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DESIGN, CONSTRUCTION, AND OPERATION OF A DIFFERENTIAL MICROMANOMETER

PART II. THEORY AND OPERATIONAL CHARACTERISTICS

Peter R. Rony

April 8, 1965

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PART II. THEORY AND OPERATIONAL CHARACTERISTICS

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ABSTRACT

A differential micromanometer capable of measuring 100 μtorr to an accuracy of ± 2% has been designed, constructed, and tested. The micromanometer is being used as a Wrede-Harteck gauge, a device that converts an atom concentration into a pressure differential in a low-pressure gaseous system.

The pressure difference is sensed by a membrane manometer constructed as a differential capacitor that forms two legs of a resonant-bridge network excited by a radio-frequency source. The bridge output (2.762 Mc/sec) is amplified and fed to a phase-sensitive detector that determines the direction of unbalance and develops a dc voltage that can be used (a) in a feedback-loop system to restore the diaphragm to its null position, or (b) in an open-loop system and recorded directly.

The most favorable system found to date consists of a Decker Corporation Model 306-2A pressure transducer operated open loop with the bridge and electronics. Differential pressures as low as 50 μtorr can be measured with a zero drift of about 30 μtorr or less per hour (approximately 1 μtorr per min) in a room regulated to within ± 0.5°C. Differential pressures of 0.5 μtorr are detectable. With a more sensitive transducer, such as a Decker Corporation Model 306-2G, the sensitivity might be increased by almost an order of magnitude over the above figures. An attenuator in the amplifier section extends the 306-2A system to differential pressures as large as 35 mtorr.

The micromanometer is calibrated electrostatically. The diaphragm constant K in the formula

$$\Delta P = KV^2$$

is determined to ± 2% by comparison of the readings produced by a known pressure differential, measured with an accurate McLeod gauge, and a voltage of known magnitude applied to one side of the differential capacitor. Once the gauge constant is known, the system can be calibrated daily by application of a series of known voltages and a plot of the recorder reading vs the square of the voltages. This calibration method eliminates completely the effects of changes of bridge voltage, bridge constant, amplifier gain, diaphragm tension, and recorder calibration. It takes five minutes to perform and need be done as seldom as twice a day.

In the pressure region of 0.1 to 35 mtorr the system is an excellent secondary pressure standard, being much more convenient and generally more accurate than a McLeod gauge. A duplicate model, constructed and tuned following the procedures given in Parts I and II of this report, worked the very first time it was tried.

The characteristics of the differential micromanometer are compared to those of ten other differential micromanometer systems: the MKS Instruments, Inc. Barotron; the Datametrics, Inc. Barocel; the micromanometers sold by the Decker Corporation, the Consolidated Engineering Corporation, and Granville-Phillips Company; and the micromanometers developed by Becker and Stehl, Opsteltin et al., Lovejoy, Cope, and Sharpless, et al. The electrostatic calibration technique can be extended to some of these systems simply by placing a low-impedance capacitor in each of the lower bridge arms.

I. INTRODUCTION

The Wrede-Harteck gauge, whose principle is based upon the different rates of effusion of atoms and their parent molecules through a Knudsen hole, incorporates one of only two absolute methods used to measure atom concentrations.[1,2,3] Two of these gauges were required for a study of atomic hydrogen in low-pressure systems. With atom concentrations of less than 5% at a total pressure of 75 mtorr, the upper limit of the differential pressure to be measured was only 1.1 mtorr. It became evident early in the investigation that existing commercial micromanometers were not adequate for the measurement of these very small differential pressures. Thus, although the development of a more sensitive differential micromanometer was not the primary object of this research, a complete transducer-electronics system had to be designed and constructed to meet the requirements of the experiment.

These requirements were: (a) the measurement of differential pressures as low as 0.1 mtorr to several percent; (b) freedom from noise and dc drift over a ten-minute time interval; (c) insensitivity to changes in gas composition; (d) insensitivity to changes in external variables, such as temperature, and electric or magnetic fields; and (e) ease or constancy of calibration within ten minutes.

The best type of transducer for the accurate measurement of small differential pressures appeared to be the capacitive displacement transducer. Lion, Vanderschmidt, and Foldvari[4] and the Rosemount Engineering Company[5] have briefly discussed its advantages over those of direct-acting pressure transducers dependent upon resistive, capacitive, piezoelectric, electrokinetic, ionization, corona discharge, or thermal effects, as well as those of other indirect-acting pressure transducers such as piston, bellows, expanding tube, or Bourdon spiral. The capacitive displacement transducer was thus chosen as the primary transducer type for conversion of a pressure change into an eventual dc electrical signal.

The capacitive displacement transducer systems considered were those sold by the Decker Instrument Corporation,[6] Lion Research Corporation,[7] Consolidated Engineering Corporation,[8] or developed by Sharpless,[3] Opsteltin, Warmoltz, and Zaalberg Van Zelst,[9,10] Cope,[11] Becker and Stehl,[12] Lovejoy,[13] and Lovering and Wiltshire.[14] During the period when the micromanometer was being constructed, two other commercial systems were advertised in the widely circulated technical literature, the Barocel[15] (made by Datametrics, Inc.) and the Baratron[16] (made by MKS Instruments, Inc.). A lock-in amplifier[17] (Princeton Applied Research Corporation) was also tried as an oscillator-detector for a bridge employing a commercial capacitive transducer (Decker Corporation Model 306-2A).

The first electronics unit—consisting of the power supply, amplifier, oscillator, phase detector, and recorder output—was designed and constructed by Kenneth W. Lamers and is described in Part I of this report.[18] I rederived the theory of the operation of the entire system; designed and constructed the bridge, capacitive displacement transducer, and calibration circuit; and calibrated and used the completed system. I also constructed and tuned a second unit, which worked the very first time it was tried.

The theory of the differential micromanometer, the design and construction of the transducer, bridge, and calibration circuit, and the operation of the electronics is described in Secs. II to V, and the calibration of the transducer is described in Secs. VI and VIII.K. The characteristics of comparative systems are discussed in Sec. VIII. A summary (Sec. IX) and a section on future developments (Sec. X) conclude the report.

II. THEORY OF THE DIFFERENTIAL MICROMANOMETER

A. Capacitive Displacement Transducer

Figure 1 shows a simplified sketch of a symmetrical capacitive displacement transducer. It consists of a thin central diaphragm of thickness h, radius R, and density ρ stretched elastically under uniform tension T, and two stationary electrodes, each of radius R', at a distance z_o from the diaphragm in its equilibrium position. If the transducer is stationary and the diaphragm not ferromagnetic, three forces can act on the membrane: a mechanical force,

$$F_{\text{mechanical}} = \pi R^2 \Delta P \tag{1}$$

a gravitational force,

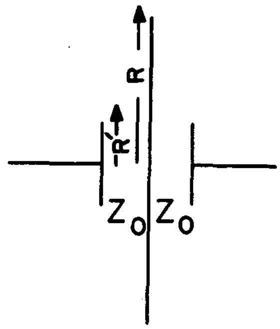
$$F_{\text{gravitational}} = \pi R^2 \rho g h \quad , \tag{2}$$

and an electrostatic force,

$$F_{\substack{\text{electrostatic}\\ \text{nonlinear}}} = \pi R'^2 \frac{\epsilon v^2}{z_o^2} \quad \text{(mass-kilometer-second notation)} \tag{3}$$

$$F_{\substack{\text{electrostatic}\\ \text{linear}}} = \pi R'^2 \frac{2\epsilon v V_P}{z_o^2} \quad \text{(mks notation)} \tag{4}$$

These forces can be produced by application of a pressure differential across the diaphragm, tilting of the capacitive displacement transducer on its side, or by application of a voltage to one or both sides of the differential capacitor while the diaphragm is grounded. Landau and Lifschitz[19] have derived formula (2) and Cope[11] has given formulas (3) and (4), including their first-order corrections. These four equations are the basis of all operation and calibration methods used for capacitive displacement transducers. Figure 2 illustrates these forces for a simplified capacitive displacement transducer.



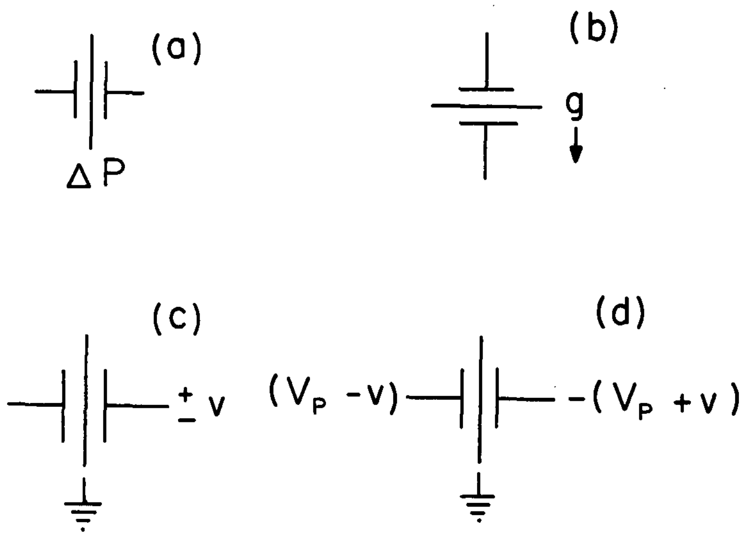


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Fig. 1. Symmetrical capacitive displacement transducer.

Fig. 2. Forces acting on a capacitive displacement transducer: (a) mechanical; (b) gravitational; (c) electrostatic, nonlinear; (d) electrostatic, linear.

B. Bridge

Figure 3 is a simplified picture of a capacitance bridge with two resonant arms. The two variable capacitors in the lower bridge arms are the two sides of a differential capacitor that senses pressure changes. The relation between the input voltage E and the output voltage e for the bridge is given by the formula

$$\frac{e}{E} = \frac{e_A - e_B}{E} = \frac{R_1 + j\omega L_1 + 1/j\omega C_1}{R_1 + j\omega L_1 + 1/j\omega C_1 + 1/j\omega C_3} - \frac{R_2 + j\omega L_2 + 1/j\omega C_2}{R_2 + j\omega L_2 + 1/j\omega C_2 + 1/j\omega C_4} \quad (5)$$

and is subject to the following conditions:

(a) The diaphragm is slightly deflected,

$$\frac{1}{j\omega C_1} \rightarrow \frac{1}{j\omega C_1} + \frac{\Delta C/C_1}{j\omega C_1} \quad (6)$$

$$\frac{1}{j\omega C_2} \rightarrow \frac{1}{j\omega C_2} - \frac{\Delta C/C_2}{j\omega C_2} \quad (7)$$

(b) the bridge arms are tuned,

$$j\omega L_1 = -\frac{1}{j\omega C_1} \quad (8)$$

$$j\omega L_2 = -\frac{1}{j\omega C_2} \quad (9)$$

(c) and the bridge is balanced,

$$\frac{R_1}{1/j\omega C_3} = \frac{R_2}{1/j\omega C_4} \quad . \quad (10)$$

When the ΔC terms in the denominators are neglected, formula (5) simplifies to,

$$\frac{e}{E} = \frac{\Delta C/j\omega C_1{}^2}{R_1 + 1/j\omega C_3} + \frac{\Delta C/j\omega C_2{}^2}{R_2 + 1/j\omega C_4} \quad . \quad (11)$$

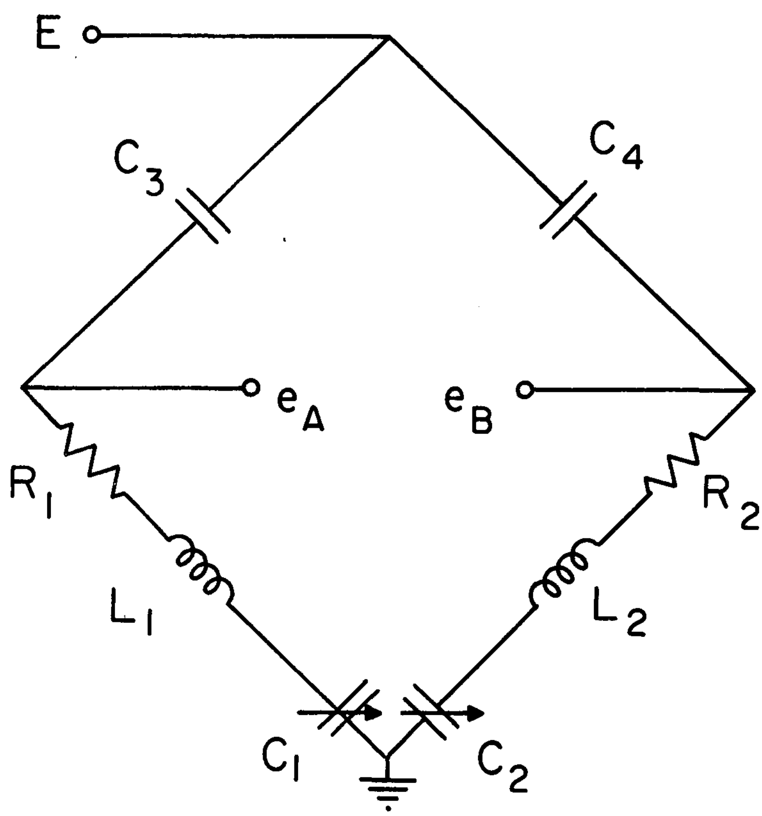

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Fig. 3. Capacitance bridge with two resonant arms. Capacitors C_1 and C_2 are parts of a differential capacitor. The output voltage is $e = e_A - e_B$.

If it is assumed that $R_1 = R_2 = R_c$, $C_3 = C_4 = C'$, anc $C_1 = C_2 = C_o$, then

$$\frac{e}{E} = 2\,\frac{\Delta C/j\omega C_o^{\,2}}{R_c + 1/j\omega C'} \quad . \tag{12}$$

The coil resistance R_c is chosen to be much smaller than the impedance of C', $1/\omega C' \gg R_c$. Therefore, the final simplified bridge formula is

$$\frac{e}{E} = 2\,\frac{C'}{C_o}\,\frac{\Delta C}{C_0} \quad . \tag{13}$$

The bridge output is thus insensitive to small changes in frequency and coil resistance, but is sensitive to changes in L (underived), C_o, and C'. All of the bridge components should therefore have a very low temperature coefficient of impedance.

C. Open- and Closed-Loop Operation

Landau and Lifschitz[19] have derived the formula for the deformation of a circular membrane of radius R placed horizontally in a gravitational field,

$$\zeta = \frac{\rho g h}{4T}\,(R^2 - r^2) \ , \tag{14}$$

where ζ is the displacement, T is the stretching force per unit length of the edge of the membrane, ρ is the density, g is the gravitational constant, and h is the thickness of the membrane. The equivalent formulas for the displacement produced by either mechanical or electrostatic forces can be obtained by replacing the "gravitational pressure" in Eq. (14) by its equivalents from formulas (1), (3), and (4).

The displacement of the point $r = 0$, which results from a pressure differential across the membrane, is defined by Cope[11] as

$$\Delta z = \frac{R^2}{4T}\,\Delta P \quad . \tag{15}$$

This formula can be written in terms of the total mechanical force acting on the diaphragm,

$$\Delta z = \frac{1}{4\pi T} F_{mechanical} . \qquad (16)$$

To a first order in Δz, the change in capacitance on one side of the symmetrical capacitive transducer is

$$\Delta C = - \frac{K C_o \Delta z}{2 z_o} , \qquad (17)$$

where

$$C_o = \frac{\epsilon \pi R'^2}{z_o} \quad \text{(mks notation)}, \qquad (18)$$

and

$$K = \left(\frac{R}{R'}\right)^2 \left\{ 1 - \left[1 - \left(\frac{R'}{R}\right)^2 \right]^2 \right\} \doteq 2 - \left(\frac{R'}{R}\right)^2 . \qquad (19)$$

This capacitive unbalance on each side of the pressure transducer produces from the bridge an output signal e,

$$e = 2 E \frac{C'}{C_o} \frac{\Delta C}{C_o} , \qquad (13)$$

which is then amplified. The final voltage v

$$v = A e \qquad (20)$$

is recorded, measured with a voltmeter, or shown as a signal on an oscilloscope.

The expressions (13), (17), and (20) can be summarized by a single formula relating the output voltage v and the pressure differential ΔP

$$v = A \frac{E C' K}{C_o z_o} \frac{R^2}{4T} \Delta P = A \alpha \gamma \Delta P , \qquad (21)$$

where

$$\gamma = \frac{E\ C'\ K}{C_o z_o} \tag{22}$$

and

$$\alpha = \frac{R^2}{4T}\ , \tag{23}$$

as defined previously by Cope. Equation (21) describes the system in open-loop operation, i.e., no feedback control. The open-loop gain is defined as the quantity $A\ \alpha\ \gamma$.

In closed-loop operation, the output signal is applied in a feedback loop to restore the diaphragm to its null position. This can be done by any one of several ways. For instance, with the assumption that the total gravitational force is always larger than the maximum total mechanical force, the output voltage v can be applied to a servomechanism that tilts the plane of the diaphragm to some angle θ with respect to the vertical. The effective displacement at any instant is given by the difference between the total mechanical and gravitational forces

$$\Delta z = \frac{1}{4\pi T}\left(\pi R^2\ \Delta P - \pi R^2\ \rho g h \sin\theta\right) = \frac{R^2}{4T}\left(\Delta P - \rho g h \sin\theta\right)\ . \tag{24}$$

Sin θ is dependent upon the voltage v applied to the servomechanism

$$\sin\theta = M_1\ v\ , \tag{25}$$

where M_1 is the appropriate porportionality constant. With Eq. (21) defining v formulas (24) and (25) simplify to

$$\Delta z = \frac{\alpha\ \Delta P}{1 + A\ \alpha\ \gamma\ \eta}\ , \tag{26}$$

where η is defined as

$$\eta = \rho g h\ M_1\ . \tag{27}$$

Equation (21) is used again to give the final formula for the closed-loop operation of the pressure gauge,

$$v = \frac{A\ \alpha}{1+A\ \alpha\ \gamma\ \eta}\,\Delta P \quad . \tag{28}$$

The closed-loop gain is defined as the quantity $A\,\alpha\,\gamma\,\eta$. If this quantity is considerably greater than one ($A\,\alpha\,\gamma\,\eta >> 1$), formula (28) simplifies to

$$v = \frac{\Delta P}{\eta}\ , \tag{29}$$

and is thus independent of changes in A, α, or γ. This illustrates the utility of a closed-loop system.

