.

8.2.1. Microbarographs

Most designs depend upon an elastic pressure-sensitive element, and a few upon a liquid column sensor.

8.2.1.1. Elastic Element Microbarographs

One of the two pioneer designs with which an enormous amount of fundamental data was accumulated was that developed by Benioff. The other by Shida is described in 8.2.1.2.

The Benioff [3911] microbarograph consisted essentially of a moving coil-type loud speaker, mounted in a suitable case with a restriction to air flow to secure the usual reference pressure. The output of the inductance coil was measured on a recording galvanometer, 1 mm deflection of which was produced by 0.001 torr. It was used to measure the low-period, low-amplitude oscillations in atmospheric pressure.

Macelwane and Ramirez [3814] designed a microbarograph similar to Benioff's to record rapid atmospheric pressure fluctuations of a period around 7 s. An inductance coil was fastened to a rubber diaphragm in the vertical plane. A fixed magnet passed through the center of the coil. The voltage developed in the coil as the diaphragm deflected was measured by a galvanometer. The chamber closed by the diaphragm was connected to the atmosphere through a restriction, adjustment of which controlled the period of response.

Saxer [4501] described an instrument designed to make the same measurements as Benioff's instrument. This was an electrical capacitance-diaphragm instrument. The output of a galvanometer was photographically recorded. Theory was presented.

Passechnik and Fedosseenko [58162] describe two microbarographs, one for laboratory and one for field use. One design was essentially the same as Benioff's, and both were used for the same purpose. In the design for field use, the pressure sensitive element consisted of a number of evacuated diaphragm capsules. A flat response was obtained for oscillation periods from about 3 to 40 s.

Baird and Banwell [4019] desired to record atmospheric pressure oscillations associated with microseisms. Their diaphragm-capacitance design is essentially as shown in figure 29, except for controlled restrictions added at P and P_0 and the addition of a rectifier. The indications of the galvanometer were recorded photographically. Normally, pressure oscillations having a period between 4 and 10 s were recorded; the sensitivity was 0.003 torr for 1 cm deflection on the photographic record.

A microbarograph developed by Cox, Atanasoff, et al. [4902], has been fully described in section 4.6.3 and shown in figure 42. Reflected explosion waves at frequencies below 1 Hz were to be detected. Their arrangement of restrictions was such that fluctuations having a frequency of 10 Hz or greater were not indicated; at a frequency of 4 Hz, the sensitivity was reduced 50 percent.

Johnson and Chiles [5784] designed a diaphragm-capacitance instrument to record pressure fluctuations caused at a great distance from explosions on the

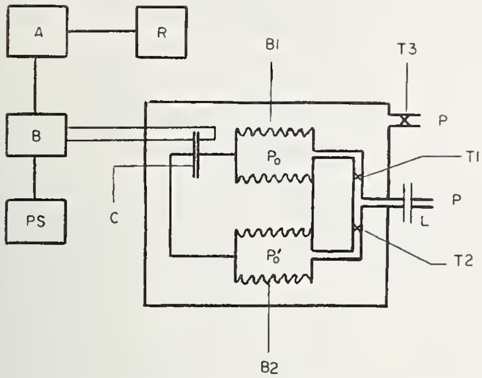

FIGURE 62. *Jones-Forbes microbarograph.*
A, amplifier; *B*, bridge; *B1*, *B2*, metal bellows; *C*, capacitance; *L*, long-line restriction; *P*, atmospheric pressure; P_0 *and* P'_0, reference pressures; *PS*, 16 kHz power supply; *R*, recorder; *T1*, *T2*, *T3*, valve restrictions.

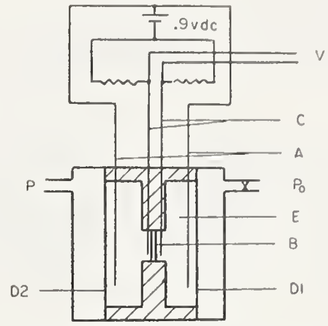

FIGURE 63. *Solion microbarograph.*
A, anode leads; *B*, cathode button; *C*, cathode leads; *D1* and *D2*, diaphragms; *E*, electrolyte; $P—P_0$, differential pressure; *V*, voltage output.

earth's surface. These fluctuations were refracted downward from the layer of the atmosphere hotter than at the surface which occurs at an altitude around 50 km. Their instrument design is essentially as shown in figure 29, except for the frequency-controlling restrictions. A dc electrical recorder was used, which required a rectifier not shown in figure 29. The system recorded large amplitude pressure waves (infrasonic), with periods in the range from 60 to 360 s. Theory and considerable experimental data are presented in their report.

Jones and Forbes [6230] designed an elaborate pressure-sensing system for measuring atmospheric pressure fluctuations. To obviate the effect of extraneous fluctuations in the reference pressure, two metal bellows were installed as shown in figure 62. The atmospheric pressure *P* is transmitted into the interior of the bellows through a line *L*, 220 m long, and other restrictions to obtain two reference pressures P_0 and P_0'. Restricting valve *T*1 is set to give a pressure lag of 120 s in bellows *B*1 and *T*2, 3 s in bellows *B*2. Valve *T*3 connects the atmosphere to the case of the instrument, and controls the cutoff point for the high-frequency end of the pressure fluctuations. A nearly flat response was obtained for a range in period from 15 to 140 s, for the above adjustments of *T*1 and *T*2. Each of the bellows was rigidly connected to a disk, forming capacitance *C*, which formed part of a bridge *B*. The output of *B* was fed through amplifier *A* to recorder *R*. The power supply *PS* had a frequency of 16 kHz. Jones and Forbes considered sources of error such as tilt and temperature changes. The sensitivity was 5×10^{-5} mbar (3.8×10^{-5} torr).

Cook and Young [62235] summarize the results of measurements of atmospheric pressure fluctuations under various circumstances. In detecting long wavelengths, such as caused by an explosion and received as a reflection from a warm layer high above the ground, the direction of the approach is also desired. To obtain this information, Cook states that four microbarographs were installed about 7 km apart. The microbarographs, which he calls microphones, were of the diaphragm-capacitance type. Their output was a frequency-modulated voltage proportional to the incident sound pressure, which is transmitted by telephone to a central location for demodulation, amplification, and recording. Comparison of the different times of arrival of the pressure wave at each microbarograph permitted the approach direction of the wave to be determined. It should be noted that short-wavelength fluctuations of the atmospheric pressure must be eliminated from both sides of the diaphragm, which was done by connecting the microbarograph inlet to the atmosphere by a long pipeline. A capillary tube restriction between the two sides of the diaphragm avoids response to very long periods but permits obtaining the desired data.