A more practical method of closing the loop is by use of an electrostatic force to null the diaphragm. The formula analogous to (24) is, for the case of a linear electrostatic force,

$$\Delta z = \frac{1}{4\pi T}\left(\pi R^2\,\Delta P - \frac{2\epsilon v V_P}{z_o^2}\,\pi R'^2\right) = \frac{R^2}{4T}\left(\Delta P - \left(\frac{R'}{R}\right)^2 \frac{2\epsilon v V_P}{z_o^2}\right) \ . \tag{30}$$

The voltage V_P is a "polarizing" voltage that is applied equally to both sides of the symmetrical capacitive transducer. Equation (21) can be used once more to give the final formula for the closed loop-operation of the pressure gauge,

$$v = \frac{A\ \alpha}{1+A\ \alpha\ \beta\ \gamma}\,\Delta P\ , \tag{31}$$

where

$$\beta = \left(\frac{R'}{R}\right)^2 \frac{2\epsilon V_P}{z_o^2}\ , \qquad \text{(mks notation)} \tag{32}$$

which is not the same as Cope's formula (25),

$$\beta = \frac{2\epsilon V_P}{z_o^2}\ . \qquad \text{(mks notation).} \qquad \text{(Cope 25)}$$

If $A\,\alpha\,\beta\,\gamma >> 1$, Eq. (31) simplifies to

$$v = \frac{\Delta P}{\beta}\ . \tag{33}$$

The total open-loop gain is

$$A \alpha \beta \gamma = A \frac{EV_P}{2\pi z_o^2} \frac{K C'}{T} , \quad \text{(mks notation)}, (34)$$

instead of

$$A \alpha \beta \gamma = A \frac{EV_P}{2\pi z_o^2} \frac{K C'}{T} \left(\frac{R}{R'}\right)^2 \quad \text{(mks notation)},$$

as was given by Cope's Eq. (30).

The operation of the open- and closed-loop system is shown schematically in Fig. 4. I have repeated the entire derivation in this section to emphasize the correct forms of Eqs. (32) and (34). Since the final output voltage is inversely proportional to β, a change in the functional form of β has a profound effect on the way the initial capacitive transducer must be designed. This correction also makes the total loop gain rather insensitive to the ratio of diaphragm and electrode radii R/R'. Finally, since Cope's Eq. (25) is incorrect, the calculated value for β in Sec. II.2 of his article is also incorrect. The agreement between his experimental and calculated values is fortuitous, as he indicated.

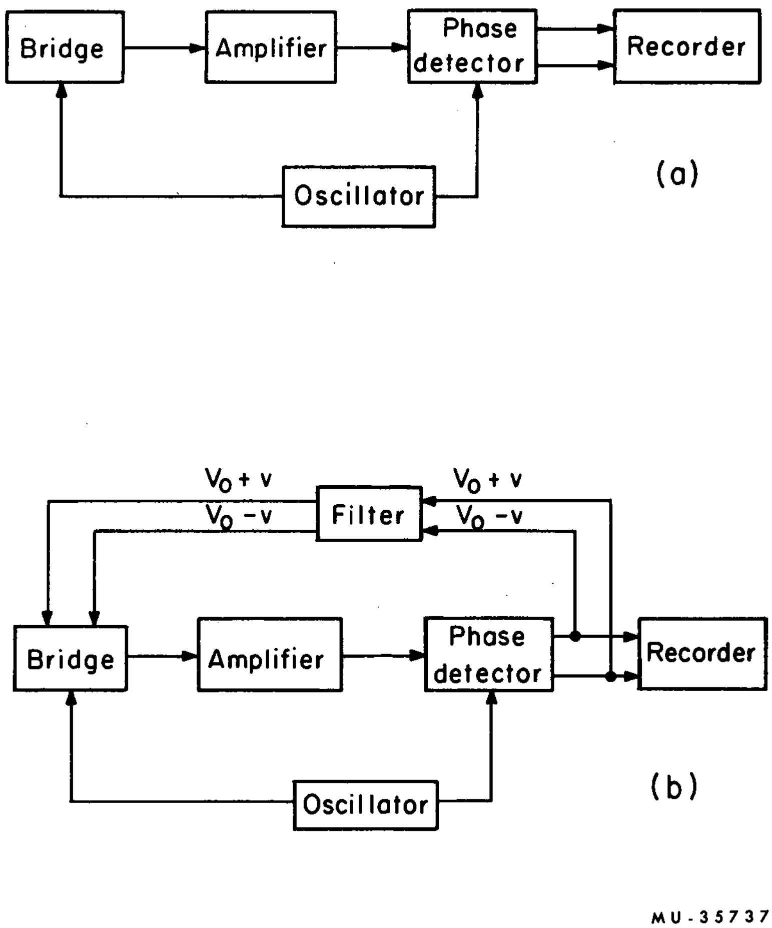

Fig. 4. Open- and closed-loop operation of the differential micromanometer: (a) open loop; (b) closed loop.

III. DESIGN AND CONSTRUCTION OF CAPACITIVE DISPLACEMENT TRANSDUCERS

A. Transducer No. 1

To test the micromanometer electronics (see Sec. IV and Ref. 18), I constructed a differential pressure transducer whose electrode-to-diaphragm spacing could be varied (Fig. 5). The diaphragm material was 1/2-mil Mylar with aluminum vapor plated on both sides.[20] The movable electrodes were of brass, the diaphragm-housing rings of aluminum, and the cover plates of Lucite. Figure 6 is a photograph of the completed unit.

The tests of the transducer with the associated electronics were not very informative. For example, the thermal stabilities of the room and especially the transducer were too poor for a good null to be maintained for long. Consequently, I was able to demonstrate only that the entire micromanometer worked as planned, that the loop could in principle be closed, and that there was a slight error in the derivation for the closed-loop operation of the system (see Sec. II and Ref. 11). After these tests were finished, I abandoned this transducer.

The poor thermal stability of the transducer was owing to the buckling and distortion of the Lucite cover plates, whose movements caused the attached brass electrodes to change positions slightly. The thermal coefficient of capacitance for each side was about 2.5 pF/°C, or 3.3%/°C.

B. Transducer No. 2

The four main components of the second capacitive displacement transducer were (a) the Mylar diaphragm, (b) the diaphragm-housing rings, (c) the gold-plated ceramic electrodes, and (d) the cover plates.

A sketch of the aluminum diaphragm-housing rings is shown in Fig. 7, together with an enlarged picture of the mating peak-and-groove fitting used to hold the diaphragm tight. Holes were provided in the diaphragm-housing rings for pressure ports, a bypass valve, and the

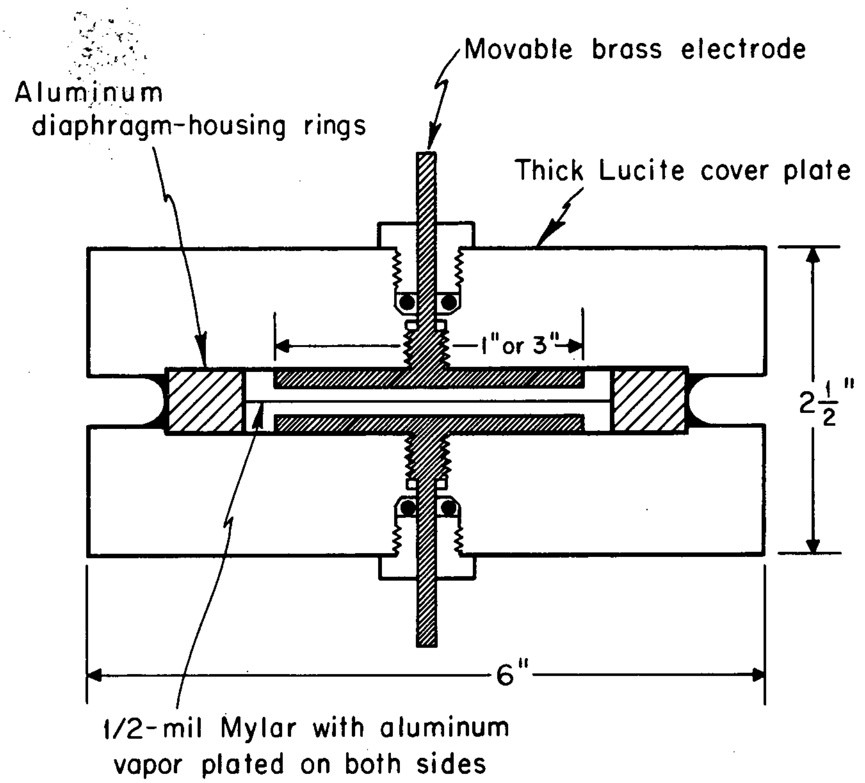

Fig. 5. Simplified sketch of transducer No. 1.

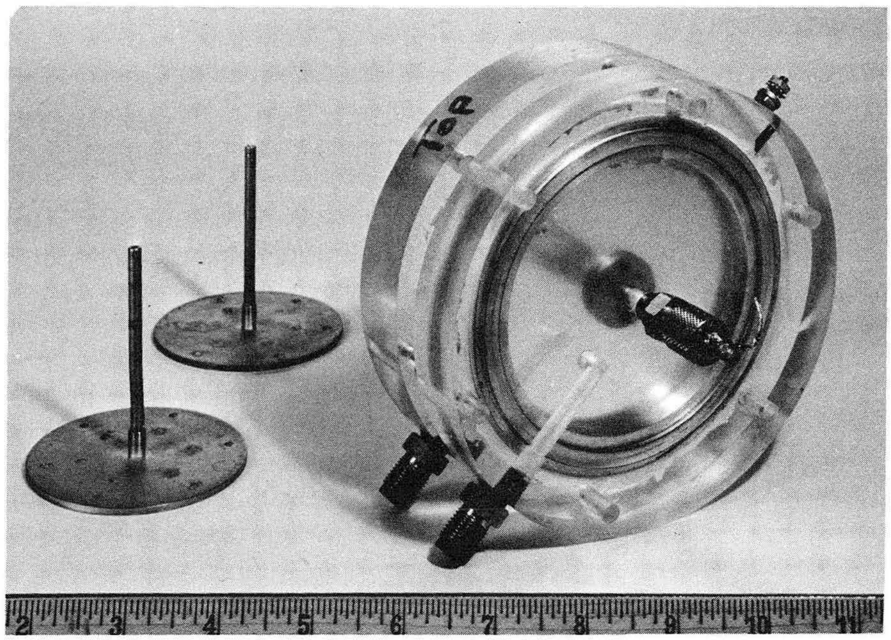

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Fig. 6. Photograph of transducer No. 1

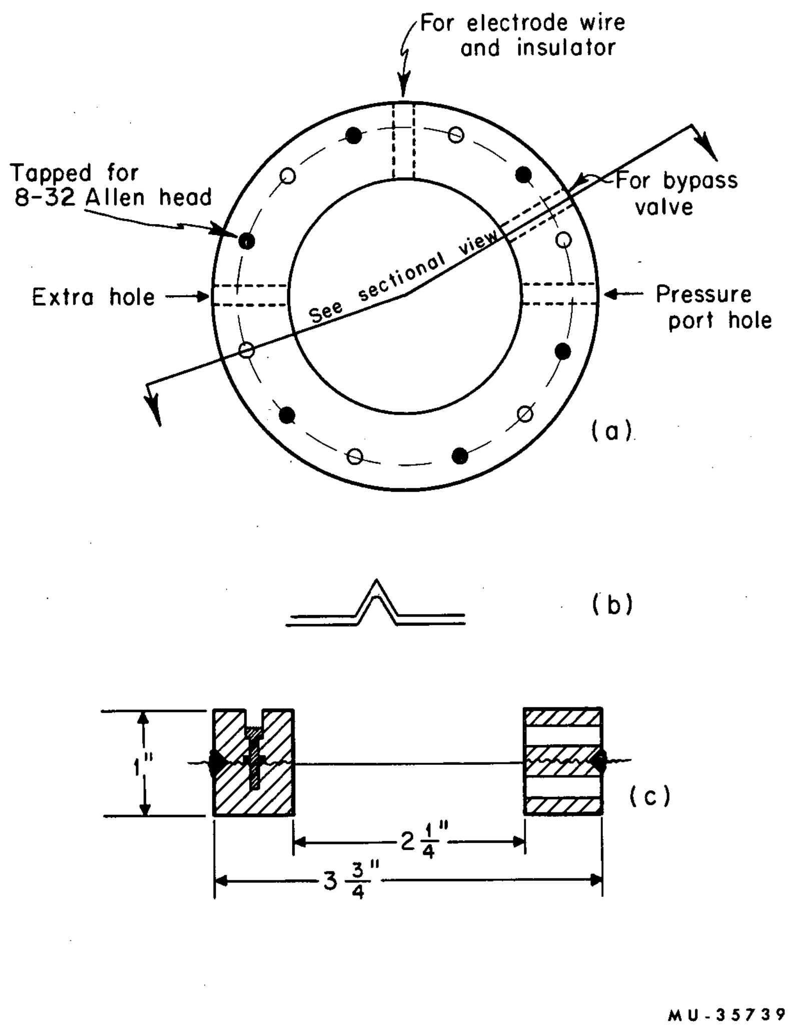


Fig. 7. Sketch of diaphragm-housing rings: (a) top view; (b) mating peak-and-groove fitting to hold diaphragm; (c) sectional view.

wires to the gold-plated electrodes. The diaphragm was clamped between the two aluminum rings and the Allen-head screws tightened to make the assembly permanent and the diaphragm taut. Use of a razor blade eliminated the excess Mylar from the shallow V-shaped groove on the outside of the rings, which was subsequently filled with red enamel (G.E. 1201 Glyptal) to provide a vacuum-to-atmosphere seal.

The membrane material was a 1/2-mil Mylar film with aluminum vapor-plated on both sides. The Mylar was quite flexible and showed remarkable resistance to tearing and to forming nicks and pinholes. The only problem I observed while using it was the abrasion of the vapor plate by sharp corners on the diaphragm-housing rings and by the semi-smooth surfaces of the ceramic-electrode pieces. This abrasion produced rings that eventually left the inner part of the diaphragm electrically isolated from ground. I eliminated the problem by filing grooves in the mating diaphragm-housing rings and by sanding down the ceramic electrode pieces in the same region. I also painted the aluminum surface on the Mylar with clear acrylic spray paint (Kerpro K-39).

The fixed electrode on each side of the differential capacitor was a 3/8-inch-thick cylindrical piece of AD-85 alumina with a 0.002-inch depression on one side. The electrical connection, a small copper rod, was glued into place in a hole drilled through the alumina so that the surface of the copper extended to within 0.002-in. of the depression surface. A coat of silver-conducting paint was applied to the copper rod and the surrounding alumina region to provide a good electrical contact for a vapor-plated film of gold with a thickness of about 5000 Å and a radius of 27/32 in.

On the side opposite the depression, a circular groove 1/4-in. wide and 3/16-in. deep was provided for some Essex Wee-Ductors—rf chokes used to tune the electrode-to-diaphragm capacitance. I included them within the pressure transducer instead of external to it to facilitate the thermal regulation of the entire transducer and thus improve the bridge stability.

After the grinding and drilling, but before applying the gold vapor plate, the ceramic piece was sintered. The sintering process had no measurable effect on the flatness of the 0.002-in. depression. A sketch of the ceramic electrode piece is shown in Fig. 8.

The gold films of the ceramic pieces were checked for high spots and then mounted directly on both sides of the diaphragm inside the diaphragm-housing rings. If any high spots were present, they were gently scraped off. The rf chokes were gently soldered to the copper rod and the wires extended through the holes in the diaphragm housing by means of ceramic spacers, which provided both insulation and rigidity for the wires. Aluminum cover plates (Fig. 9) were then screwed down on O-rings (M.S. 29513 No. 130 and 6230 No. 8) provided to apply (a) pressure on the ceramic pieces and (b) a vacuum-to-atmosphere seal, respectively. Viton O-rings were used to minimize outgassing. Finally, the glass pressure ports and copper tubing for a Hoke bypass valve were glued in their respective places in the diaphragm-housing rings with the aid of a viscous, white, fast-curing epoxy resin (Armostrong Products Co. Type A-2 Adhesive).

Photographs of the diaphragm, diaphragm-housing rings and cover plates (Fig. 10), the ceramic electrode piece (Fig. 11), and a closed unit complete with bridge assembly (Fig. 12) are shown.

In anticipation of inequalities in the depth of the 0.002-in. depression and in the flatness of the rims, six ceramic pieces were initially made. The capacitance between the gold surface and a flat rigid aluminum surface was determined and a pair with nearly identical values of capacitance was chosen. Unfortunately, the members of the first pair did not match each other too well when pressed together and tightened within the transducer housing. I observed large changes in the capacitance value of both sides when I fiddled with the Allen-head screws in the cover plate. These changes were presumably due to deviations from flatness of the outer rims of the ceramic pieces. By trial and error, I found another pair that had excellent thermal stability. With this pair slight readjustments of the Allen-head screws in the cover plates had no significant effect on the capacitance value of either side. To within the errors of the L-C meter (Tektronix Type 130), I observed no

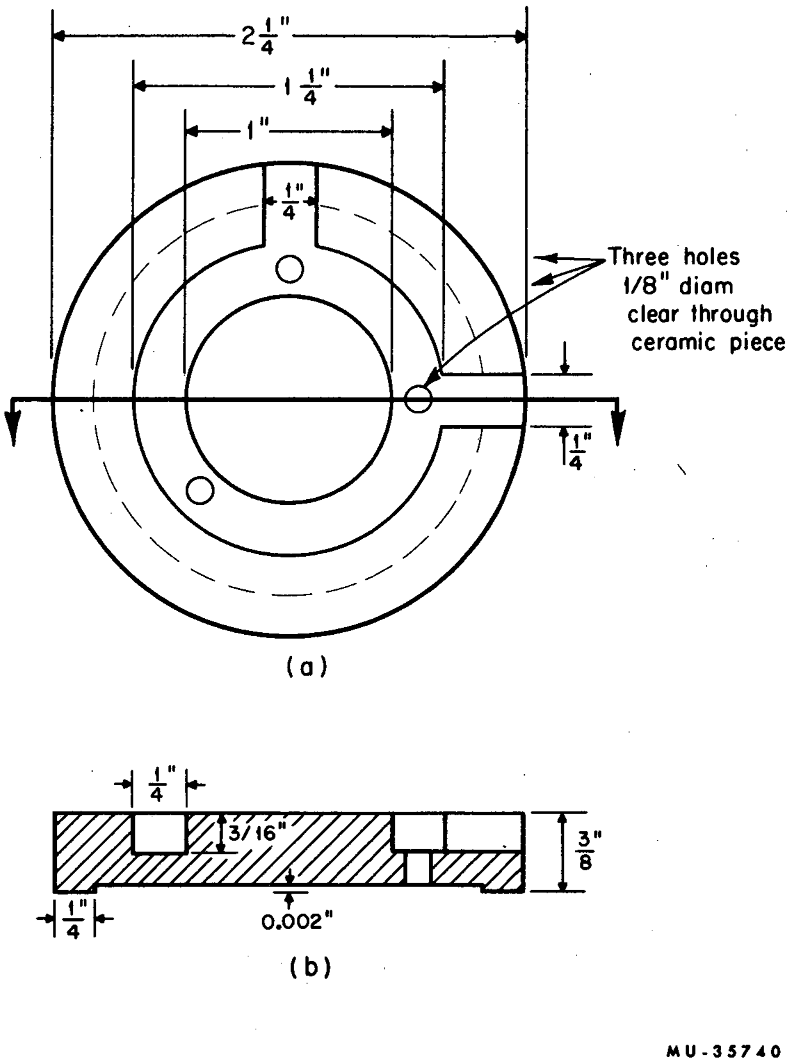
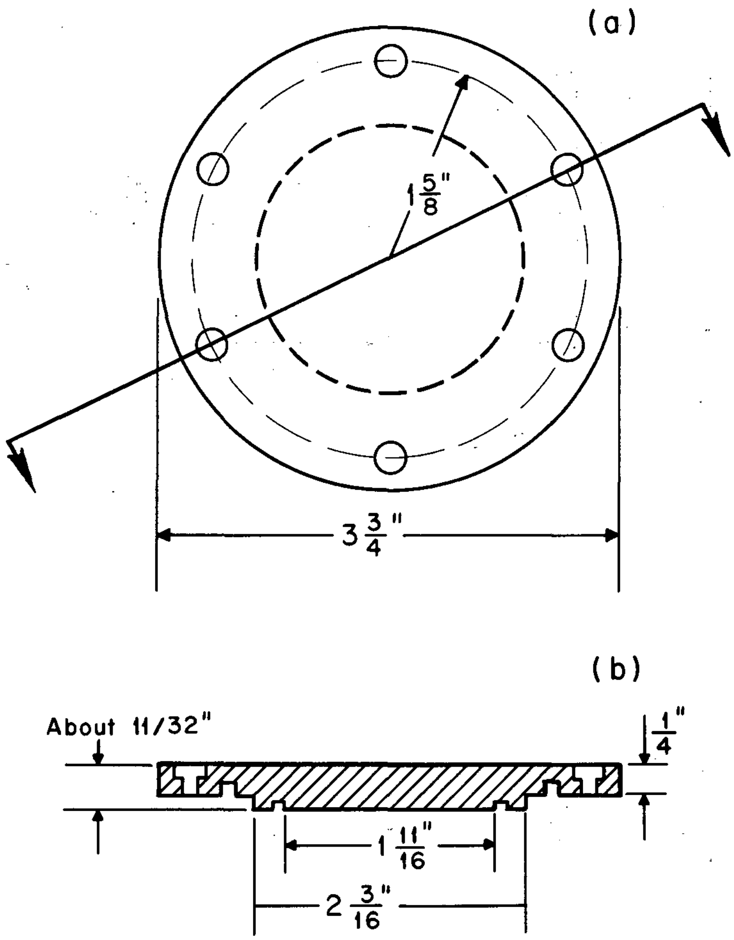


Fig. 8. Sketch of ceramic fixed-electrode piece: (a) top view; (b) sectional view.



9. Sketch of cover plate: (a) top view; (b) sectional view.

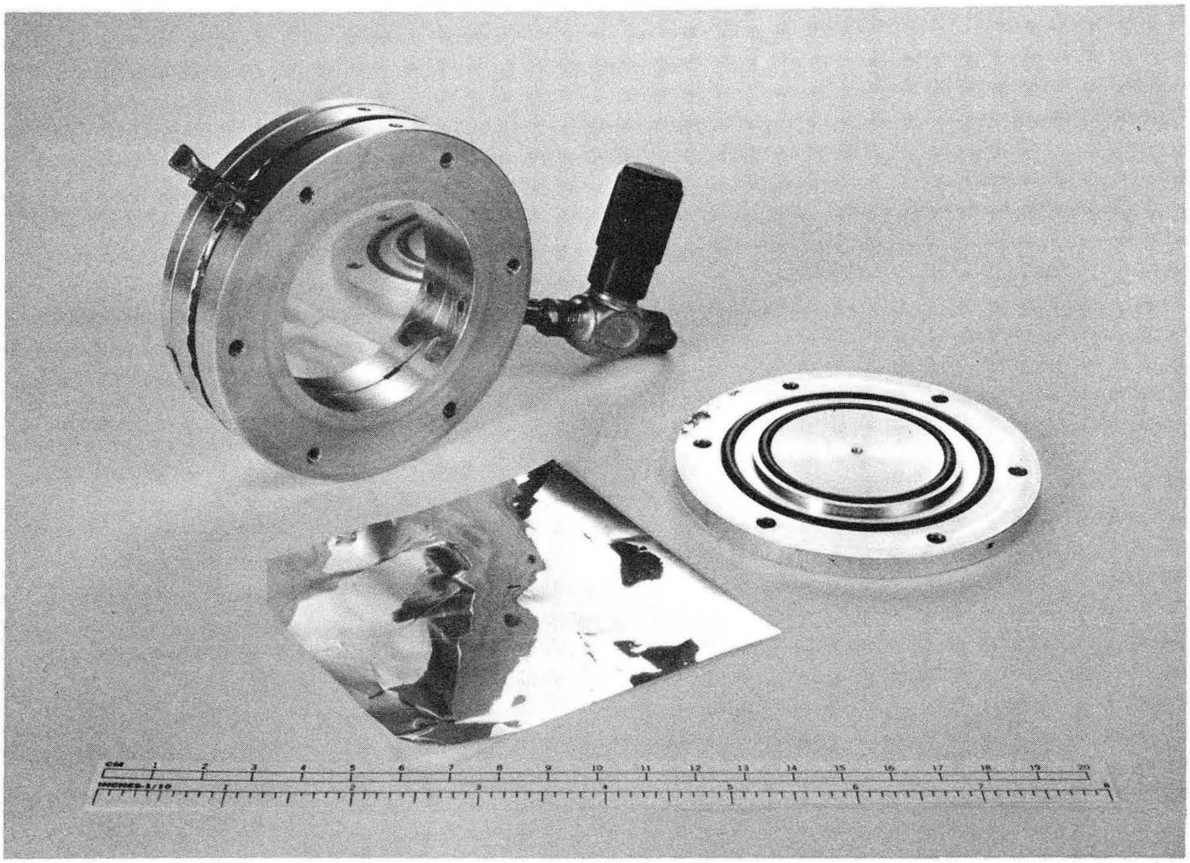


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Fig. 10. Photograph of diaphragm, diaphragm-housing rings, and cover plate.

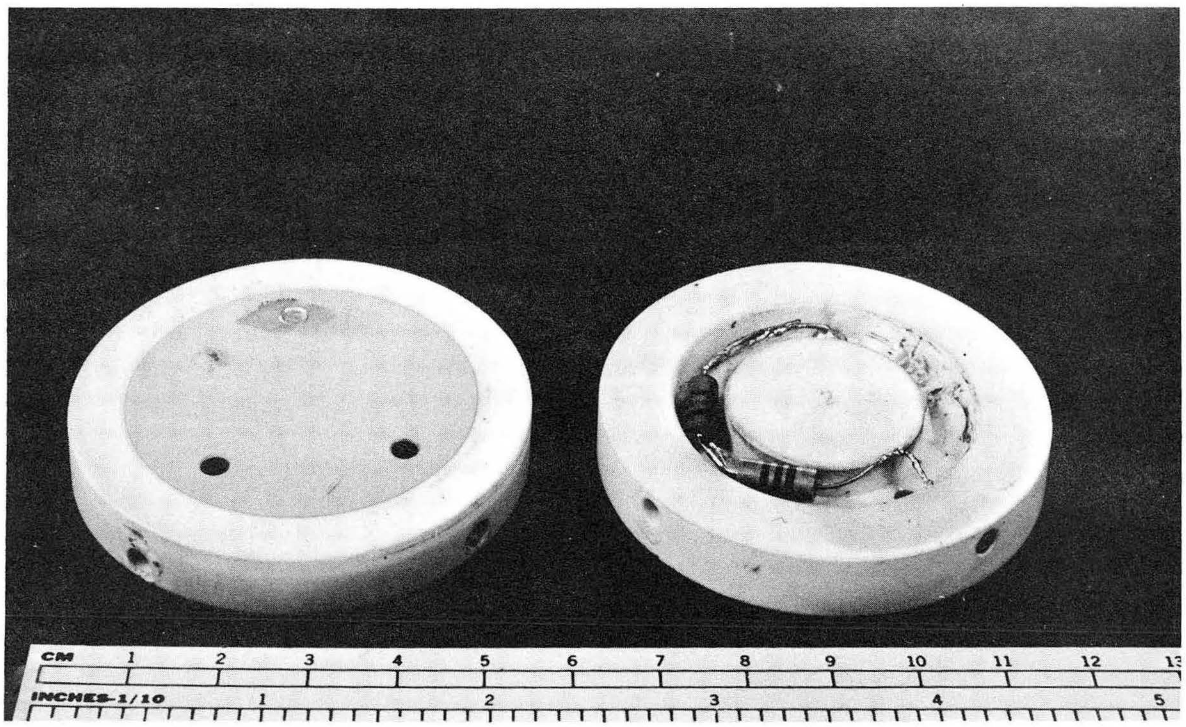

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Fig. 11. Photograph of ceramic fixed-electrode piece.

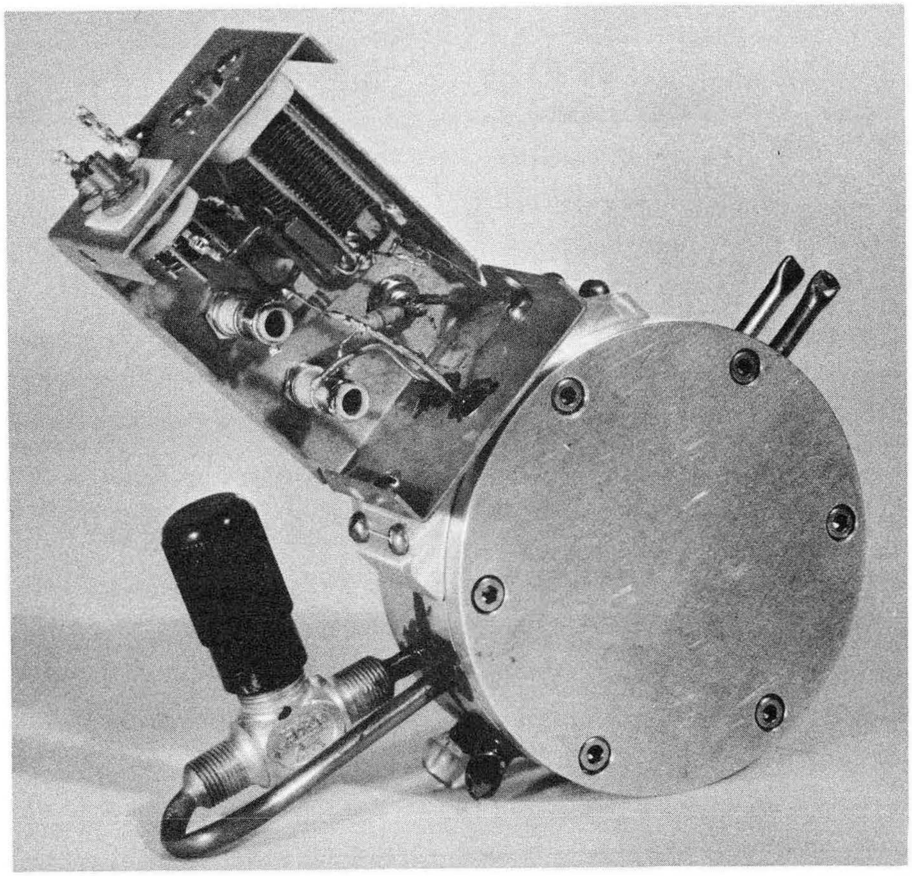

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Fig. 12. Photograph of closed transducer No. 2 with bridge assembly on top.

capacitance change in either side between 0°C and 28°C. If 1 pF was the error in these capacitance measurements, then each side had a stability of better than 1 part in 7500 per °C, a value which is quite reasonable.

I would like to make a few suggestions to improve the design of this transducer. First, the grooves for the Essex Wee-Ductors can be eliminated. These rf chokes appear to have a poor temperature coefficient of inductance and can be replaced by inductors wound on coil forms (National Radio XR50) and connected in the bridge assembly external to the transducer unit. Secondly, glass with a low thermal coefficient of expansion can probably be substituted for the ceramic pieces. It may be easier to grind glass to produce two matching pieces than to grind and sinter alumina.

As a third and more important suggestion, I would avoid constructing the transducer and purchase a commercially manufactured one. With the proper facilities and talents initially available, the time spent machining the aluminum pieces, making the ceramic pieces, vapor plating the gold, and assembling the entire unit was about 50 hours. For no more than $300—and perhaps less—a transducer can be purchased from the Decker Instrument Corporation; such a transducer behaves, in open-loop operation, better than the one I constructed for closed-loop operation. The open-loop system was eventually used in preference to the closed-loop one.

Finally, with further improvements in commercial micromanometers, a homemade system may be completely unnecessary.

IV. DESIGN AND CONSTRUCTION OF THE ELECTRONICS

Since the design and construction of the electronics have already been described in Part I of this report,[18] they are not summarized here. The circuit diagrams and several of the photographs of the completed unit and its components are included from the preceding report (Figs. 13 to 18).

A. Power Supply

During the testing and operation of the power supply, certain improvements were made. The unit initially was plugged directly into the line. This resulted in a dc drift, in both the 125- and 75-V power-supply outputs, that was visible in the final recorder tracing as a slow fluctuation. By use of a Sola Constant Voltage Transformer with semi-square-wave output, this drift was eliminated and the operation of the entire electronics unit considerably improved. The Zener diodes were also readjusted to prevent operation problems resulting from insufficient plate voltage to the Nuvistors. The power-supply diagram (Fig. 15) has already been modified to reflect the changes made.

B. Oscillator

A variable differential capacitor (E. F. Johnson Co. No. 160-303), 0.5 to 5.0 pF, was placed in parallel with the 4.5 to 100 pF differential capacitor (No. 148-306) already present. This new capacitor was extremely useful in fine-tuning adjustments.

The upper part of the bridge was temporarily removed from the oscillator housing and placed in the transducer housing in anticipation of efforts to thermally regulate the environment of the transducer and bridge. The high capacitance of the cable from the oscillator to the bridge forced me to decrease the number of turns in L2 (Fig. 13). As the performance of the entire system was excellent without the use of thermal regulation, the upper part of the bridge was replaced in the oscillator housing and the value of L2 increased again.

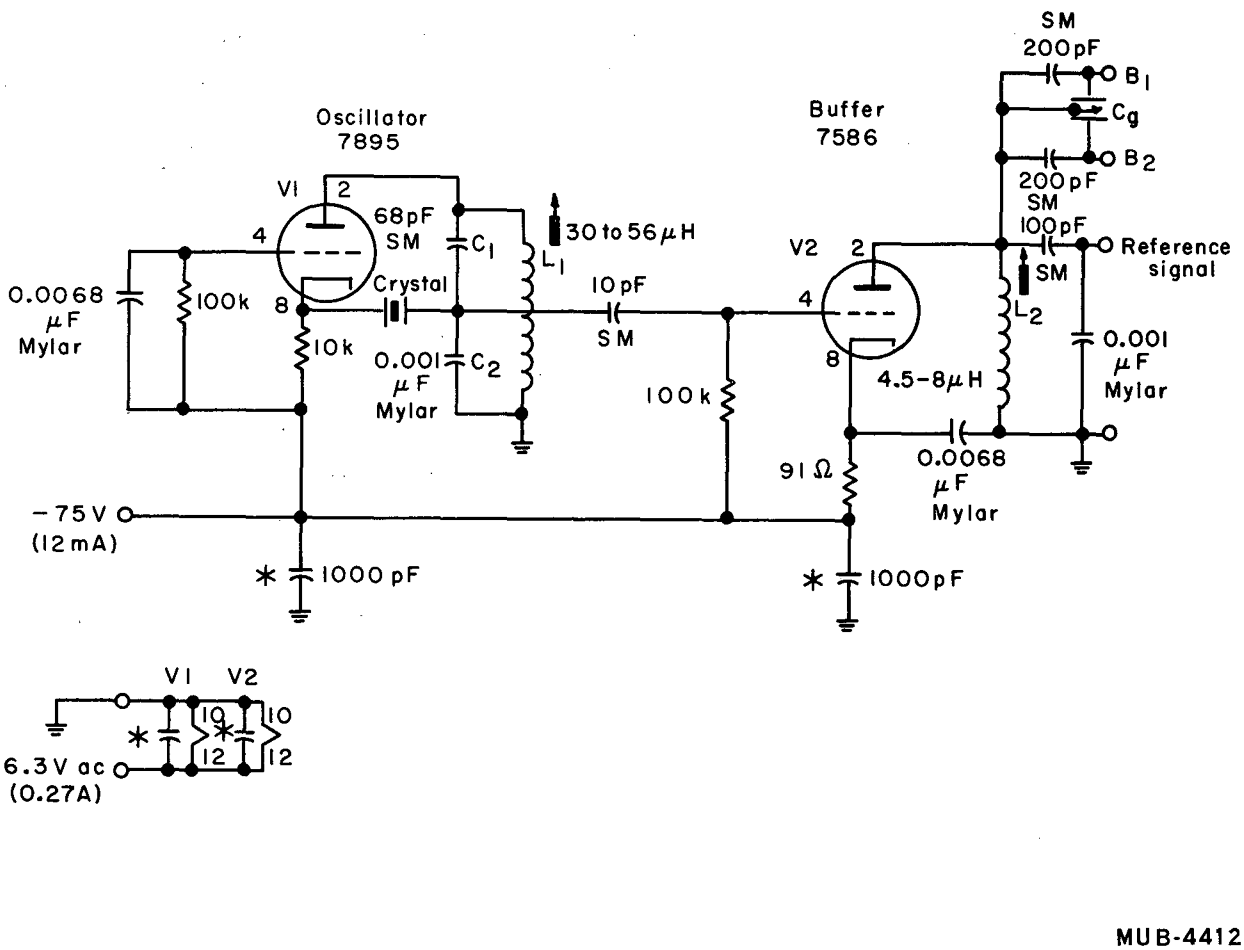

Fig. 13. Schematic diagram of the generator. All resistors are 1/4 W. Inductance L_1 comprises 64 turns of No. 32 Formvar wound on National Radio Corp. form XR50; L_2 is 25 turns of No. 22 Formvar wound on form XR50. The crystal (type CR-18/U) operates at 2762.500 kc/sec. C_g is a 4.5- to 100-pF differential variable air capacitor, type S, No. 148-306 manufactured by E. F. Johnson Co. Capacitors marked with an asterisk are 1000-pF ceramic feed-through type; those indicated by SM are silver-mica. Tubes V1 and V2 are Nuvistors.