Sinclair [65351] designed a microbarograph using a vacuum tube transducer operated by a diaphragm capsule. See section 4.10 for a description.

Collins, Richie, and English [64279] propose their "Solion" design as a microbarograph. In figure 63, diaphragms *D*1 and *D*2 enclose a chamber filled with a water solution of an iodide and iodine. A porous plug *B* permits slow liquid flow when a pressure $P - P_0$ is applied, say on diaphragm *D*2. A dc voltage of 0.9 V is impressed between anode wires *A* and cathode wires *C*. Due to dissociation of the iodide on one side of the cathode button *B* and recombination on the other, a voltage develops across *V* while a flow through *B* exists. The output varies from 0.1 to 0.9 V for a pressure range from 0.1 to 1000 dynes/cm² (7.5×10^{-5} to 0.75 torr). The frequency range of response was between 0.003 and 50 Hz.

8.2.1.2. Liquid Column Microbarographs

The Shida microbarograph, designed in 1918 and still in use in 1956, is described by Namekawa [3617] and shown in figure 64. In U-tube manometer *U*, *L*1 is water and *L*2 a mineral oil, specific gravity about 0.9. A float *F* is suspended at the interface of *L*1 and *L*2. A platinum filament *W* connects pulley *PU*1 to the float, to iron wire *M*, and to counterweight *C*1. Electromagnetic damping is provided by coil *E* and iron wire *M*. Another filament connects pulleys *PU*1 and *PU*2, terminating in counterweight *C*2. A record of the float motion against time is obtained on smoked paper *RS* by pen *RP*. A reservoir *RE*, about a cubic meter in

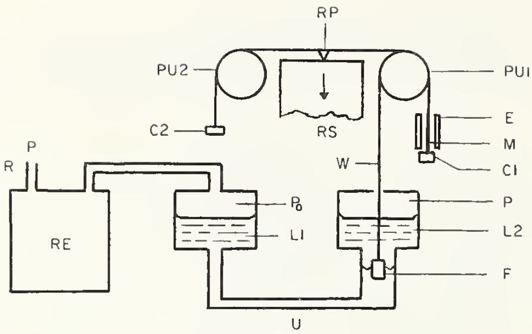

FIGURE 64. *Shida microbarograph.*
C1 and *C2*, counterweights; *E*, damping coil; *F*, float; *L1*, water; *L2*, oil; *M*, iron rod; *P*, atmospheric pressure; P_o, *reference pressure; PU1* and *PU2*, pulleys; *R*, restriction; *RE*, ballast volume; *RP*, pen; *RS*, smoked chart; *U*, U-tube manometer; *W*, platinum wire.

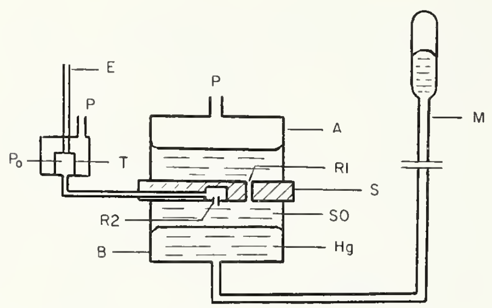

FIGURE 65. *Van Dorn microbarograph.*
A, upper chamber; *B*, lower chamber; *E*, leads to electric recorder circuit; *M*, barometer tube; *P*, P_o, atmospheric and reference pressure; *R1*, *R2*, restrictions; *S*, wall betwene *A* and *B*; *SO*, silicone oil; *T*, pressure transducer unit.

volume, is buried underground for temperature stability and is connected to the atmosphere through restriction *R* and to one leg of the U-tube, which is maintained at reference pressure P_0. The oil surface in the other leg is subjected to atmospheric pressure *P*. The natural period of the system was 7 s. Atmospheric pressure fluctuations having a period from several minutes to 30 min were recorded. A pen deflection of 1 mm corresponded to a pressure change of 0.025 torr. Sources of error were considered in [3617], as indicated from the theory governing its operation.

Ericsson [62236] used a magnetic float in a U-tube, which controlled the inductance in coils installed outside of the manometer tube. The restrictions to pressure equalization in two legs of the U-tube were such that the microbarograph responded to atmospheric pressure fluctuations having periods between 2 and 1200 s. The pressure range was from 10^{-7} to 10^{-3} of an atmosphere (roughly 10^{-4} to 1 torr).

Van Dorn [60119] designed the microbarograph shown in figure 65 to determine the correlation of atmospheric pressure fluctuations with surface water waves. The fluctuations were measured by a barometric mercury column *M*. This was connected to cistern *B*. Silicone oil filled the space in *B* below metal separator *S*, and had a free surface in chamber *A* above *S*.

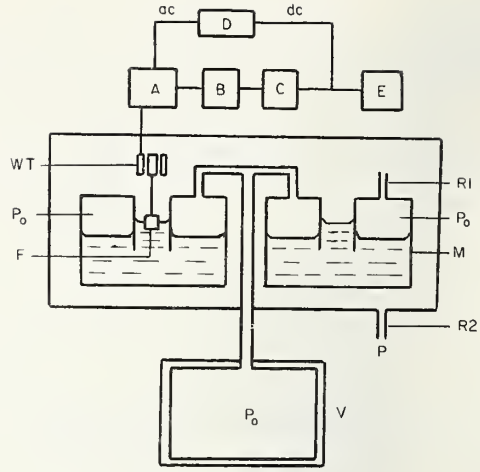

FIGURE 66. *Donn microbarograph.*
A, phase-sensitive circuit; *B*, amplifier; *C*, demodulator; *D*, modulator; *E*, microfilm recorder; *F*, cork float; *M*, shallow U-tube manometer; *P*, atmospheric pressure; P_o, reference pressure; *R1*, *R2*, restrictions; *V*, insulated volume; *WT*, electrical pressure transducer.