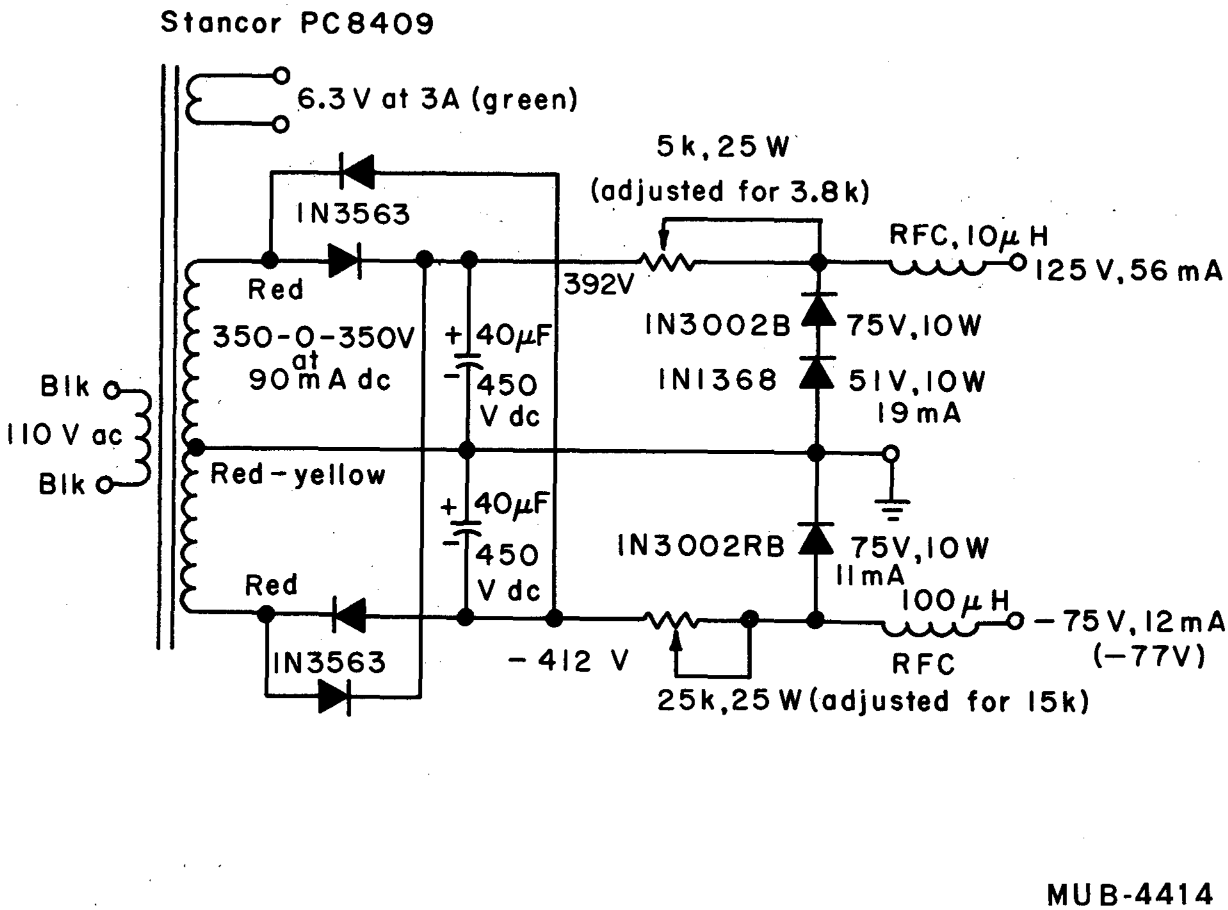

Fig. 14. Schematic diagram of the null detector. The 27k resistors are 1/2 W; all others are 1/4 W. Asterisks denote 1000-pF ceramic feed-through capacitors, C_d is a 4- to 30-pF ceramic trimmer, all other pF capacitors are silver-mica, and all μF capacitors are Mylar. The 7587 is an RCA Nuvistor. Coils L_1 through L_8 comprise 64 turns of No. 32 Formvar wound on National Radio Corp. form XR50; L_6 is center-tapped. All coils are wound counterclockwise viewed from the tuning end. Inductances L_1 and L_2, L_5 and L_6, L_7 and L_8 are mounted as shown in Figs. 16 and 18 to form transformers.

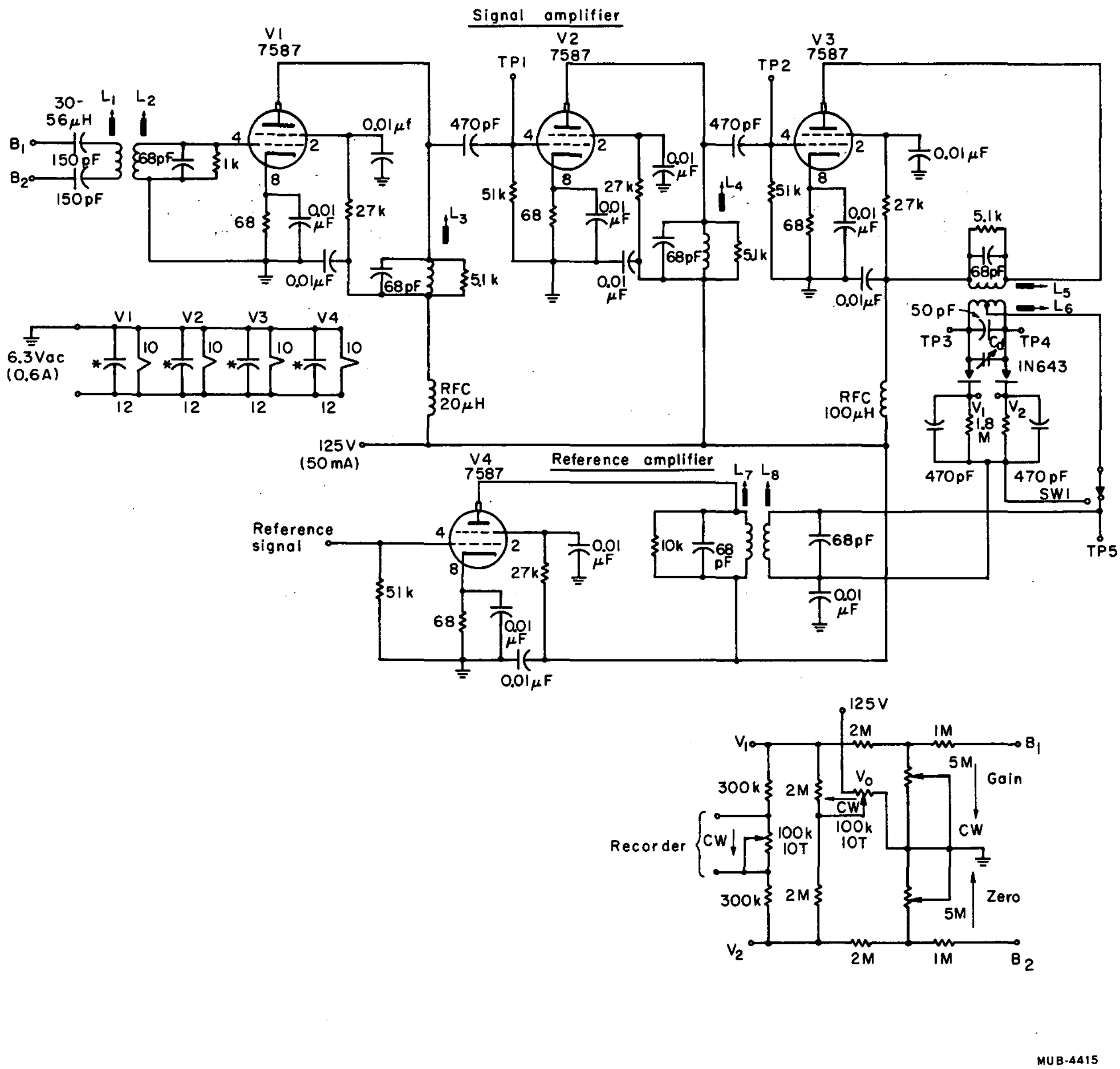

Fig. 15. The power supply. All voltages and currents were measured when operating with a Sola voltage-regulating transformer. Without this transformer, 392 V becomes 453 V, -412 V becomes -486 V, 19 mA becomes 32 mA, and 11 mA becomes 15.4 mA. The 40-μF capacitors should have a 500-V working voltage if the Sola transformer is not used.

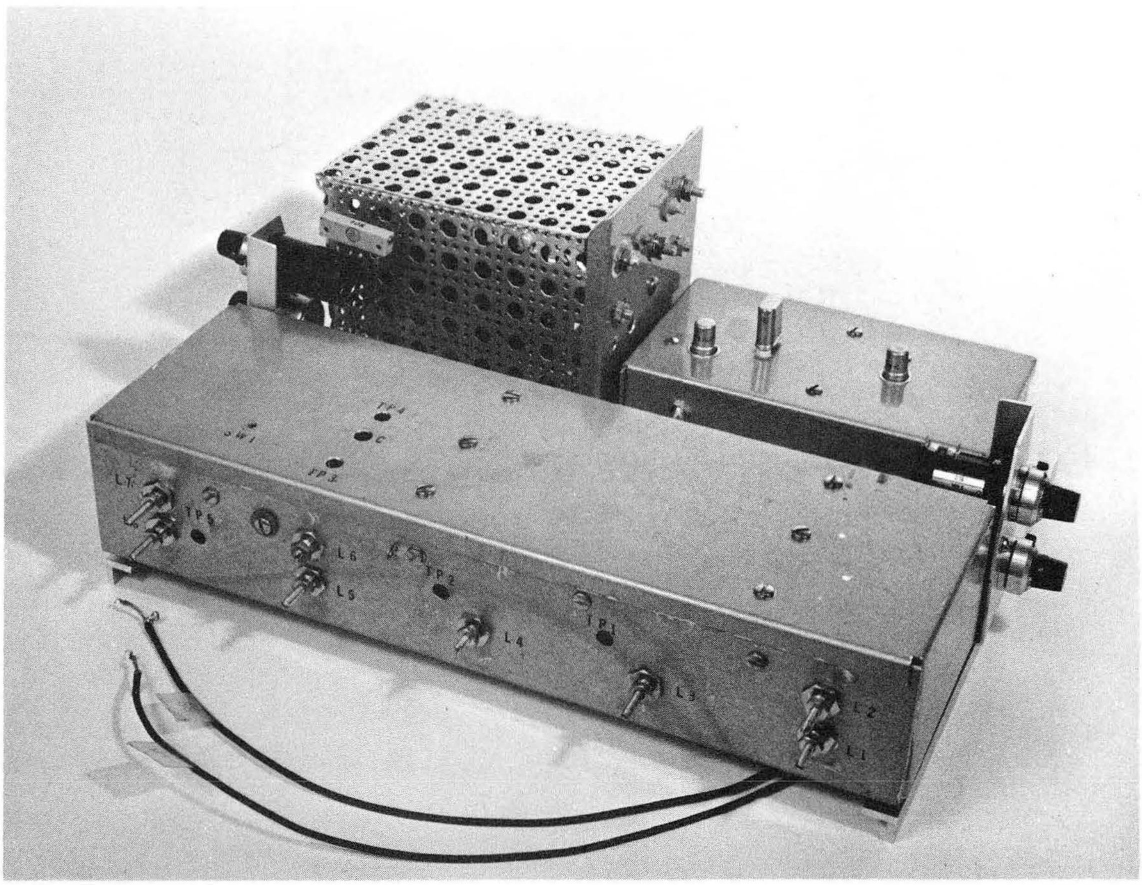

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Fig. 16. Top-front view of the electronics. The remotely located pressure transducer is not shown. Construction is modular. The null detector is in the foreground. The power supply is at left rear; the generator module is to its right.

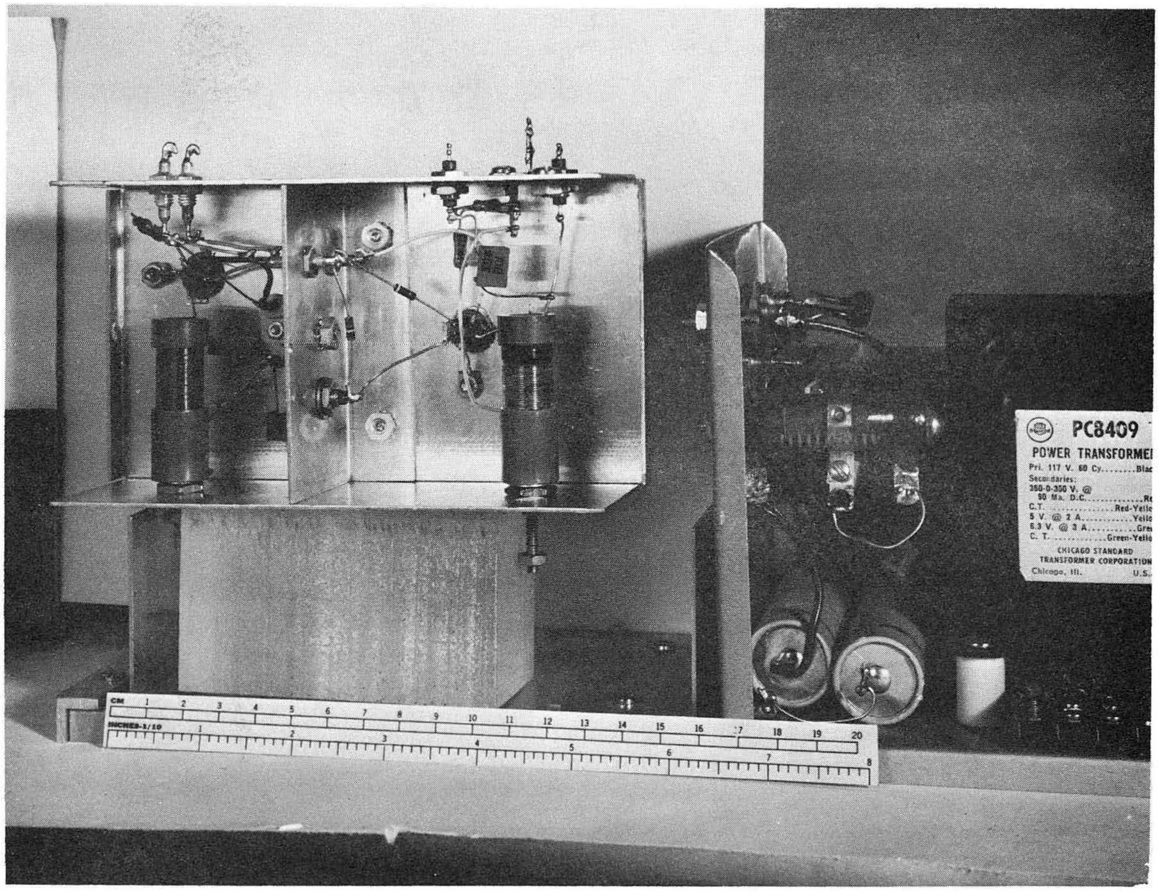

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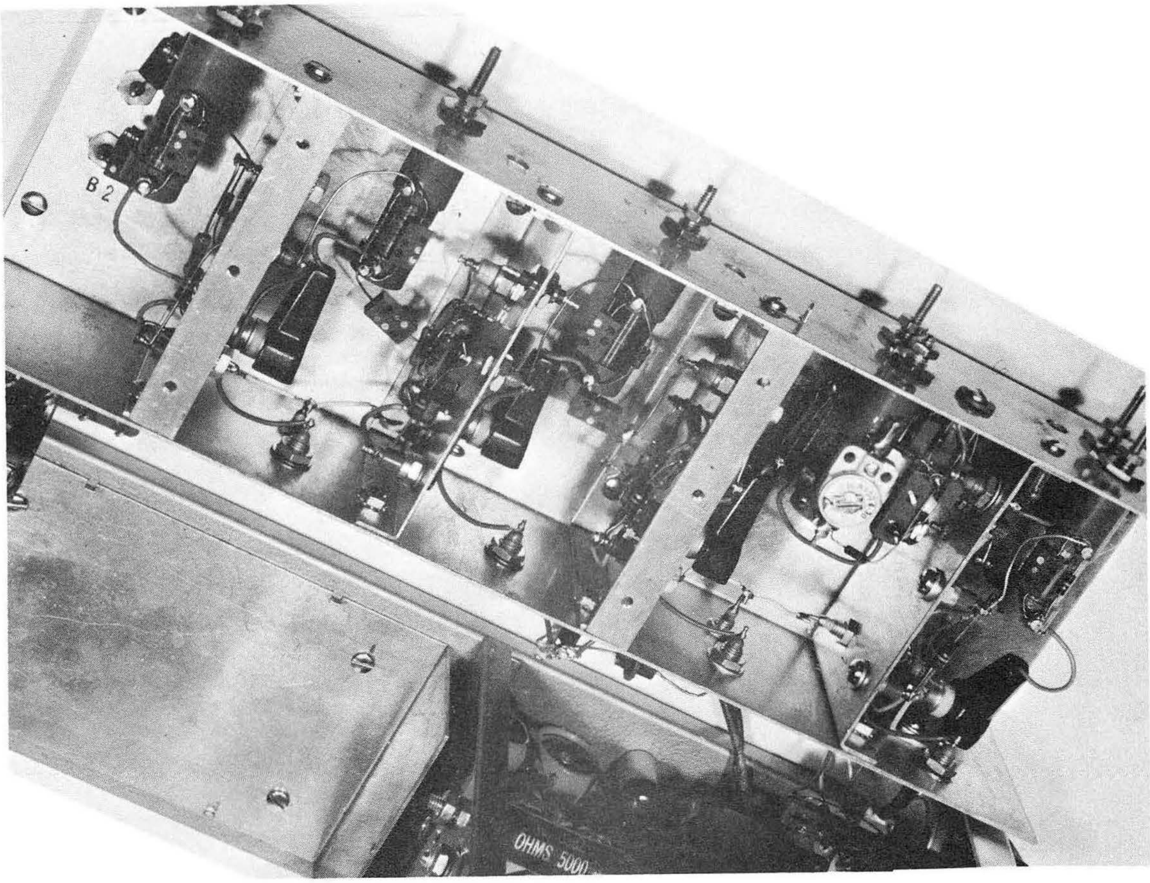
Fig. 17. Generator module tilted so that it can be viewed from underneath. The oscillator compartment is to the left, buffer at right. Upper part of bridge has been removed from oscillator housing.



ZN-4553

Fig. 18. Null detector, top-front view with cover removed. The unit is separated into compartments. It is important that two of the dividing plates (second from left and the one at the right) be tapped to receive screws holding the top cover-plate down. This tapping improves intercompartment shielding, and helps to prevent oscillation.

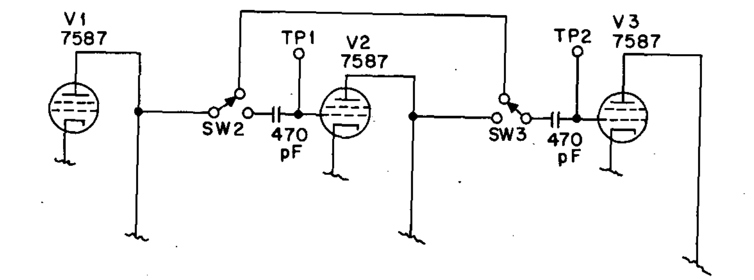
C. Amplifier

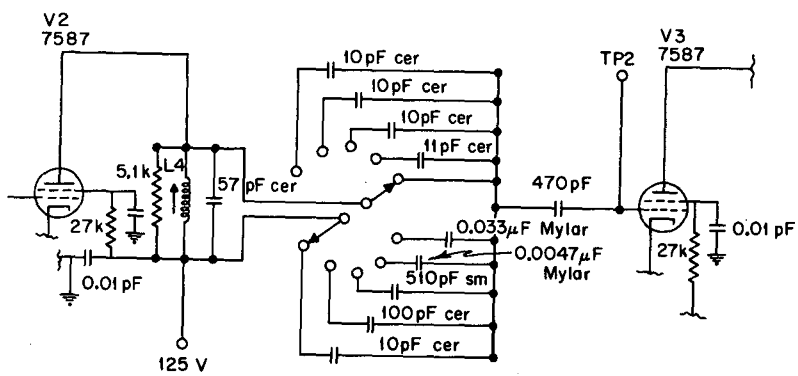
The only change in the amplifier was the inclusion of an attenuator to decrease the signal entering the third Nuvistor and the detector, thus preventing their saturation. Two microswitches were first tried to permit the second Nuvistor stage of the amplifier to be bypassed completely (Fig. 19). The bridge was first nulled with the second state present so I could take advantage of the additional sensitivity. The two switches were then depressed by means of screws through the amplifier housing and the reference-signal inductor, L7, retuned to give maximum recorder output. These switches provided an attenuation factor of ≈ 0.03, but were abandoned in favor of an alternative method of attenuation.

As factors other than 0.03 were desired, a capacitance divider was installed in the resonant circuit of the second Nuvistor stage. A 2-pole 5-position nonshorting steatite rotary switch (Centralab PS-105) produced attenuation factors of approximately 1, 0.1, 0.02, 0.002, and 0.0003 (Fig. 20). It was necessary for me to retune inductors L4 and L7 when changing the attenuation setting from 1 to any other value. Changing from 0.1 to 0.02 or 0.002 required less adjustment of L4 and L7. The attenuation factor of 1 was primarily used to null the bridge.

D. Recorder Output and Closed-Loop Control

The recorder output and closed-loop potentiometer circuit (Fig. 15) were changed to correspond to that of Opsteltin et al.[10] [Fig. 21(a)]. To decrease the output signal and the load of the recorder-output circuit on the detector stage, 1.47-MΩ metal-film resistors were substituted for the 300-kΩ resistors. When the electronics unit was operated open loop, only the recorder resistance divider was needed [Fig. 21(b)]. To eliminate the tendency of the electronics to oscillate parasitically when the loop was closed, two RC filters (time constant 0.1 sec) were included in the feedback loops to the bridge.





MU-35742

Fig. 19. Circuit diagram of stage-bypass switches.

Fig. 20. Circuit diagram of capacitance divider. Small ceramic (cer), mylar, or silver-mica (sm) capacitors are used.

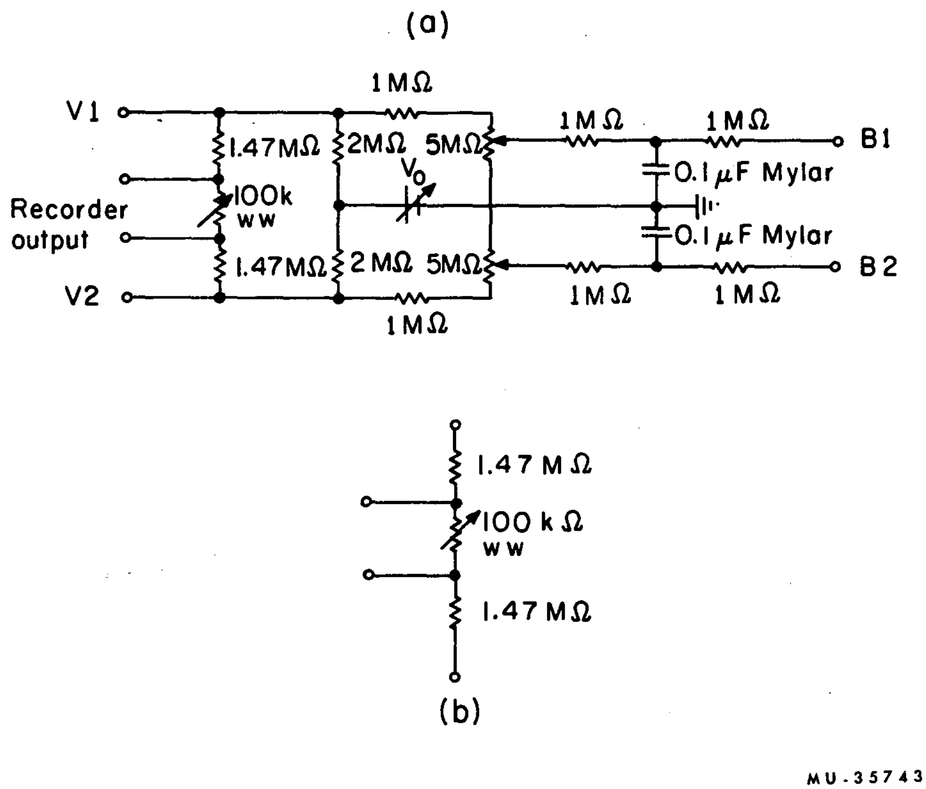


Fig. 21. (a) Recorder output, V_0 and closed-loop controls; (b) recorder output.

A 10-mV recorder (Type G Speedomax) was used in all tests and experiments with the differential micromanometer. As the recorder performs best with an output impedance of 2000 Ω or less, the wire-wound potentiometer setting was generally kept as low as possible.

E. Bridge

As two completely different pressure transducers were used, two separate bridges had to be constructed. For both, the top part of the bridge, located in the oscillator housing, remained the same (Figs. 22 and 23). The first transducer, D1, with a nominal capacitance of 270 pF on each side, required only 12 μH to tune out the capacitance (Fig. 24). The lower part of the bridge was housed in a Minibox (Bud Radio, Inc. CU-2101-A) located on the pressure transducer (Fig. 12). The other transducer (Decker Corporation Model 306-2A) required a shunt capacitance of 68 pF and a series inductance of 40 μH in each of the lower bridge arms (Fig. 25). The 68-pF shunt capacitor reduced the bridge sensitivity by a factor of $C_o/(C_o + C_2) = 0.16$. The aluminum housing of the Decker sensor provided ample room for the lower bridge components (Fig. 26).

The temperature stability of the two bridges was quite good, although no exact measurement of the thermal coefficient was ever attempted. The stability of the Lamers-Rony closed-loop system was somewhat inferior to the Decker-Lamres-Rony open-loop system, probably because of the higher thermal coefficient of impedance in components L1 or perhaps D1 in the Lamers-Rony system.

Table I lists the components given in Figs. 22, 24, and 25.

F. Calibration Procedure

In certain instances, closed-loop operation wasn't possible because one of the transducers (Decker Corporation Model 306-2A) was not sufficiently sensitive as the pressure-sensing element. Thus the

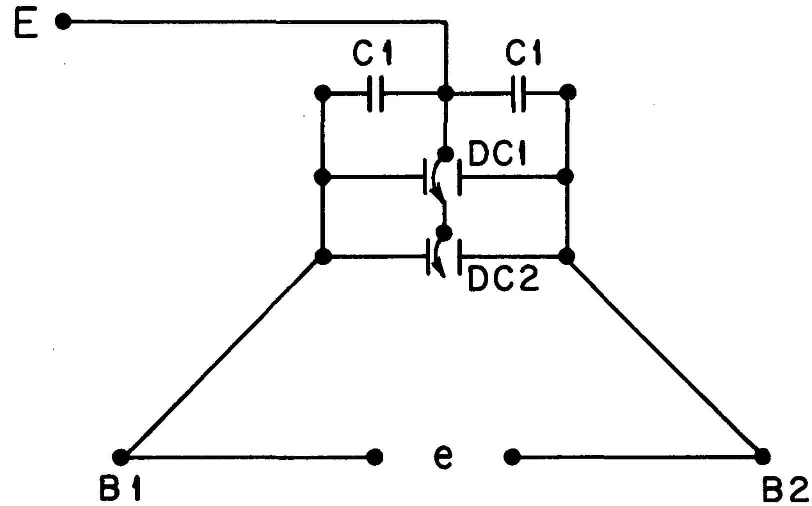


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Fig. 22. Upper part of bridge (located inside oscillator housing).

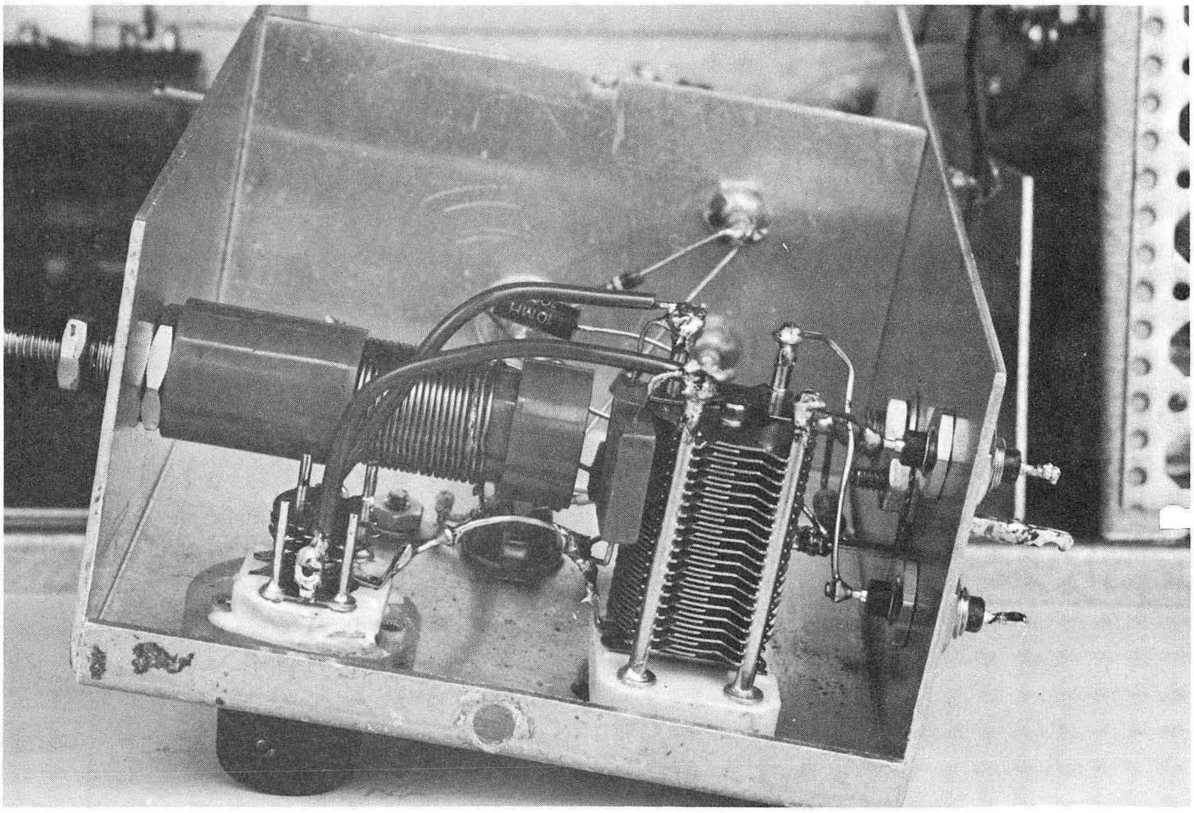

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Fig. 23. Photograph of upper part of bridge.

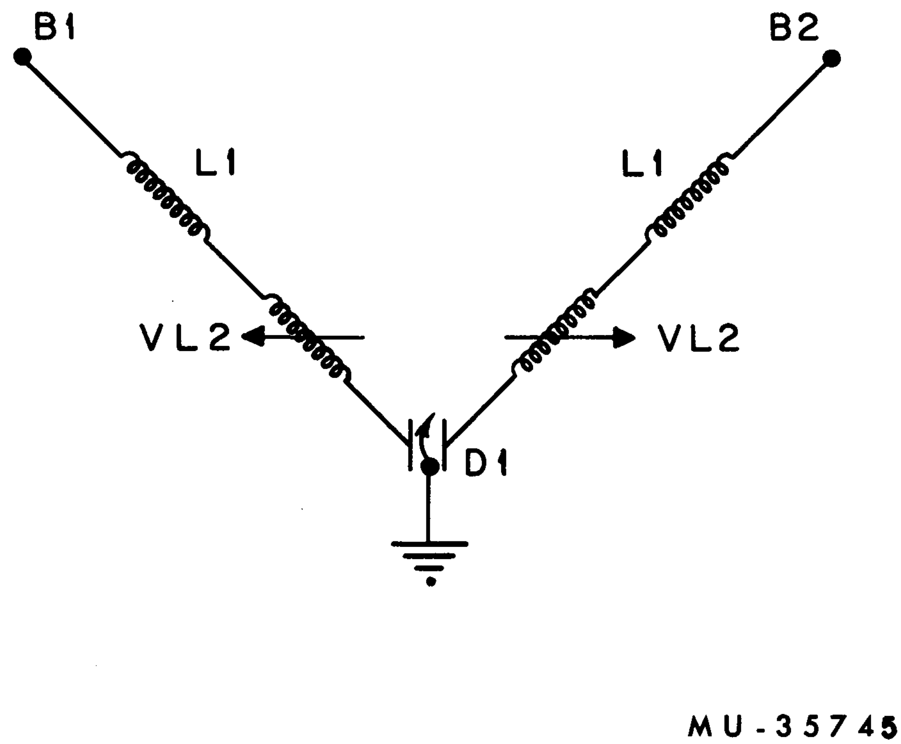

Fig. 24. Lower part of bridge in Lamers-Rony system.

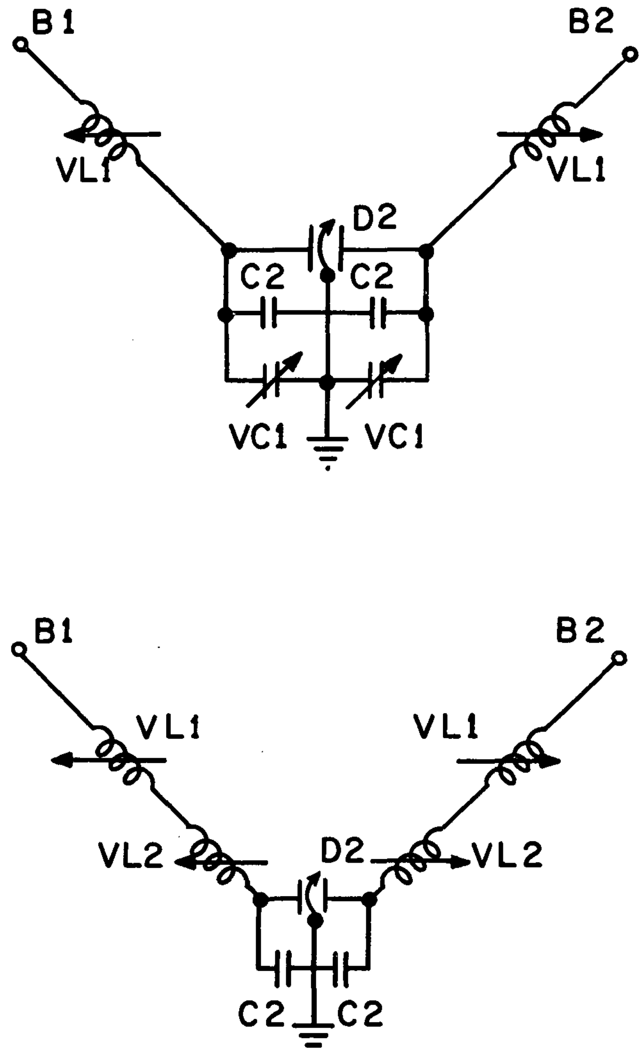

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Fig. 25. Alternative forms for lower part of bridge in Decker-Lamers-Rony (DLR) system.