Chamber *A* and the transducer were connected to the atmospheric pressure at *P*. An adjustable screw restriction *R*1 connected chambers *A* and *B*. The bellows of a commercial pressure transducer *T* (unbonded wire strain gage) was connected to the silicone oil in chamber *B* through restriction *R*2. *E* designates the leads to a Wheatstone bridge and a recorder. In operation, the atmospheric pressure *P* from chamber *A* is transmitted to the oil in chamber *B* through restriction *R*1, and then to transducer *T* through *R*2, to obtain the reference pressure P_0. Restriction *R*1 cuts off measurement of high frequencies, and *R*2, low frequencies. The entire instrument was mounted in a well, which was packed with diffusers to minimize the effect of turbulence in the atmosphere. The useful range was 5 mbar (3.75 torr), for which the resolution was ±0.05 mbar, with greater sensitivity possible. The response was linear for fluctuation periods from 15 to 8000 s.

Donn [58161] also devised a U-tube manometer for measuring atmospheric pressure fluctuations in order to correlate them with ocean surface waves. In figure 66, *M* is the shallow U-tube, shaped somewhat like a doughnut. One leg is entirely closed off except for a restriction *R*1 which cuts off all but the slow pressure changes, and thus controls the reference pressure P_0. The other leg, much smaller in cross-sectional area, contains a cork float *F* to which is attached a commercial electrical transducer *WT*. The U-tube assembly is enclosed in a case, which is connected to the ambient pressure *P* through restriction *R*2, which cuts off undesired high-frequency fluctuations. An insulated ballast volume *V* is connected to the reference pressure side of the manometer to stabilize P_0. The manometer liquid was diethyl sebacate. The output of the transducer was fed to phase-sensitive circuit *A*, to amplifier *B* and modulator *D*, demodulator *C*, and recorded on microfilm recorder *E*. The response was linear for fluctuations having periods between 10 and 200 s. It was stated that the resolution was 0.002 mbars (0.0015 torr), which corresponds to about 0.02 mm head of the manometer liquid.

8.3. Elevation From Pressure Measurement

Since atmospheric pressure varies with elevation (or altitude), extensive efforts have been made to apply this fact in making land surveys. One primary difficulty exists. The atmospheric pressure varies with time, and from point to point on the earth's surface. Thus, in precise work the pressure must be measured simultaneously at the base or reference point and at the point the elevation of which is desired. A quiescent atmosphere is required. The point-to-point variation in atmospheric pressure inherently limits the method to small distances from the base.

Thus, while instrumentation is available having a sensitivity of 1 or 2 ft at sea level, equivalent to 0.028 torr per foot, realization of this accuracy in field surveys is not easily obtainable. See Kissam [4418]. Most of the altimeter designs are based on the deflection of an evacuated diaphragm capsule or bellows. Pertinent designs have been discussed in section 4.

One novel design, that described by Stripling, Broding, and Wilhelm, [4931] merits a brief description. A temperature-controlled chamber contains a bellows. The volume of the chamber can be varied by extending or contracting the bellows so as to bring its pressure into equilibrium with atmospheric pressure. The change in bellows volume, indicative of the change in chamber pressure, is measured through a gear train and a counter attached to the bellows. Pressure equilibrium is indicated by a liquid bubble in a horizontal tube connecting the chamber with a second chamber at a stabilized atmospheric pressure attained by the restriction through which it is connected to the atmosphere. Note that change in ambient pressure, not pressure, is measured. Field tests indicated an average error of 0.8 ft with a maximum of 1.2 ft. This is equivalent to about 0.03 torr.

8.4. Low Vapor Pressure

Consideration in this section is restricted to micromanometers useful only for measuring low vapor pressure. Vane gages primarily used to measure low vapor pressure may have other applications and therefore are covered separately in section 5.

Generally, in the pressure range of interest here, the Knudsen effusion method is used. Two primary designs are available. In one proposed by Knudsen in 1909, the mass of vapor effusing from an orifice in unit time is measured, from which data the vapor pressure is computable. In the other, the vapor effuses so as to produce a torque, which is measured by the angular deflection of a wire filament. At vapor temperatures above ambient, either method is usable; below ambient, only the effusion-torque method is practical.

In addition to designs based on the effusion from orifices, a dewpoint design for measuring the vapor pressure of mercury amalgams will be described. This is useful only when the effusing vapor temperature is above ambient, and an optical transmission method is available.

8.4.1. Effusion-Weight Method

Douglas [5441] designed an apparatus for measuring the vapor pressure of calcium in the temperature range from 800 to 900 °C, where the vapor ranged from 1.2×10^{-3} to 41×10^{-3} torr. The design is shown schematically in figure 67. Here F is the furnace; S, the calcium sample; $SL1$ and $SL2$ are slits to guide the effusing vapor to cover glass C. A shutter SH is operated to control the time interval of depositing vapor on C. Any one of eight cover glasses can be placed to receive vapor deposits by means of rotatable table R. The time interval during which vapor is deposited on C must be measured. Douglas obtained the mass of vapor deposited by means of titration. The accuracy in measuring vapor pressure was ± 5 percent.

The mass of the deposited vapor can also be obtained by means of a microbalance, as in the design developed by Herlet and Reich [5788] indicated in figure 68. Here the sample S is in furnace F, heated electrically by coil E. The effusing vapor impinges on disk D, hung from beam B, in turn attached to spiral spring SP. The deflection of beam B as the vapor deposits on D is indicated on scale SC. Not shown in the figure is a photocell and feedback arrangement by which the beam B is maintained in the null position,

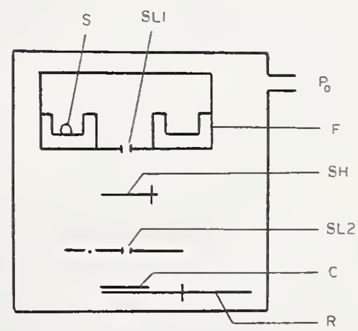

FIGURE 67. *Effusion-weight vapor-pressure gage.*
C, cover glass receptacle; F, furnace; P_0, vacuum; R, rotatable table; S, calcium sample; SH, rotatable shield; $SL1$, $SL2$, flow directing slits.