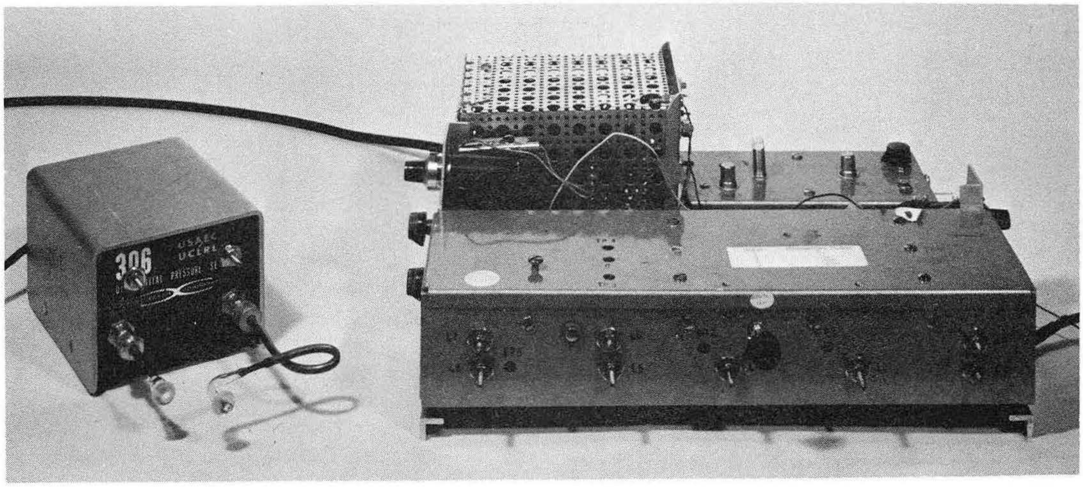

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Fig. 26. Photograph of lower part of bridge in DLR system.

Table I. Bridge Component List.

Symbol	Component
C1	200-pF silver-mica capacitor
C2	68-pF silver-mica or Vytramon ceramic capacitor
VC1	10-pF variable capacitor (JFD Electronics Corp. Model VC-11)
D1	Differential-capacitance pressure transducer designed by author, $C_o \approx 270$ pF
D2	Differential-capacitance pressure transducer (Decker Instrument Corporation Model 306-2A or any of the 306-2 series), $C_o \approx 13$ pF
DC1	100-pF differential air capacitor (E. F. Johnson Co. No. 148-306)
DC2	5-pF differential air capacitor (E. F. Johnson Co. No. 160-303)
L1	10- to 15-μH composed of Essex Wee-Ductor microchokes
VL1	64 turns of No. 32 Formvar copper wire wound on coil form (National Radio XR50)
VL2	0.4 to 0.8 μH adjustable coil (Miller No. 4501)

condition $A \alpha \beta \gamma$ very much greater than 1 was not satisfied and no real improvement was produced by closing the loop. Fortunately, open-loop operation was usually much more convenient and accurate, provided only that the line voltage was regulated and the system gain calibrated one or more times each day.

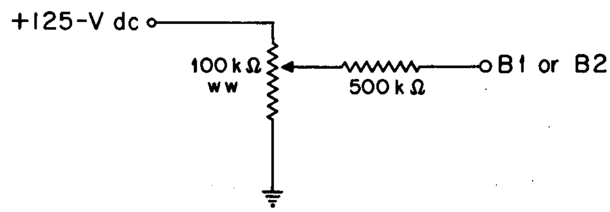
The electronics unit was operated open loop by disconnecting the feedback loop at the output terminals of the bridge (B1 and B2) and by providing a nonlinear electrostatic calibration circuit between either B1 or B2 and ground (Fig. 27). A miniature 10-turn wire-wound potentiometer was used because of its compactness. Initially, it loaded down the power-supply output and produced oscillations in the amplifier. This was remedied by readjustment of the Zener-diode current. A 10-turn wire-wound 500kΩ potentiometer would be preferable if space is available. A linear electrostatic calibration circuit is also shown (Fig. 28).

Further details about the actual calibration procedure are given in Sec. VI.

G. Additional Construction Details

As indicated in Part I of this report,[18] the primary objectives were to (a) develop the simplest possible instrument that could be duplicated and operated by someone with little electronic background, and (b) minimize its expense. On both points this unit has been a success. With no prior experience in electronics or assembling Heathkits, I was able to construct a second unit in about three days. By following the tuning procedures carefully,[18] I made the unit work the very first time.

The amplifier and oscillator housings were made from No. 17 and No. 238 LMB chassis boxes.[21] The oscillator-interstage-component plate was taken from a cut-up chassis box (No. 238), whereas the power-supply component plate, the amplifier interstage plates, and the base plate for the power supply and oscillator were taken from several cut-up chassis boxes (No. 17). The amplifier and base plate were mounted on a 1/8-in.-thick 1/2-in. L-shaped aluminum rod (each bar of the "L" was 1/2-inch



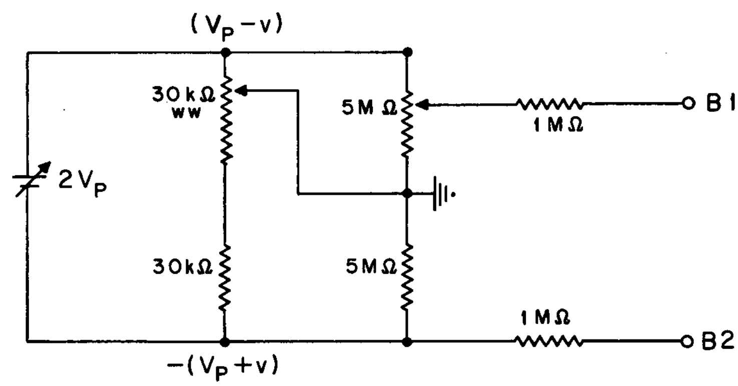


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Fig. 27. Non-linear electrostatic calibration circuit.

Fig. 28. Linear electrostatic calibration circuit.

long). This material (aluminum L-shaped rod) was also used in the amplifier to prevent interstage oscillations (Fig. 18).

The circuit diagrams and photographs (given in Part I or in Figs. 13 to 18 in this paper) illustrating the physical construction are adequate for the electronics to be duplicated. The circuit diagram of the amplifier in Fig. 29 shows the divisions between the amplifier stages. Templates for (a) the amplifier housing, (b) the oscillator housing, (c) the power-supply component plate, (d) the oscillator interstage component plate, (e) the first, second, and third amplifier interstage component plates, (f) the amplifier interstage component plate between the detector and reference-signal stages, and (g) the power-supp and oscillator base plate have been made and are available from the author, c/o The Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, Missouri, or from the Technical Information Division at the Lawrence Radiation Laboratory, Berkeley (Electronics Engineering Drawings Nos. 5V 713 and 5V 714).

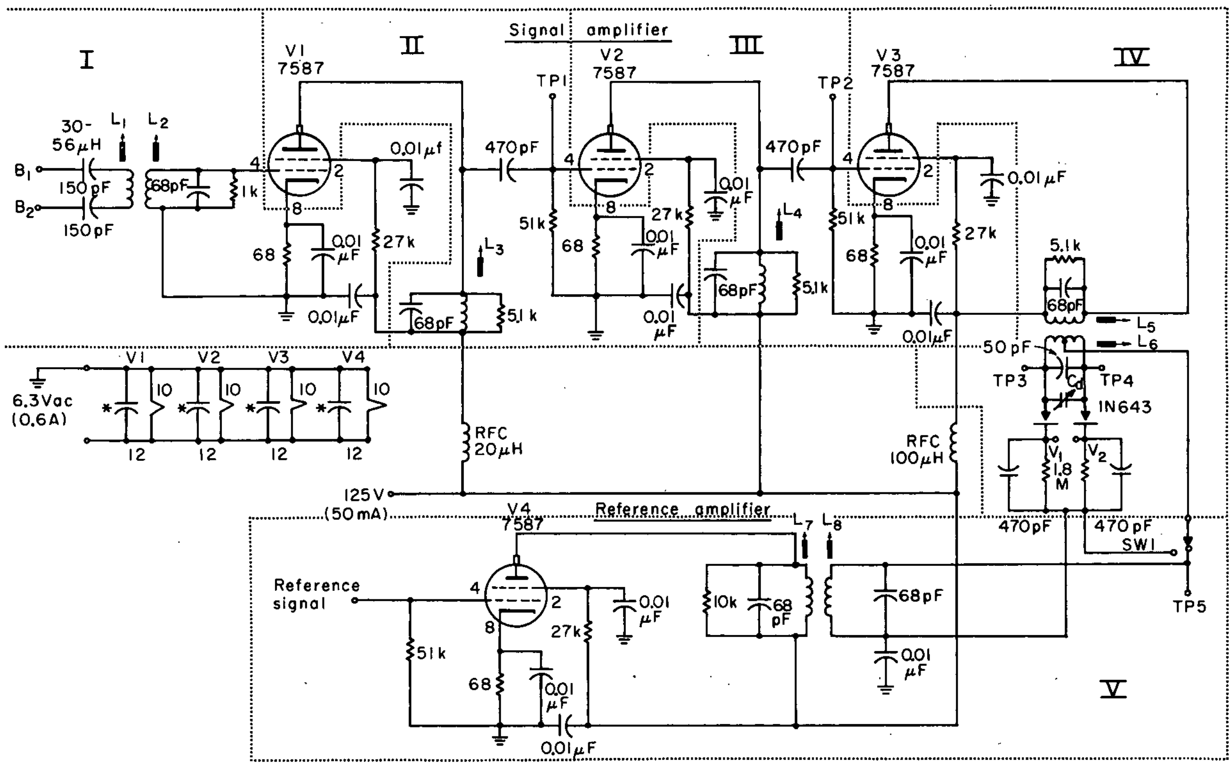


Fig. 29. Schematic diagram of the null detector showing divisions between the amplifier stages in the constructed unit.

V. OPERATION OF THE ELECTRONICS

A. Additional Tuning Instructions

The following changes should be made to the tuning instructions given in Part I:[18]

Transducer Element

1. Monitor B1 with scope probe; tune L1 or VL1 on side B1 for minimum.
2. Monitor B2 with scope probe; tune L1 or VL1 on side B2 for minimum.
3. If a dual-trace oscilloscope is available, set to "alternate sweep" and monitor B1 and B2 with separate probes. Superimpose the waveforms, then adjust L1 or VL1 and DC1 (oscillator) until the waveforms are identical in shape and amplitude.
4. Steps 1, 2, and 3 are the coarse adjustment for null. Make fine adjustment by connecting the scope probe to monitor TP2 at the null detector and then adjusting DC1, DC2, L1 or VL1, and VL2 or VC1 for the best possible null. With the bridge tuned and L1, L2, L3, and L4 in the null detector properly adjusted, a null of less than 200 mV peak-to-peak can be easily obtained.

Null Detector

1. Monitor TP2. With the bridge intentionally out of balance, adjust L1 and L2 for maximum output. Balance the bridge and adjust L3 for maximum output. If the voltage at TP2 is greater than 1 volt, pp, the bridge should be adjusted for a better null.
2. Monitor TP3, depress SW1, then adjust L4, L5, and C_d for maximum output. NOTE: When the bridge is being nulled, no attenuation should be applied to the signal. Once the bridge has been properly nulled, the desired attenuation factor should be set and L4 readjusted for maximum output. Before assembly, the L6 slug is positioned so that the inductance from the tap to each end of the coils is the same (use LC meter).
3. Same as indicated in Part I.

Zero-and-Gain and V_o Controls

Instead of a zero-and-gain control, separate gain controls for each side of the differential manometer have been provided [Fig. 21(a)].

1. Set V_o to a value suitable to the measurement.
2. Monitor TP2 with a test probe and simultaneously increase both gain controls. Stay within 2 volts peak-to-peak bridge unbalance at TP2.
3. If oscillations become evident, increase the feedback loop filtering or check the amplifier.

If the unit is operated open loop, the gain and V_o controls are not needed and should be disconnected from terminals B1 and B2. A fine open-loop adjustment can be made to all variable inductors in the oscillator and amplifier by the use of an electrostatically applied "pressure." By maximizing the deflection between zero differential pressure and the applied electrostatic pressure, variable inductors L1 and L2 in the oscillator and L3, L4, and L5 in the amplifier can be adjusted. Variable inductors L7 and L8 in the amplifier are always tuned to bring the reference and signal waveforms into phase. This procedure is recommended primarily when large signal-attenuation factors such as 0.002 or 0.0003 are used.

B. Miscellaneous Details

With no signal attenuation and all inductors adjusted for maximum output, the Decker-Lamers-Rony system began to show deviations from output linearity at about 0.2 mtorr! Saturation of the amplifier-detector unit, therefore, imposed the upper limit on the operation of the system. This upper limit was increased by attenuating the signal within the amplifier, but can also be increased by redesigning the resonant bridge to give decreased output for a given pressure change.

The maximum pressure measured by the Decker-Lamers-Rony system with an attenuation factor of 0.0003 was only 35 mtorr before saturation effects began to appear. The upper limit of the system can still be extended by an additional factor of 50, giving a theoretically useful range of 0.1 mtorr full scale to 1.87 torr full scale. The upper limit of the system can be further increased by use of one of the less sensitive Decker transducers, 306-2B to -2E.

In closed-loop operation, the lower limit on the operation of the system was primarily determined by the thermal drift in the bridge components. In open-loop operation, the lower limit was dependent on (a) the thermal drift in the bridge components, (b) changes in the amplification factor due to changes in the + 125-V dc plate voltage or aging of the Nuvistors, (c) changes in the operation of the detector. No attempt was made to separate these factors for any of the individual systems developed. No thermal regulation of the Decker-Lamers-Rony system, not even by means of insulating material, was ever needed.

Since the pressure transducer was not moved and the ambient temperature did not fluctuate greatly, the bridge null did not change greatly from day to day. Under such circumstances the oscilloscope was not needed and components DC2 and VL2 or VC1 were adjusted only slightly to re-null the bridge.

The best place for grounding to the line or pipe was the ground terminal in the center of the amplifier unit just opposite the power-supply base plate. Grounding at other points in the second Decker-Lamers-Rony system produced a very small but noticeable dc fluctuation in the recorder signal.

VI. CALIBRATION OF THE DIFFERENTIAL MICROMANOMETER

A. Pressure Calibration

In open-loop operation, one can calibrate a capacitive displacement pressure transducer by any of three different methods, (a) mechanically against a known differential pressure, (b) electrostatically with a known voltage, and (c) gravitationally, by turning the transducer on its side. Pressure calibration is generally the most precise, although it frequently is time consuming, requires special calibration equipment, can't usually be done *in situ*, and is difficult to do accurately at differential pressures of less than 5 mtorr.

Figure 30 is a schematic diagram of the pressure-calibration apparatus. A differential pressure is produced using a diffusion pump and helium gas. The pressure of the gas, ranging from 0.2 to 35 mtorr, is measured by a McLeod gauge (Consolidated Vacuum Corporation Model GM-100A). The micromanometer is usually calibrated electrostatically simultaneously. An alternative pressure calibration apparatus is shown in Fig. 31.

I spent considerable effort trying to calibrate the pressure transducer against a known differential pressure in the range 0.5 to 2.0 mtorr. The McLeod gauge was abandoned because the readings at that low level could not be made with sufficient accuracy. The alternative calibration method was likewise unsuccessful because of the extremely poor signal-to-noise ratio characteristic of the small-signal operation of the Decker differential micromanometer.

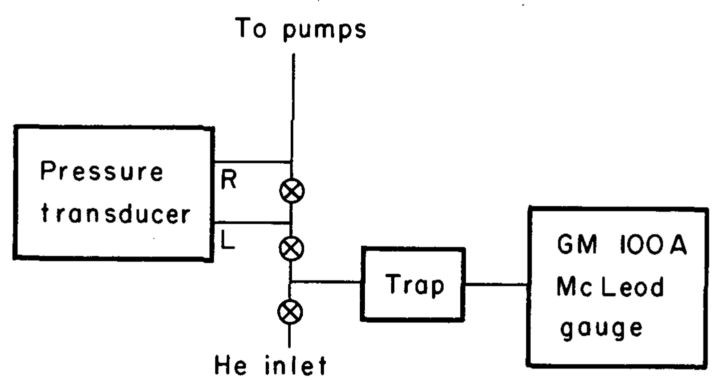
Several alternatives for making a pressure calibration at approximately 2.0 mtorr were considered:

(a) Purchasing a more sensitive McLeod gauge,

(b) Purchasing a more sensitive Decker sensor,

(c) Making a different type of McLeod gauge, a pressure amplifier, by using the Decker 306-2A sensor to measure the pressure of the compressed gas in the closed volume,

(d) Changing the McLeod gauge fluid from liquid Hg to concentrated sulfuric acid or di-n-butyl phthalate.



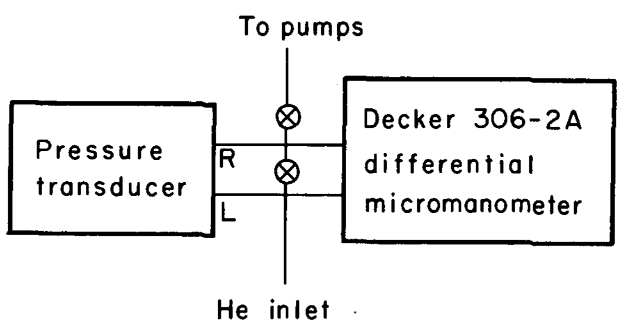


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Fig. 30. Pressure calibration apparatus.

Fig. 31. Alternative pressure calibration apparatus.

Alternatives (a) and (b) were immediately rejected since their cost was too great for the improvement possible and (c) was not tried because of the large residual volume on one side of a typical Decker sensor. Alternative (d) was considered to the extent that tests were made of the wetting and capillary behavior of the two liquids in closed glass capillaries. The formation of trapped drops could be prevented if the McLeod gauge is operated carefully, but a thin liquid film of undetermined thickness would remain on the capillary walls and would probably influence the calibration constant of the nonlinear scale in the McLeod gauge.