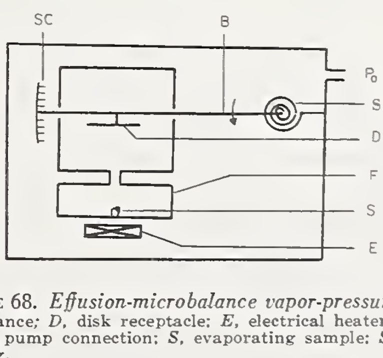

FIGURE 68. *Effusion-microbalance vapor-pressure gage.*
B, microbalance; D, disk receptacle; E, electrical heater; F, furnace; P_0, vacuum pump connection; S, evaporating sample; SC, scale; SP, spiral spring.

and the electrically generated balancing force measured on an electrical recorder. The sensitivity obtained was 10^{-7} torr. The vapor pressure of pump oils was measured in the range from 10^{-6} to 10^{-2} torr in the temperature range from 40 to 160 °C.

Habermann and Daane [64202] applied the microbalance, nulled electromagnetically, designed by Edwards and Baldwin [5176] to measure the vapor pressure of substances at temperatures up to 2000 °C. Their paper dwells mainly on the furnace design required to function at this temperature.

In all of the above described designs, the mass of the effused vapor was measured. Alternatively, the mass lost by the sample as a function of time can be measured.

Carrera, Walker, et al. [63346], and Suzuki and Wahlbeck [6625], describe microbalances in which the effusion cell is weighed by a microbalance against time while evaporation takes place. From such measurements the vapor pressure of pure substances is computable. Suzuki and Wahlbeck measured vapor pressure as low as 10^{-4} torr, at sample temperatures up to 1500 °C. Carrera et al. were interested in vapor pressure measurements in the temperature range 1600–2500 °C. They discuss an improvement in sensitivity by allowing the balance beam to deflect and measuring the deflection by an electrical capacitor, one plate of which was attached to the beam. The associated electronic circuit to obtain the beam deflection is described, but development of the design had not reached the test stage.

Ditchburn and Gilmour [4115] published a review and bibliography (93 references) on vapor pressure measurement in 1941, which may even now be of interest. A later survey was made in 1966 by Cooper and Stranks [6628].

Theoretically, as first given by Knudsen:

$$P = \frac{m}{KAt}\left(\frac{2\pi RT}{M}\right)^{1/2} \qquad (17)$$

where P is the vapor pressure in dynes per square centimeter if all other terms are in cgs units; m is the mass of vapor effused in time interval t; A is the cross-sectional area of the orifice; R is the universal gas constant; T is the temperature in kelvins; M is the molecular weight in the vapor phase; and K is the sticking probability.

Witman [5268], and others also, discusses the assumptions underlying eq (17), and sources of error:

(a) Free molecular flow of the vapor must exist. The mean free path must be at least 10 times the smallest dimension, usually that of the orifice or slits. Practically, this limits the method to measuring vapor pressures above about 10^{-2} torr.

(b) The reflection of the molecules in the furnace must be diffuse.

(c) The molecules must enter the orifice or slits with a cosine distribution of directions.

(d) The molecules must enter uniformly over the face of the orifice or slits.

Usually the sticking coefficient is assumed to be unity.

Douglas [5441] substituted a narrow rectangular slit in cases where the circular slit was too large in comparison with the mean free path. He, as well as other experimenters, pointed out that the vapor must be monatomic; otherwise, fractionation may occur. The indicated vapor pressures will be in error to the degree that the evaporating substance contains volatile impurities.

Birks and Bradley [4930] mention the cooling of the evaporating substance as evaporation proceeds as a source of error. This is intensified by the necessity of maintaining vacuum conditions surrounding the furnace.

Cooke [5649] presents theory for the drop in the vapor pressure along the path of the vapor from the evaporating substance to the orifice through which it effuses. This pressure drop is a function of the cross-sectional area of the orifice. Experimental data on the effect of various orifice areas were presented to establish the validity of the calculation, and to give a method for applying a correction.

8.4.2. Effusion-Torque Method

The design presented by Pratt and Aldred [59179], and shown schematically in figure 69, is essentially that first proposed by Volmer [3112]. In the figure, C is a graphite effusion cell containing the evaporating substance. The vapor effuses through two holes, 180 degrees apart, causing a torque to act on the cell which angularly deflects tungsten filament $F1$. Tantalum filament $F2$ is rigid in comparison with $F1$. On rod R is mounted a mirror M, which reflects a light beam passing through window W to a scale, by which the deflection of $F1$ is measured. An aluminum disk D mounted on R is in the field of alnico magnet DM to provide damping. A silica tube T is the furnace. The highest furnace temperature was 1000 °C. The vapor pressure was measurable in the range from 10^{-5} to 10^{-2} torr, with an accuracy at low pressures of ± 10 percent, and at high, ± 1 percent.

Wessel [5175] improved Vollmer's furnace design to obtain a maximum temperature of 1500 °C, Searcy and Freeman [5494], to 1900 °C, and Peleg and Al-

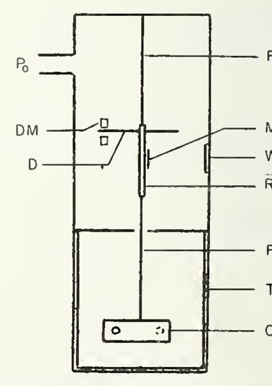

FIGURE 69. *Effusion-torque vapor-pressure gage.*
C, graphite effusion cell; *D*, aluminum disk; *DM*, damping magnet; *F1*, *F2*, flexible and stiff wire filaments; *M*, mirror; P_o, vacuum pump connection; *R*, rod; *T*, silica tube; *W*, window.

cock [6622], to 2500 °C. All used torsion suspension filaments.

Klumb and Lueckert [5946] describe a design similar to that shown in figure 69, and stated its pressure range to be 10^{-1} to 10^{-4} torr.

Balson [4728] modified the Volmer design by adding a cold trap in the space above the furnace in order to condense the effusing vapor. He constructed six effusion cells of varying sensitivity, with the most sensitive having a sensitivity of 5×10^{-6} torr per millimeter of scale deflection.

Rosen [60188] added an electromagnet to control the position of rod D, figure 69, by which the filament $F1$ was kept in the null position. The nulling electric current was measured to obtain the vapor pressure. He noted that by use of a photocell and feedback, the null position of $F1$ could be maintained automatically. No performance data were given.

Peters and Herrick [6714] applied their automated optical system for measuring angular deflection to measuring the torque produced by a diffusion cell.

The theory for the effusion-torque method is given by both Neumann and Voelker [3210] and Pratt and Aldred [59179]. By the latter

$$P = \frac{2K\alpha}{a_1 q_1 f_1 + a_2 q_2 f_2} \tag{18}$$

where P is the vapor pressure in dynes per square centimeter if all other terms are in cgs units; K is the torsion constant of the suspending filament; α, its angular deflection; a_1 and a_2 are the cross-sectional area of the two effusion holes respectively; q_1 and q_2, their distance from the suspension axis; and f_1 and f_2 are correction factors developed by Clausing [Dushman B491] to take care of end effects.

The underlying assumptions and sources of error are those discussed in section 8.4.1.

8.4.3. Dewpoint Pressure Divider

Kapff and Jacobs [4724] devised a dewpoint method of securing vapor pressures at temperatures below which the effusion-weight method took too long to obtain a measurement. The idea is to obtain the dewpoint of the vapor at a temperature lower than that in the furnace. If the vapor pressure at the higher temperature is known, that at the lower dewpoint temperature can be computed. In figure 70, L is the liquid sample, temperature controlled. The vapor effuses through nozzle N, through slit S to chrome-plated mirror M. The mirror on which the vapor condenses is viewed through window W. Theoretically,

$$\frac{P2}{P1} = \frac{d^2}{4a^2} \cos\theta \left(\frac{T2}{T1}\right)^{1/2} \tag{19}$$

where $P1$ is the vapor pressure of the liquid at temperature $T1$; $P2$ is the vapor pressure at mirror temperature $T2$ when the impinging and evaporating vapor are in balance; θ, a, and d, are physical dimensions as indicated in the figure. The pressure of other gases in the system must be held to pressures below 10^{-4} torr. The pressure $P1$ exceeds $P2$, which justifies the designation of pressure divider. The instrument was used to obtain vapor pressure $P2$ for pump oils from measured values of $P2/P1$. For the particular geometry used, $P2/P1$ was about 10^{-3}; $T1$, about 360 K; and $T2$, about 300 K. To determine $P2$, $P1$ must be measured, which was done by the effusion-weight method in the range 10^{-4} to 10^{-3} torr. Values of the vapor pressure in the region of 10^{-7} torr are obtainable by the pressure divider. The accuracy was estimated at $\pm$ 30 percent. The values of $P2$ obtained were significantly lower than those obtained with ionization gages, by as such as 100 percent. The source of the discrepancy was not investigated.

8.4.4. Optical Transmission Gage

Morgolis [6621] developed a method for measuring the vapor pressure of mercury amalgams. In figure 71, $Q1$ and $Q2$ are quartz optical cells, $Q2$ contains a drop of pure mercury and $Q1$ contains a small quantity of the mercury amalgam. These cells were installed in chamber T, the temperature of which could be controlled in the range 25 to 125 °C. The cells were illuminated by a mercury vapor lamp L with the 2537 °A line, which is strongly absorbed by mercury vapor. The light transmitted through the cells was received by a spectrophotometer S. At a given temperature the transmission through $Q1$ was measured: the temperature was then adjusted to obtain the same transmission through $Q2$. Thus, the vapor pressure of the amalgam at the adjusted temperature equaled the vapor pressure of the mercury. The latter is known. The pressure range covered by the temperature control was 0.0017 to 0.9 torr.

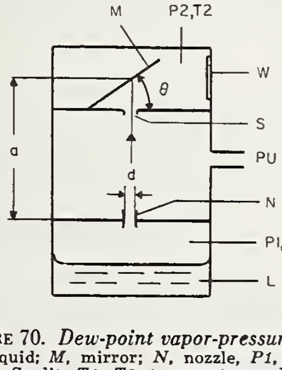

FIGURE 70. *Dew-point vapor-pressure gage.*
L, evaporating liquid; *M*, mirror; *N*, nozzle, *P1*, *P2*, pressures; *PU*, pump connection; *S*, slit; *T1*, *T2*, temperatures; *W*, window.

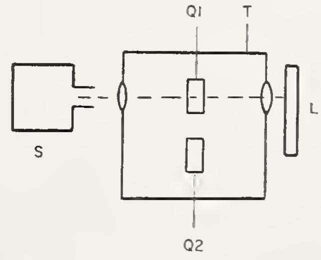

FIGURE 71. *Optical transmission gage.*
L, mercury vapor lamp; *Q1*, *Q2*, quartz transmission cells; *S*. spectrophotometer; *T*, temperature controlled chamber.

8.5. Low Differential Pressure at High Pressure

Ring gages capable of withstanding high pressure have been mentioned in section 2.11.3 and are discussed by Schmidt [3601].

A null-type U-tube manometer developed by Reamer and Sage [6008], in which the null position of a diaphragm was detected by a linear differential transformer, is described in section 2.6.2. Up to 15,000 psi absolute, the differential pressure was measurable with a precision of 0.05 torr, with an accuracy of 0.25 torr.

Bell [65348] developed a null type U-tube manometer, also described in section 2.6.2. An inductance detector controlled a servomotor which moved one leg of the U-tube vertically to bring the liquid surface to a null position. The differential pressure range was from 0.02 to 100 in of liquid column for absolute pressure to 2500 psi.

8.6. Corrosive Gases

The problem here is to avoid using materials which corrode when in contact with the fluid, the pressure of which is to be measured. Elastic elements, diaphragms or metal bellows, and connecting lines, can be made of materials which do not corrode. Then any of the transducers, in contact with the elastic element but external to the corrosive fluid, can be used to make the measurement. One design for the purpose is that of Sancier and Richeson [5617], described in section 4.6.1. Another is that of Spence [4021], described in section 4.3.2, where avoidance of interaction of gases with mercury is its only virtue.

8.7. Distant Indication

This section concerns situations where the indication of the pressure is desired at a location at some distance from the source of the pressure. One solution is to connect the instrument to the source of the pressure by tubing. The lag may be high so that the dynamic response is poor, but the use of connecting tubing is practical in many cases. The tubing lag has been discussed in section 8.1.

Another solution is to place the pressure-sensitive element close to the pressure source, use an electrical transducer, and transmit its output by electrical leads to the desired location. This is much more satisfactory where rapid dynamic response is required. In general, transmission of a modulated frequency is the ultimate solution, since amplification of the signal does not interfere with the modulated frequency. The pressure element and its transducer are placed close to the pressure source, as is the electrical circuit producing the frequency modulation signal. Electrical leads may connect to the indicating means, or in the ultimate, may be telemetered by radio, as in the case of the radiosonde.