In an attempt to eliminate this wetting, films of tin fluoride and Teflon were applied. The tin fluoride provided some improvement. Teflon was difficult to apply uniformly to a closed capillary by the method of Berg and Kleppner,[22] but did show considerable promise as a capillary-coating material. The use of di-n-butyl phthalate and Teflon would decrease the lower range of a typical McLeod gauge by more than a factor of ten, eliminate the problem of cold-trap pumping, and also eliminate the possible contamination of the system by mercury vapor. The problem of gas dissolution in the McLeod gauge fluid would still remain.

The problems of calibrating at very low differential pressures were finally eliminated by attenuation of the amplifier signal and calibration at a higher pressure range. At pressures of 35 mtorr the McLeod gauge provided very reliable results.

B. Gravitational Calibration

Gravitational calibration is generally limited to a very small pressure range and is usually awkward to perform. When a pressure transducer is moved, the external leads to the bridge frequently change their relative position, producing a spurious bridge unbalance in addition to the gravitational "pressure." Rotational flexibility in the vacuum equipment, which can be quite a problem in many systems, is required.

C. Electrostatic Calibration

Electrostatic calibration of the capacitive displacement transducer requires (a) a diffusion or mechanical pump to maintain the ambient pressure in the system at a very low level, (b) a calibration circuit shown in Figs. 27 and 28, and (c) a regulated source of 300 V dc. A regulated power supply (Lamda Electronics Corporation) is quite convenient for (c). The only limitation of this method is that it is generally limited to small pressure differentials and to bridge configurations that permit such a calibration, i.e., a simple capacitance bridge or one of its modifications. The majority of commercial micromanometers have unsuitable bridge configurations and therefore seemingly cannot be electrostatically calibrated. However, this particular limitation can be bypassed (Sec. X).

To make an absolute electrostatic calibration, we must know three parameters: (a) z_o, the diaphragm-to-electrode spacing, (b) R, the radius of the diaphragm, and (c) R', the radius of the electrode. The quantity R' is known exactly from the construction of the pressure transducer, and R is known reasonably well but may depend slightly on the method of clamping the diaphragm. The formulas[23]

$$C = 0.0885\epsilon\left\{\frac{\pi R'^2}{z_o} + R'\left[\ln\frac{16\pi R'}{z_o} + 1 + f\left(\frac{s}{z_o}\right)\right]\right\} \qquad (35)$$

$$C = 0.278\epsilon\,\frac{R'^2}{z_o} \qquad (z_o \ll R') \qquad (36)$$

are used to calculate the spacing z_o from the value of the capacitance of each side of the capacitive transducer. The quantities R' and z_o are in cm and C is in pF; $f(s/z_o)$ can usually be neglected.

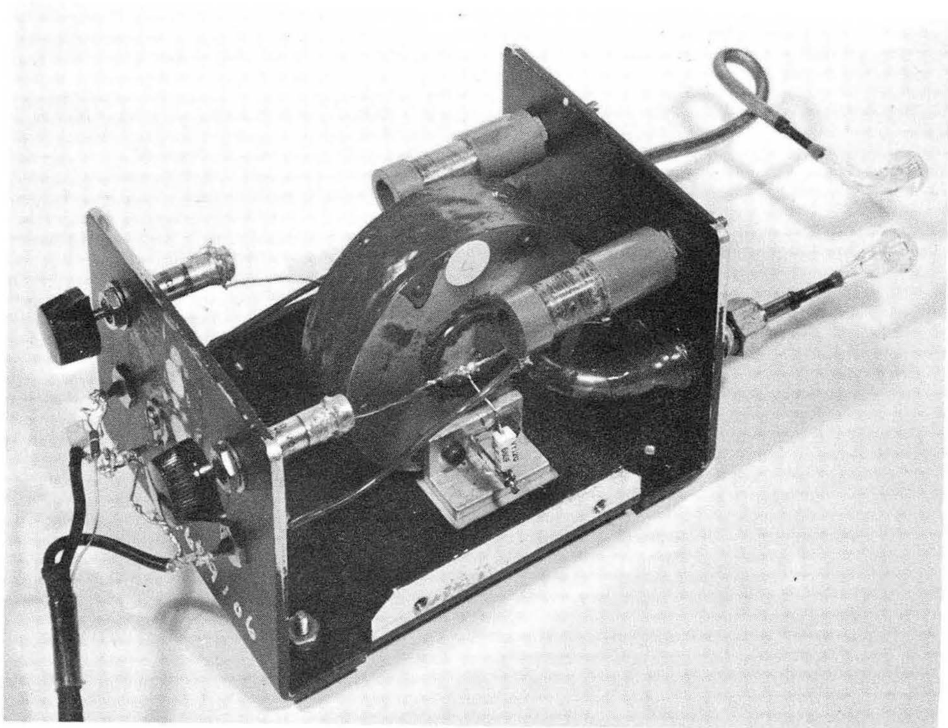
D. Experimental Calibration Procedure

The best compromise of the above methods is to experimentally determine the electrostatic gauge constant by simultaneously performing a calibration with a known differential pressure. When the gauge constants for each side are determined, calibration with a known differential pressure need not be performed again. Even with the micromanometer attached to the experimental equipment, it is a simple matter to electrostatically check the relative change in the open-loop gain.

To perform an electrostatic calibration, first evacuate both sides of the transducer with a diffusion pump to produce a stable reference level. Set the calibration potentiometer to zero, null the bridge, choose the correct amplifier attenuation factor, and adjust the recorder output potentiometer, in the order given. Allow the zero level to stabilize for as much time as is necessary. Turn the calibration potentiometer to apply a voltage to one side of the transducer. Allow the resultant recorder reading to stabilize for two minutes, then decrease the voltage successively to zero in about five equal intervals; allow about 20 seconds for each reading to become constant. A typical calibration measurement on the recorder-chart paper resembles a series of steep steps (Sec. VIII.K.4).

The difference between the zero reading and the various steps is then plotted as a function of the square of the voltage. If the micromanometer is operating correctly, the resultant curve is linear. A deviation from linearity at the higher potentiometer settings indicates that the amplifier or detector is saturating and that those data points are invalid. The linear curve also may not always pass exactly through zero. This indicates that the choice of zero reading is incorrect, but is of no consequence otherwise since only the slope of the curve is important. Calibration curves for the previous recorder readings are also given in Sec. VIII.K, item 4.

The ease and convenience of this method of calibration deserves to be emphasized. Because the calibration is done directly at the transducer, it eliminates completely the effect of changes in bridge voltage, bridge constant, amplifier gain, diaphragm tension, and recorder calibration. It takes five minutes to perform and need be applied as little as two times per day, since the open-loop gain, defined as $A \alpha \gamma$, rarely changes by more than 1 or 2% over an eight-hour period. It is particularly well suited for the low-pressure regions at which other calibration methods begin to fail. Finally, once the electrostatic constant is known, only a source of regulated dc voltage is needed to calibrate the micromanometer no matter where it is located (Fig. 32).



ZN-4956

Fig. 32. Photograph of the complete DLR system.

VII. CHOICE OF A DIFFERENTIAL MICROMANOMETER SYSTEM

It is unfortunate that there is no publication analogous to Consumer Reports to guide scientists and engineers in choosing commercial scientific equipment. Advertising brochures are frequently vague or incomplete and understandably ignore problems and critical deficiencies associated with the equipment. Companies are occasionally slow or reluctant to divulge necessary information. Finally, authors of technical articles are generally uninterested or are not allowed to elaborate on the problems associated with the equipment they have used.

The proper choice of any piece of scientific equipment usually requires a wide knowledge of the assets and liabilities of the devices sold commercially or described in the technical literature. As is frequently the case with graduate students or investigators entering a new field, this knowledge and experience has not been accumulated by the person initiating the investigation. The result is a considerable waste of time and money by the student or investigator who must improve a piece or equipment that hasn't come up to expectations.

Perhaps the only general recommendations that can be given here are to procure as much critical information as possible about the particular commercial instrument being considered, and to borrow and test it out in a typical application. Alternative actions are searching discussions with the manufacturer or its representatives or, better yet, with nearby scientists who are using or have used the particular instrument. On request, a company should be prepared to inundate a potential purchaser with brochures, operation and maintenance manuals, circuit diagrams, examples of actual use, calibration curves, and typical recorder readings. Many companies fail to do this even after the instrument has been purchased.

The above comments apply to all scientific equipment in general and to electronic differential micromanometers in particular. As the purpose of this report is to describe the experience associated with the choice, construction, and operation of a differential micromanometer that can measure a pressure of 0.1 mtorr to several percent accuracy, it is appropriate to discuss the characteristics of several commercial micromanometers and some given in the technical literature.

The following comments represent the author's own first- or second-hand experience and personal evaluation of the instruments considered. They are incomplete in places, but at least they may be a useful beginning for those who have had no previous experience with such gauges. Attention is always restricted to the one or two most sensitive differential manometers manufactured by the companies considered and to the most sensitive ones described in the technical literature.

VIII. CHARACTERISTICS OF DIFFERENTIAL MICROMANOMETER SYSTEMS

A. System Characteristics

In evaluating the various differential micromanometers, I considered only the following characteristics of the devices:

a. Developer or manufacturer of the micromanometer,

b. Cost,

c. Long-term zero stability or the temperature coefficient of zero stability,

d. Short-term zero stability (over a 30 second time interval),

e. Sensitivity at ΔP = 1 mtorr,

f. Full-scale voltage,

g. Full-scale pressure,

h. Linearity,

i. Type of null (open loop, closed loop, or manual),

j. Possibility of applying an electrostatic pressure,

k. Response time,

l. Output impedance,

m. Differential overpressure rating.

The zero stability usually determines the applicability of a particular micromanometer for high-precision work or the measurement of very small differential pressures; it is usually governed by the temperature coefficients of the bridge components, whether they are capacitors, inductors, resistors, transformers, diodes, or ionization transducers.

A micromanometer that can be nulled is usually more precise than an open-loop one. The response time is usually limited by the capacitive transducer and not by the electronics. The differential overpressure should be at least one atmosphere to avoid damage to the micromanometer when a break occurs suddenly in the vacuum system. Since the more readily available recording and indicating instruments measure voltage, the output impedance of the micromanometer should be as low as possible. The application of an electrostatic "pressure" is a particularly convenient method of calibrating or nulling a micromanometer. In a null system, the linearity is essentially that of the null-readout mechanism. In open-loop systems, the linearity depends on many factors.

Other characteristics important for many types of investigations are:

n. Precision,
o. Long-term reproducibility,
p. Susceptibility to electromagnetic interference,
q. Susceptibility to line-voltage fluctuations,
r. Noise,
s. Outgassing and leak properties,
t. Bakeability,
u. Temperature coefficient of sensitivity,
v. Provision for temperature control of the transducer,
w. Provisions for re-calibrating the amplifier,
x. Acceleration sensitivity,
y. Volume of each transducer side and inlet ports,
z. Radius of diaphragm,
aa. Radius of electrode,
bb. Diaphragm-to-electrode spacing,
cc. Diaphragm material and thickness,
dd. Materials of construction,
ee. Ease of operation,
ff. Size,
gg. Weight.

The precision is generally good to excellent for null micromanometers and only fair to good for open-loop ones. The long-term-reproducibility characteristic governs the frequency of recalibration of an open-loop instrument not otherwise provided with an amplifier recalibration mechanism. The susceptibility to interference and line-voltage fluctuations reflects on the degree of shielding and regulation as well as the overall design of the micromanometer electronics. Since most modern laboratories are plagued with external-noise problems, an on-site test of the instrument is recommended.

The bakeability, outgassing, and leak properties of the pressure transducer are extremely critical characteristics when measurements are made in closed systems. Manufacturers' brochures do not include these characteristics. Knowledge of the temperature coefficient of sensitivity is important when an open-loop micromanometer is calibrated at one temperature and operated at a considerably different one. A small inlet port and transducer-side volume is important in certain applications. Knowledge of the diaphragm and electrode radii as well as the diaphragm-to-electrode spacing is required when an electrostatic calibration is applied to the transducer.

It has been assumed that important convenience features such as decade attenuators and a panel meter are present in all of the commercial micromanometers being evaluated. They need not be considered here because they usually are the features emphasized in advertising brochures.

Table II summarized 12 characteristics for 13 differential micromanometer systems.

B. MKS Instruments, Inc.

The zero stability of a Baratron (Model 77H-3), located at the Lawrence Radiation Laboratory, Livermore, was measured only after this report was nearly finished. A visual check of the meter drift for a full-scale meter reading of 1 mtorr over a period of 2-1/2 hours demonstrated that the zero stability was ± 20 μtorr or better per hour. If information on the existence and fine characteristics of this micromanometer had been available in the catalog file of the Berkeley Laboratory, my work on developing a differential micromanometer probably never would have been started.

The Baratron appears to be the best electronic differential micromanometer available commercially today. A three-fold improvement can be achieved in characteristics c, d, and e in Table II by use of their 1 torr full-scale unit. The ouptut is ± 50 mV dc or ± 500 mV ac no matter what meter range is selected. Instead of the diaphragm's

Table II. Differential micromanometer characteristics.

a. Company	b. Dollars	c. mtorr/hr or mtorr/°C	d. mtorr	e. mV/mtorr	f. Volts	g. torr	h. ±%	i.	j.	k. msec	l. ohms	m. atm.
A*	$2565	0.02/hr*	0.01*	50*	0.05*	3*	0.15	OL, MPN*	No	10	ns	1.3
B	1800	<0.09/°C	0.05	0.5	5	10	0.05 or 0.5	OL	No	2	3500	1
C	2650	5/°C	0.1	na	na	0.15	0.2	MN	Yes	na	na	1
D	695	1.9/hr*	0.5	5*	10	1.9*	2	OL	No	5(est)	2200	2
E	--	<0.003/hr	0.001	500μA/mtorr	ns	0.02	<2(est)	OL*	Yes	ns	ns	ns
F	--	1.5/°C	0.03(est)	ns	ns	ns	0.25 (est)	CL*	Yes	ns		ns
G	--		0.001				0.1	OL, CL, MN	Yes	ns	ns	1
H	--	ns	ns	220	70	0.30	0.1	CL*	Yes	ns	250k 2.5m	ns
I	--	0.1/hr	<0.1	1000	ns	ns	ns	OL*	Yes	ns	ns	>1
J	650	0.4/hr	0.05	2	3.6	1.9	ns	OL	No	5	15k	2
K*	--	4/hr	0.2	--	--	--	--	OL, MN	Yes	5		2
L*	--						<0.5	CL, MN	Yes	*		--
M	--	0.03/hr*	0.001			0.035*	<0.5	OL, MN	Yes	5		2

A. MKS Instruments, Inc., "Barotron," Model 77H-3 and Indicator.

B. Datametrics, Inc., "Barocel," Type 1012 Meter and Type 511-10 Sensor.

C. Consolidated Engineering Corporation, Type 23-105 Micromanometer.

D. Decker Corporation, Model 306-2 Meter and Model 306-2A Sensor.

E. E. W. Becker and O. Stehl.[12]

F. Robert L. Sharpless, K. C. Clark, and Robert A. Young.[3]

G. J. J. Opsteltin, N. Warmoltz, and J. J. Zaalberg Van Zelst.[9,10]

H. J. O. Cope.[11]

I. D. R. Lovejoy.[13]

J. Decker-Lion composite system.

K. Decker-PAR composite system.

L. Lamers-Rony system.

M. Decker-Lamers-Rony system No. 1.

ns or na indicate either that the property has not been specified or else that it is not applicable to the system considered. The small letters at the column heads refer to the same characteristics listed at the beginning of Sec. VIII.A.

*Consult Secs. VIII.B to VIII.J.

being restored to its initial position, a pseudo-null effect is produced by nulling the resultant bridge voltage. This manual pseudo-null (MPN) feature still permits high-precision work and is one of the key features of the instrument. The only apparent bad feature of the Baratron is its price, which, though perhaps reasonable, may impose a strain on some budgets.

As this report was being typed, I received a bulletin describing tests performed on a modified Type 77H-1 head and Type 77M-XPR indicator circuit to increase their overall short-term and long-term zero stability. When the head was stabilized at room temperature with the regulating heat off, the long-term zero stability was typically 10 μtorr per 30 min and the minimum detectable pressure was 1 μtorr. With the regulating heat on, and on/off heating cycle caused a zero change of 10 μtorr. The definite usefulness of this bulletin only strengthens the convictions I stated in Sec. VII. Detailed information of this type certainly helps me to choose electronic equipment.

This modified unit is now as good as the systems that Kenneth W. Lamers and I have developed and described in UCRL-11218, Parts I and II.

C. Datametrics, Inc.

As the Barocel, made by Datametrics, Inc., was not tested or in use at the Laboratory, the company's specifications only were used in appraising its performance. It appears to be a fine instrument, but probably cannot measure 100 μtorr to within several percent because the short-term zero stability is only of the order of 50 μtorr. Its lack of either a direct-null or pseudo-null feature probably makes it less useful for high-precision work than the Baratron. The calibration-voltage feature appears attractive for checking for drifts in the gain of the amplifier and detector stages.

D. Consolidated Engineering Corporation

Investigators at the Berkeley and Livermore LRL sites have had varying degrees of luck with the CEC micromanometer. The key variable is the thermal coefficient of zero stability, which can be considerably lower than the 5 mtorr/$^{\circ}$C specified by the company, improving the operation of the instrument. The company deserves praise for its excellent operation and maintenance manual. However, for the same amount of money, I consider the Baratron a superior micromanometer.

E. Decker Corporation

I purchased or borrowed three meters and sensors (Decker Corporation Model 306-2A) and found them to be the least-suitable commercial differential micromanometers. I, as well as other investigators at the Lawrence Radiation Laboratory, Berkeley and Livermore, and at the University of California, have experienced the following difficulties with their instruments:

a. In small closed-volume work, the Decker pressure transducer either outgasses or leaks, which makes such studies difficult to perform;

b. The poor cable connections at the meter and high-impedance sensor make the gauge quite sensitive to electromagnetic interference;

c. The short-term fluctuations in the zero point can be as large as 0.3% in a 30-second interval, rendering the gauge useless for high-sensitivity or high-precision measurements;

d. A gradual drift in the amplification factor necessitates occasional recalibrations;

e. On some devices, the deviations from linearity are definitely in excess of the company specifications of 2%;

f. Burnout of the ionization transducer after 5000 or more hours of use necessitates the purchase of a new one and a recalibration of the gauge.