Tsukakoshi, et al. [64276], in their semiconductor strain gage manometer, described in section 4.7, transmitted a dc signal from 2 to 300 m with no difficulty. They avoided the transmission of high-frequency ac current.

Attention is also called to the vibrating wire gage described in section 4.12, which is useful primarily for distant indication of the pressure.

8.8. Miniature Pressure Cells

Although mainly suitable for measuring pressure just above the micromanometer range, reference to developments of small elastic element pressure cells may be of interest. In some measure these developments give an idea of the minimum diameter of the pressure cell achievable for use in the micromanometer range. Wrathall [5280] describes diaphragm gages which are $\frac{1}{4}$ to $\frac{1}{2}$ in in diameter, with three different types of transducers: (a) resistance wire strain gage bonded to the diaphragm, pressure range $\frac{1}{2}$ and $\frac{1}{4}$ psi; electrical capacity, pressure range 2 and 8 psi; and variable reluctance, lowest pressure ranges 1 and 8 psi. The resonant frequency of the various elements was in the range 2300 to 30,000 Hz.

Delmonte [5279] describes a miniature diaphragm element, with an unbonded resistance wire strain gage as the transducer, which was $\frac{1}{2}$ in in outside diameter, and could be made to have a pressure range as low as 1 psi.

Pettersson and Clemedson [5059] used a silver diaphragm in a transducer unit, 8 mm in diameter by 20 mm long, to measure fluctuations in blood pressure. The limiting sensitivity was 1 to 2 mm of water (0.07 to 0.15 torr).

Dimeff, et al. [6215], in their vibrating diaphragm instrument described in section 4.11, used in a wind tunnel, had a diaphragm as small as 0.28 in in diameter. Pressures as low as 10^{-4} torr were measurable.

Massey and Kavrak (6604) designed a miniature pressure gage with a fast response. In figure 72, T is a steel tube 0.04 in (1 mm) in diameter. A platinum wire PT passes through the tube. One end of the tube is cut away and shaped to obtain a flat, rigid surface, at which location the platinum wire is also flattened. A disk of conducting rubber, as small as 0.045 in in diameter and 0.020 in thick, is placed between the flattened sections of the tube and wire. Since the flattened platinum wire is flexible, changes in ambient pressure compress or expand the rubber insert, which changes the electrical resistance of the rubber. The electrical resistance is measured by the output of

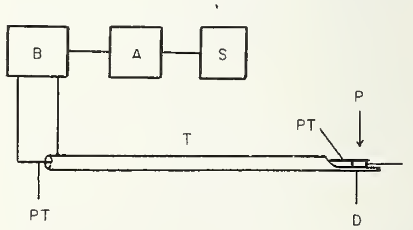

FIGURE 72. *Miniature dynamic micromanometer.*
A, amplifier; *B*, Wheatstone bridge; *CR*, conducting rubber; *D*, rigid disk; *P*, pressure; *PT*, platinum wire; *S*, oscilloscope; *T*, steel tube.

Wheatstone bridge *B*, amplified and displayed on oscilloscope *S*. The sensitivity obtained was 0.04 torr; the indications were independent of frequency in the range 20 to 6000 Hz. The resistance of the rubber decreased 1 percent per degree Celsius rise in temperature in the interval 10 to 50 °C.

8.9. Oxygen Partial Pressure

The measurement of oxygen pressure in a gas mixture is particularly important in respiration studies. This necessity stimulated the development of the Pauling oxygen meter [4631]. While its sensitivity probably does not quite qualify it as a micromanometer, its unique operating principle justifies its description. The Pauling instrument is based on the fact that oxygen is paramagnetic, while other gases commonly mixed with it in the atmospher are diamagnetic. In figure 73, a small glass dumbbell *G* is hung from quartz fiber *F* which carries mirror *M*. The dumbbell is in the field of a strong magnet *MA*. The glass balls are hollow and filled with either air or an inert gas. As the partial pressure of oxygen in a gas at pressure *P* entering the cell changes, the dumbbell rotates, the torsion of which is balanced by the quartz fiber. A light beam reflected from mirror *M* to a scale measures the balancing torque. Generally, the scale is graduated in percent oxygen, as low as 0 to 5 percent with an accuracy of 1 percent of the range, but it can also be calibrated in pressure units. Assuming a total gas pressure of 760 torr, the 5 percent meter would have an accuracy of about 0.4 torr, probably limited at lower total pressures to about 0.1 torr. The force on the dumbbell is proportional to the product of two factors, the magnetic field gradient, and the difference in magnetic susceptibility (between the dumbbell and the surrounding gas). Later developments have included the application of an electrostatic voltage, to maintain the dumbbell in a null position and to provide a feedback to maintain the null automatically. A recorder of the electrostatic nulling voltage has also been added.

Weissbart and Ruka [6113] tested successfully the feasibility of an oxygen meter using an electrolytic element, and developed its theory. It operated at temperatures above 500 °C. The test setup is shown in figure 74, where *E* is the solid electrolyte $(ZrO_2)_{.85}\ (CaO)_{.15}$. *T* is a tube kept evacuated; *T1* is the inlet tube for the gas mixture, and *T2* is the output tube. Furnace *F* is temperature controlled. The two sides of *E* are connected to a potentiometer. The output emf was found to be proportional to the logarithm of the oxygen pressure at a given temperature in the range 611 to 649 °C for mixtures of stable gases. When reactions occurred in a gas mixture, the residual oxygen pressure was indicated. The emf was in the range 0.05 to 0.20 V for oxygen pressures from 0.2 to 100 torr.

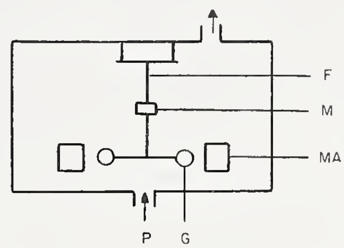

FIGURE 73. *Pauling oxygen meter.*
F, quartz filament; *G*, glass dumbbell; *M*, miror; *MA*, magnet; *P*, gas entrance.

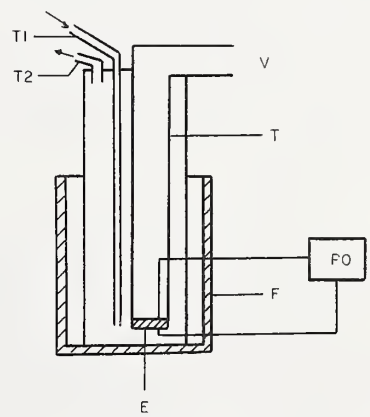

FIGURE 74. *Weissbart and Ruka oxygen meter.*
E, solid electrolyte; *F*, furnace; *PO*, potentiometer; *T*, tube; *T1*, gas mixture inlet tube; *T2*, gas outlet; *V*, vacuum source.

9. Calibration Techniques

Two principal techniques exist: static calibration and that for determining the dynamic response. Factors affecting the static performance (mainly those due to temperature change) usually can be determined by controlled variation of the affecting condition, and will not be considered further.

9.1. Static Calibration

Calibration is required of very few types of micromanometers, mainly those dependent on an elastic element, piezoelectric gages, and the effusion-type vapor-pressure gage.

Generally, calibration of an instrument involves comparison of its readings with those of a standard instrument, both subjected to the same pressure. A standard instrument is here defined as one where the pressure can be calculated from easily made measurements and without ambiguity. In many cases, only determination of length and mass are required. The production of a computable pressure is another way of obtaining a calibration.

There follows a discussion of standard instruments which are, or could be, used as a calibration standard.

9.1.1. U-Tube Micromanometer

Of the many forms of measuring liquid column heights in U-tubes which have been described in section 2, the simple design by Thomas and Cross described in section 2.2.1 is preferable, if the high-accuracy micromanometers are to be calibrated. This is a U-tube with legs at least 2 in in diameter, with an index attached to a micrometer in each leg to measure the displacement of the two liquid surfaces. Either mercury or a low-density fluid can be used; either differential or absolute pressure can be measured. With mercury as the liquid, the uncertainty with 2-in legs was 4×10^{-3} torr, and with an oil, 4×10^{-4} torr [6701]. Further improvement in performance is believed possible.

Other accurate means of measuring the liquid column height which could be used in a standard instrument are: (a) optical interferometers (sect. 2.5), and (b) the electrical capacitance transducer (sect. 2.6.1).

9.1.2. McLeod Gage

Some experimenters have used a McLeod gage to calibrate micromanometers measuring absolute pressure. The chief advantage of its use is that its range extends downward well into the high-vacuum region (10^{-3} to 10^{-6} torr). However, the uncertainty in the measured pressure is likely to be as great as 10 to 20 percent. Discussion in detail is out of place here, since the McLeod gage is classed as a vacuum gage and not as a micromanometer.

9.1.3. Piston Gage

As a standard for measuring differential pressure at absolute pressures above about 1 torr, the air-lubricated, tilting piston gage is suitable down to about 0.01 torr, with an uncertainty of 1 or 2×10^{-3} torr. See section 5. For measuring absolute pressures, Douslin and Osborn [6596], section 5.1, have lowered the range to 0.01 torr, with an uncertainty at that pressure of 1×10^{-3} torr. Further development work is needed to set the pressure limits within which this gage is useful as a standard.

9.1.4. Gas Column Manometers

The standards described in the next four paragraphs involve the production of a known pressure which can be applied in some manner to a micromanometer which is to be calibrated. The first of these is the gas column manometer, useful only for low differential pressure at atmospheric pressure or above (see sect. 3). Sensitivities as good as 3×10^{-6} torr have been obtained, but the device has been rarely used.

9.1.5. Gas Volume Expansion

Here a gas at a higher and easily measured pressure and volume is expanded into an evacuated chamber of known volume from which the final pressure can be computed. It is primarily used to calibrate vacuum gages. Arney and Henderson [6813] describe a mobile calibrator of this type to secure pressures in the range 10^{-3} to 30 torr. In the range 10^{-3} to 1 torr the accuracy was $\pm$ 1.3 percent.

9.1.6. Vapor Pressure

The vapor pressure of a pure substance is a function of temperature only and can be used to calibrate absolute micromanometers if the temperature of a closed system is closely controlled. For this application, the vapor pressure-temperature curve must be known and, of course, must be in the required pressure range. The difficulty is to locate substances with conveniently usable vapor pressure-temperature curves, so that there has been practically no development of the method.

Strictly speaking, the pressure produced in the device proposed by Pappas [6620] is not a vapor pressure, but it is akin to it. The complex Na_2UF_8 dissociates to give a gas uranium hexafluoride UF_6, and a solid NaF. The gas pressure varies with the temperature of the solid in accord with the relation:

$$\log P = 10.88 - 5.09 \times \frac{1000}{T} \tag{20}$$

where T is the absolute temperature in degrees Kelvin and P the pressure in torr. At a pressure of 0.001 torr the temperature is 95 °C; at 0.01 torr, 123 °C; at 0.05 torr, 145 °C. While the given pressure-temperature relation may be in question and precautions must be taken to use pure Na_2UF_8, as pointed out by Pappas, the dissociation pressures may be useful as a calibration standard for absolute pressures in the rather difficult calibration region between 0.01 and 0.001 torr. Further experimentation is required to determine more accurately the dissociation pressures and the possible errors.

Futch [6130] used the vapor pressure of ice from -100 to -40 °C to calibrate ionization gages in the pressure range from 10^{-4} to 10^{-1} torr. It could equally well be used to calibrate micromanometers.

9.1.7. Centrifugal Micromanometer

A known differential pressure in the vicinity of atmospheric pressure is produced by the centrifugal micromanometer. The best design is that proposed by Kemp [5955], described in section 7. The range of pressures produced was from 3.6×10^{-4} to 1.5 torr, with an accuracy of 1 percent.

9.1.8. Elastic Element Gage

The micromanometer based upon a diaphragm-capacitance, pressure-sensitive element has practical application as a calibration standard. Drawin [6081] considers its application for measuring absolute pressures in the range from 10^{-5} to 1 torr, and Ryzhov [63345] for the range from 0.001 to 0.1 torr. The chief difficulty is in obtaining a valid pressure-deflection relation for the diaphragm, usually flat and under tension. However, both Drawin and Ryzhov avoided this difficulty by developing theory for the case where the diaphragm was maintained in the null position. See section 4.5.1. Drawin checked his computed sensitivity for one instrument against a McLeod gage and found deviations within $+3.0$ and -2.7 percent, for 22 observations and 8 different gases. Within these deviations, only one source of error is significant, that due to instrument temperature change, which can be avoided by maintaining the micromanometer at constant temperature. See section 4.5.4. Ryzhov stated that the error in his design was 1 percent.

If the diaphragm is of uniform thickness and is free to deflect, the instrument sensitivity can be obtained by computation in another way. Tilting the diaphragm, say 90° and 180°, changes the indication by an amount equivalent to a pressure which is computable from the weight and dimensions of the diaphragm. In any event, checks on the constancy of the sensitivity can be obtained when desired by the tilting procedure.

In view of the need for an alternative to the McLeod gage in the absolute pressure range 10^{-5} to 10^{-2} torr, further development of the capacitance gage as a working standard is worthwhile. See section 4.5.

9.2. Dynamic Calibration

In general, the response of micromanometers to fluctuating pressure or a rapid change in pressure can be determined either by subjecting it to a varying pressure of known frequency and amplitude, or to a step change in pressure made in a time interval which is small compared to the response time of the instrument. The calibration is simplified if a micromanometer is available which has a response time greatly superior to that of the instrument under test. As has been previously stated, ordinarily dynamic calibration is of practical importance only for elastic-element gages. In the case of microbarographs, the problem is to restrict indications to pressures varying within a selected band of rather low frequencies for which calibration offers no great difficulty.

It is obvious that the micromanometer as a whole has to be calibrated, but that the speed of response is determined chiefly by the slowest element, either the elastic element, the transducer, the amplifying circuits, or the recorder. The fastest response is obtainable with electrical transducers, in which case, with ordinary care in designing the electrical circuits, the limiting element is the elastic element.

There is an immense literature on methods of dynamic calibration of instrumentation measuring pressures above the micromanometer range, but this for the most part is not applicable to micromanometers. However, the monograph by Schweppe, Eichberger, et al. [63343], covers a wide variety of dynamic calibration methods and should be mentioned.

A number of methods used to produce pressure oscillations of known amplitude and frequency in the micromanometer will next be described.

9.2.1. Pressure Step Produced

Thureau and Lemière [62123] had two chambers, one with a volume of 2 cm³, the other 1000 cm³, separated by a fragile diaphragm. The diaphragm pressure element was installed in the larger chamber which was initially at a lower pressure. Rupturing the diaphragm subjected the micromanometer to about 1/500 of the initial pressure difference in the two chambers. Reflected pressure waves in the large chamber gave a vibratory response with a frequency of about 16,000 Hz on an oscilloscope, later confirmed as the natural frequency of the micromanometer. These reflections were reduced by modifying the installation of the micromanometer in the test chamber. The pressure step can be calculated and compared with the static and dynamic response of the micromanometer to give the needed information.

The above is a variation of the quick opening valve between two spaces at different pressures, and of the shock tube commonly used to obtain a pressure step at pressures above the range of interest here.

The rupturing of a soap bubble by pressure has been used to obtain a pressure step in the micromanometer range. Pressure steps of 0.1 mbar (0.07 torr) are obtainable but are hard to reproduce. This method provides an excellent quick check of the frequency response of microbarographs.

9.2.2. Fluctuating Pressures Produced

A number of widely different methods of producing fluctuating pressures of known amplitude and frequency will be described. None appear to be applicable at low absolute pressures.

The pistonphone was developed to determine the performance of microphones and has been similarly applied to elastic element micromanometers. It is described by Beranek [4932]. The theory involved in computing the pressure amplitude is described by Biagi and Cook [5495] and Gerber [64280, 64281]. Simply, the pistonphone consists of a small chamber, at one end of which is a small diameter piston installed in a hole in the chamber wall and the instrument under test at the other end. This piston is driven at known frequencies and measured amplitudes by an elecromagnetic driver. As the piston oscillates the pressure in the chamber varies by an amount which can be calculated from the air volume changes in the chamber and from assumptions made as to the degree the pressure change is adiabatic.

Rideal and Robertson [5570] used a loudspeaker to impinge pressures of controlled frequency on a capacitance-diaphragm micromanometer. The output of the micromanometer, and the input to the loudspeaker indicative of the frequency, were displayed on an oscilloscope. The response of the micromanometer was frequently independent up to 10^4 Hz.

Miles [64273] developed a method of determining the dynamic response of diaphragms, which is equally useful for elastic element micromanometers. A piezoelectric oscillator was devised to obtain adequate amplitude of the pressure. Two polarized disks of ceramic lead zirconium titanate, one of which expands and the other contracts when frequency-controlled voltage is imposed, were cemented together. The disk assembly was installed in one end of a small volume and the diaphragm under test at the other end. Oscillations of the disk act like a pump in producing a pressure fluctuation. The natural frequency of the disk used was 8600 Hz, which limited the frequency which could be imposed. The diaphragm was connected to a wire strain-gage transducer, the output of which was displayed on an oscilloscope together with information on the frequency of oscillation of the disk. Incidentally, Miles gives data on the natural frequency of a number of sizes and thicknesses of flat diaphragms.

Massey and Kavrak [6604] had the problem of determining the dynamic response of a miniature micromanometer depending on the electrical conductivity of a rubber. A water column was kept in vibration at measured frequencies by a moving coil drive. The frequency range was from 1 to 10^4 Hz, and the amplitude from 10^{-4} to 0.5 in of water (1.9×10^{-4} to 0.9 torr), the latter measured by a vibration transducer. The micromanometer unit was installed at the lower end of the water column. An oscilloscope indicated both the output of the micromanometer and of the vibration amplitude transducer. The response was independent of frequency in the range from 20 to 6000 Hz.

Fehr, Ben-Ary, and Ryan [6713] modified a loudspeaker to obtain a piston action, and used it to produce pressure oscillations in a chamber to which the instrument to be calibrated was connected. They determined the relation between power input and pressure oscillations at known frequencies. A microbarograph which was calibrated had a flat response in the frequency range from 0.001 to 22 Hz in the range from 10^{-2} to 10^3 dynes/cm^2 (roughly, 7×10^{-6} to 0.7 torr). The calibration procedures and techniques were covered in considerable detail.

10. References

The number of the references are conveniently the same as those given in the bibliography, NBS Monograph 35 [6101], and its supplement [6708], to which readers are referred for titles and indexed content. Quite a few references, some previous to 1960 and all subsequent to 1965, are not listed in Monograph 35. This method of identification accounts for the fact that the reference number listed below for any one year are not consecutive.

In the list, book numbers are prefixed by B, the first two digits indicate the year of issue, and the last digit distinguishes those listed for any one year.

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