Basically, the ionization transducer does not involve a good transducer principle for high-precision or high-sensitivity work. Associated with its use are a poor thermal coefficient and considerable very-low-frequency noise. I have never experienced any real difficulties with leaks or outgassing, but I haven't done the type of closed-volume experiment in which they would appear. Enough other investigators have mentioned such problems to lend credence to the statement that they do exist. Some have gone to the extremes of disassembling the transducer and repotting it. One has said that the white fixed-electrode pieces are responsible for the outgassing.

On the positive side, the Decker system is inexpensive and the pressure transducer does have a superior temperature stability, as is indicated in Sec. VIII.

Based on my own observations, I cannot recommend the complete Decker system for anything but a rough indication of the differential pressure within the range of the various sensors. The frustration and waste of time associated with its use for higher precision or sensitivity measurements are just not justified.

F. E. W. Becker and O. Stehl

The differential micromanometer system developed by Becker and Stehl[12] has the best long- and short-term zero stability of any system considered. The reason for its excellent performance is a superb capacitive displacement transducer, which unfortunately may be hard to duplicate perfectly. Their work indicates that the measurement of differential pressures of 10 μtorr with several percent accuracy is definitely feasible. Electrostatic calibration of such a gauge provides an opportunity to make an excellent secondary pressure standard in this pressure region.

G. J. J. Opsteltin, N. Warmoltz, and J. J. Zaalberg Van Zelst

In their first paper, Opsteltin et al. described a convenient way of tuning a resonant-leg capacitance bridge without the use of a dual-probe oscilloscope.[9] They also mentioned that they can measure 10 μtorr to 10% under conditions of constant room temperature.

H. Decker-Lion Composite System

The differential micromanometer consisting of a pressure transducer (Decker Corporation 306-2A), a compact unit (Lion Research Company Model 201), and general-purpose probe (Model GP 311) was called the Decker-Lion composite system for lack of a better description.

By thus eliminating the Decker ionization transducer and 306-2 meter, the short- and long-term zero stability were improved by factors of ten and five, respectively. The susceptibility to noise was also reduced. When the dc voltage was stabilized to 0.1%, the resulting fluctuation in the zero point was less than 75 μtorr. The large temperature coefficient of 3 mtorr/$^{\circ}$C was measured by laying a heating tape around aluminum foil encapsulating the compact unit, probe, and a nonimmersion thermometer. The diodes in the bridge were probably responsible for this large temperature coefficient.

By enclosing the probe and compact unit in a temperature-controlled container, an order of magnitude improvement in the long-term zero stability can possibly be achieved. The transducer may still be subject to the outgassing and leak problems mentioned previously. A more sensitive Decker transducer, Model 306-2G, can extend the lower limits of the composite micromanometer. Specifications on the long-term stability of the amplfier gain should be obtained from the manufacturer because the gauge cannot be calibrated electrostatically.

If low cost is a fundamental consideration in the purchase of a commercial electronic differential micromanometer, this system is probably the best to date. The Lion Research Company does sell a pressure transducer, which, unfortunately, does not have the sensitivity of the composite system.

I. Decker-PAR Composite System

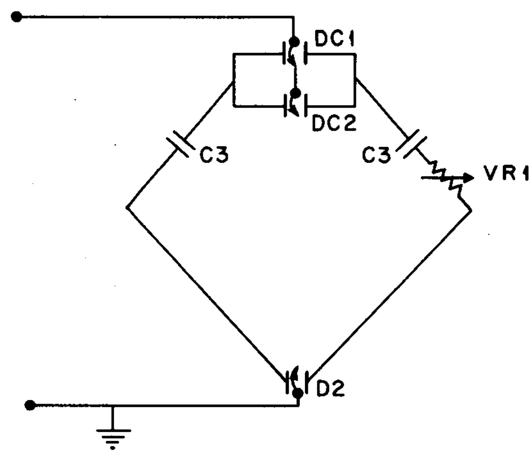
The differential micromanometer consisting of a capacitive transducer (Decker Corporation 306-2A) and a lock-in amplifier (Princeton Applied Research Corporation Model JB-4) was called the Decker-PAR composite system for lack of a more descriptive name.

This system was tried as soon as it became evident that the Decker transducer had an extremely good temperature stability. With such exceptional stability, any high-quality electronic amplifier-oscillator-detector system could in principle be used with good results. If these efforts were successful, the necessity for others to build a transducer and electronics would be eliminated.

A lock-in amplifier was borrowed for a brief period from Dr. Tetsuo Hadeishi. A model JB-5, which had a peak frequency of 150 kc/sec, was desired, but only a JB-4, with a peak frequency of 15 kc/sec, was available. A bridge at this frequency was successfully constructed and nulled (Fig. 33). The bridge output went through an interstage transformer and a preamplifier to the lock-in amplifier. The JB-4 output was fed into a 10-mV full-scale Speedomax recorder (Fig. 34).

The Decker-PAR system behaved comparably to the Decker 306-2 system described previously, showing slightly greater long-term drift and slightly less short-term low-frequency noise. When it became apparent that the Decker-Lamers-Rony system was two orders of magnitude better, work on this system was quickly abandoned.

Such a system should work well if proper attention were given to it. A higher bridge frequency, such as 150 kc/sec, should be used to decrease the bridge impedance. Any inexpensive narrow-band tuned amplifier would be more appropriate than the Princeton Applied Research JB-4 or JB-5.



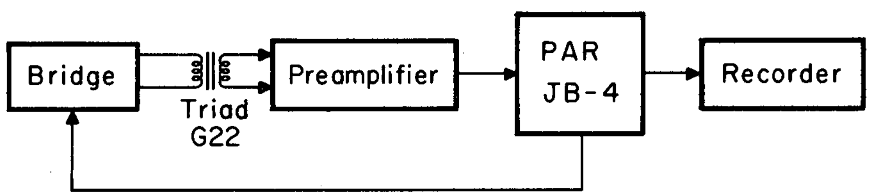


Fig. 33. Bridge for Decker-PAR composite system. C3 is a 15 pF ceramic capicator and VR1 is a 10 kΩ micropot.

Fig. 34. Block diagram for Decker-PAR composite system.

J. Lamers-Rony System

The differential micromanometer consisting of a capacitive transducer and bridge (constructed by P. Rony) and the associated electronics (constructed by K. W. Lamers) was called the Lamers-Rony system for lack of a better name.

The design and construction of the capacitive transducer has been given previously (Sec. III.B). It was built primarily to provide (a) high sensitivity, (b) high static capacitance on each side, (c) low temperature coefficient of capacitance, (d) compactness, (e) ease of reassembly, (f) adequate shielding from electromagnetic interference, and (g) ease of thermal regulation. Requirements (a) and (b) were necessary to operate the system closed loop.

The completed unit did fulfill these specifications. Some of its characteristics are:

a. Effective diaphragm radius, R: 2.2 cm,
b. Radius of fixed gold-plated electrodes, R': 2.15 cm,
c. Thickness of gold plate: several thousand angstrom units,
d. Diaphragm material: 1/2-mil Mylar with aluminum vapor plated on both sides,
e. Static capacitance of each side, C_o: about 270 pF,
f. Diaphragm tension: not measured or calculated,
g. Diaphragm-to-electrode spacing, z_o: about 50μ,
h. Capacitance change for a pressure difference of 1 mtorr: not measured.

The unit was so sensitive that it was not possible to calibrate it accurately against a CVC GM-100A McLeod gauge. The closed-loop gain was approximately 40. Exhaustive tests were abandoned when it was observed that the open-loop stability of the Decker-Lamers-Rony system was better.

The chief advantage of the latter system was that it had a very convenient gain control, and thus a wider effective pressure range for calibration and measurement than the Lamers-Rony system. Applying an attenuator in the amplifier of the closed-loop system would essentially negate the value of the closed-loop feature. In addition, the transducer (Decker Corporation 306-2A) was more rugged and the diaphragm less susceptible to tearing by a sudden overpressure of 1 atmosphere.

K. Decker-Lamers-Rony System

1. Summary of Characteristics of the Original Decker System

The differential micromanometer consisting of a capacitive transducer (Decker Corporation 306-2A, serial number 73), a bridge (by P. Rony), and the associated electronics (designed by K. W. Lamers and constructed by P. Rony) was called the No. 1 Decker-Lamers-Rony system (DLR No. 1) for lack of a better description. A similar system consisting of an equivalent transducer (serial number 162), a bridge (by P. Rony), and electronics (by K. W. Lamers) was given the designation, DLR No. 2. Both were eventually used as Wrede-Harteck gauges in a study of the kinetics of atomic hydrogen in a low-pressure system.[24]

The characteristics specified by the Decker Corporation for the 306-2A transducer are:

a. Normal operating pressure range: ±1.87 torr (±1.00 in.water),
b. Linearity: ± 2% over the full range or better,
c. Radius of fixed electrodes, R': 1/4 in.,
d. Effective radius of diaphragm, R: 1 in.,
e. Diaphragm material: 0.3-mil stainless steel,
f. Differential pressure required to short the diaphragm and a fixed electrode: about 4.5 torr,
g. Overpressure: 2 atmospheres differential,
h. Natural frequency of diaphragm: approximately 1000 cps,
i. Chamber volume: 0.15 $in.^3$

For the entire system, consisting of the transducer and a 306-2 meter, the Decker Corporation gives the additional specifications:

(i) Zero statiliby: 0.1% of full scale or better in the range 50° to 100°F,
(ii) Temperature Coefficient of stability: $-0.5\%/^\circ$F,
(iii) Noise level: typically 2.5 mV rms at zero differential pressure (= 0.47 mtorr),
(iv) Full-scale output: ± 10 volts.

I experimentally verified both the long-term zero stability, which varied as much as 1.5 mtorr over an hour period, and the "noise" level as shown on the recorder tracing, which was typically 0.3 mtorr peak-to-peak.

The static capacitance, C_o, of each side of the two transducers was measured with a capacitance bridge (General Radio type 1615-A) equipped with a 1-kc/sec oscillator (General Radio type 1311-AO. Several ceramic capacitors (Vytramon) were also tried as a check of the bridge's operation (Table III). The use of a much shorter connecting wire with lower capacitance was responsible for the decrease in capacitance of the No. 1 transducer sides in the October measurements. The capacitance figures still include stray capacitances within the transducer and any other errors in the measurement. Thus, though the measurements were quite precise, they were probably not very accurate, as the difference in the No. 1 transducer readings in September and October adequately illustrates. I did expect readings somewhat closer to 10 pF for each side.

The capacitance change in each side of the transducer for a pressure difference of 1 mtorr can be calculated with formulas (15), (17), (19), and (23),

$$\frac{\Delta C}{C_o} = -K\frac{\Delta z}{z_o} \approx -\frac{\Delta z}{z_o} = -\frac{\alpha \Delta P}{z_o} = -\frac{\Delta P}{(\Delta P)_{short}} \qquad (37)$$

where α is determined from the measured diaphragm-to-electrode spacing z_o and the differential pressure required to short the diaphragm and electrode, approximately 4.5 torr,

$$\alpha = \frac{(\Delta P)_{short}}{z_o} \quad . \qquad (38)$$

With a value of 13.5 pF for the static capacitance C_o and 0.009 cm for z_o, the following extra transducer specifications can be calculated:

j. Capacitance change for pressure difference of ± 1 mtorr: ± 0.003 pF,

k. Capacitance change for minimum detectable pressure difference (with DLR No. 1 system) of 500 ntorr (0.0005 mtorr): 1.5 aF (0.0000015 pF),

Table III. Capacitance measurements for pressure transducers (Decker Corporation 306-2A) and ceramic capacitors.

	Capacitance (pF)	Dissipation factor
September 22, 1964		
Ceramic capacitors (Vytramon)		
6.8 pF	6.648	--
10.0	9.878	--
15.0	14.847	--
22.0	21.951	--
No. 1 Transducer (serial No. 73)		
Left side	13.6437	0.00538
Right side	14.8040	0.00400
October 16, 1964		
No. 1 Transducer (serial No. 73)		
Left Side	13.149	
	13.121	0.0061
Right side	13.618	
	13.606	0.00410
No. 2 Transducer (serial No. 162)		
Left side	13.072	
	13.060	0.0053
	13.065	
Right side	12.767	
	12.758	0.00668

l. Deflection Δz for pressure difference of ± 1 mtorr: 200 Å,

m. Deflection for minimum detectable pressure difference of 500 ntorr: 0.1 Å.

Items k and m dramatize the sensitivity of the DLR system. The value in m doesn't conflict with the uncertainty principle because it is the average central deflection for a large number of atoms—the diaphragm.

2. Summary of Characteristics for the Decker-Lamers-Rony System No. 1

The characteristics of the complete Decker-Lamers-Rony system No. 1 (DLR No. 1) are:

a. Linearity: about 0.5% when not used as a null instrument;

b. Short-term zero stability (30 sec): 1 μtorr (0.001 mtorr);

c. Long-term stability: 30 μtorr/hour or better;

d. Values of amplifier signal-attenuation factors: 0.0003, 0.002, 0.02, 0.1, and 1;

e. Minimum differential pressure detectable: 500 ntorr;

f. Noise: not measured but very small;

g. Thermal coefficient of zero stability: not measured but very small;

h. Thermal coefficient of sensitivity: not measured;

i. Susceptibility to line-voltage fluctuations: small because Sola Constant Voltage Transformer was used;

j. Susceptibility to electromagnetic interference: small;

k. Response time: about 5 msec;

l. Differential overpressure: 2 atmospheres;

m. Recorder-output attentuation factor: 0.00034 to 0.032; usually 0.0068 or 0.0102;

n. Output impedance: 1 kΩ to 100 kΩ; usually 20 or 30 kΩ;

o. Location of pressure sensor: remote;

p. Type of calibration possible: pressure or electrostatic;

q. Thermal insulation: only what aluminum case provides; additional insulation possible;

r. Thermal regulation: none provided, regulation possible;

s. Bakeability: negative;

t. Volume of each transducer side and inlet ports: not measured (about 5 cm^3);

u. Volume of transducer side: 0.15 $in.^3$;

v. Acceleration sensitivity: not measured;

w. Outgassing and leak properties: that of the Decker 306-2A transducer;

x. Cost: parts, approximately $100; transducer, $300 or less; time, about 40 to 60 hours total construction time if parts and equipment are easily available;

y. Normal operating range: 0.1 mtorr full scale to 35 mtorr full scale; extension to 1.87 torr possible;

z. Possible operating ranges: lower limit may possibly be extended 10×, upper limit can be extended 100× or more.

In Figs 35 and 36, the original Decker micromanometer and the DLR No. 1 system are compared with respect to normal operating range (with ±2% accuracy), short-term stability, and long-term stability.

The open-loop gain, closed-loop gain, and other characteristics can be calculated on the basis of the following parameter values for equations (21) to (23) and (31) to (34):

C_o = 13.5 pF,

z_o = 0.009 cm,

$(\Delta P)_{short}$ = 4.5 torr,

V_o = 125 volts,

A = 175,000-V dc/V rms = 62,000-V dc/V pp,

E = 8.8-V pp,

C_{shunt} = 68 pF,

$\frac{C_o}{C_o+C_{shunt}}$ = 0.167,

C' = 250 pF,

K ≈ 2,

R' = 1/4 in., $\left| \beta = 6.63 \cdot 10^{-7} \frac{V_o}{z_o^2} \left(\frac{R'}{R}\right)^2 \right.$ mtorr/V dc

R = 1 in.

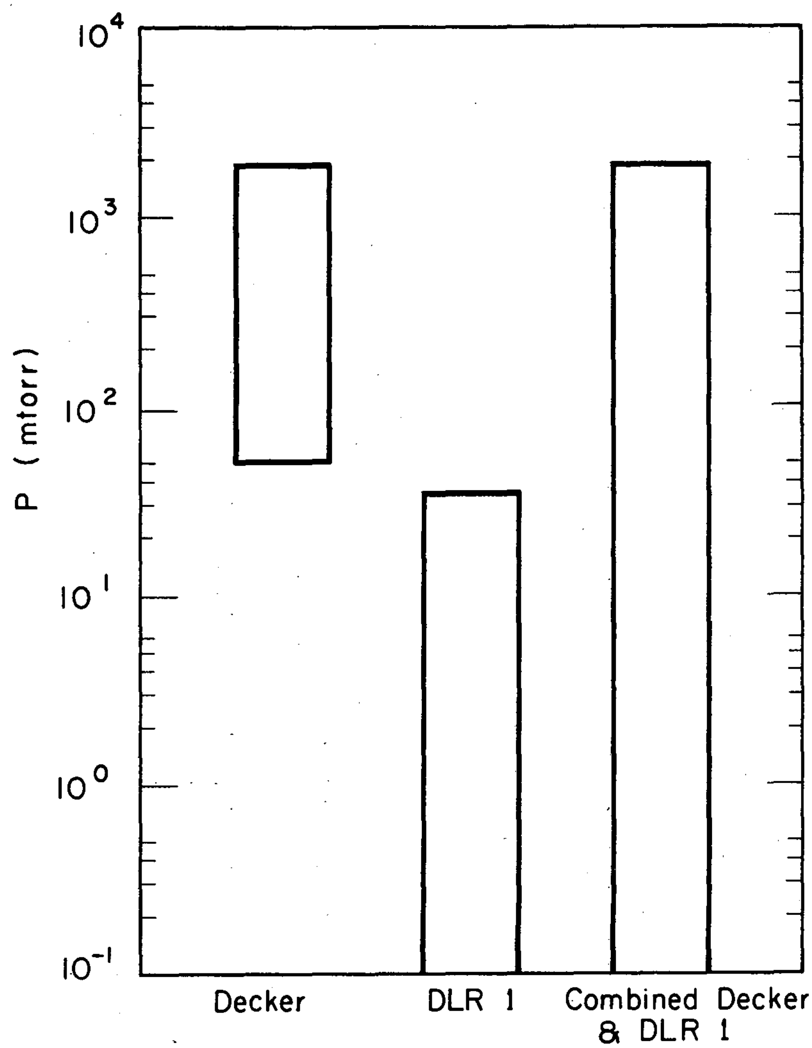


Fig. 35. Normal operating range of Decker and DLR No. 1 systems.

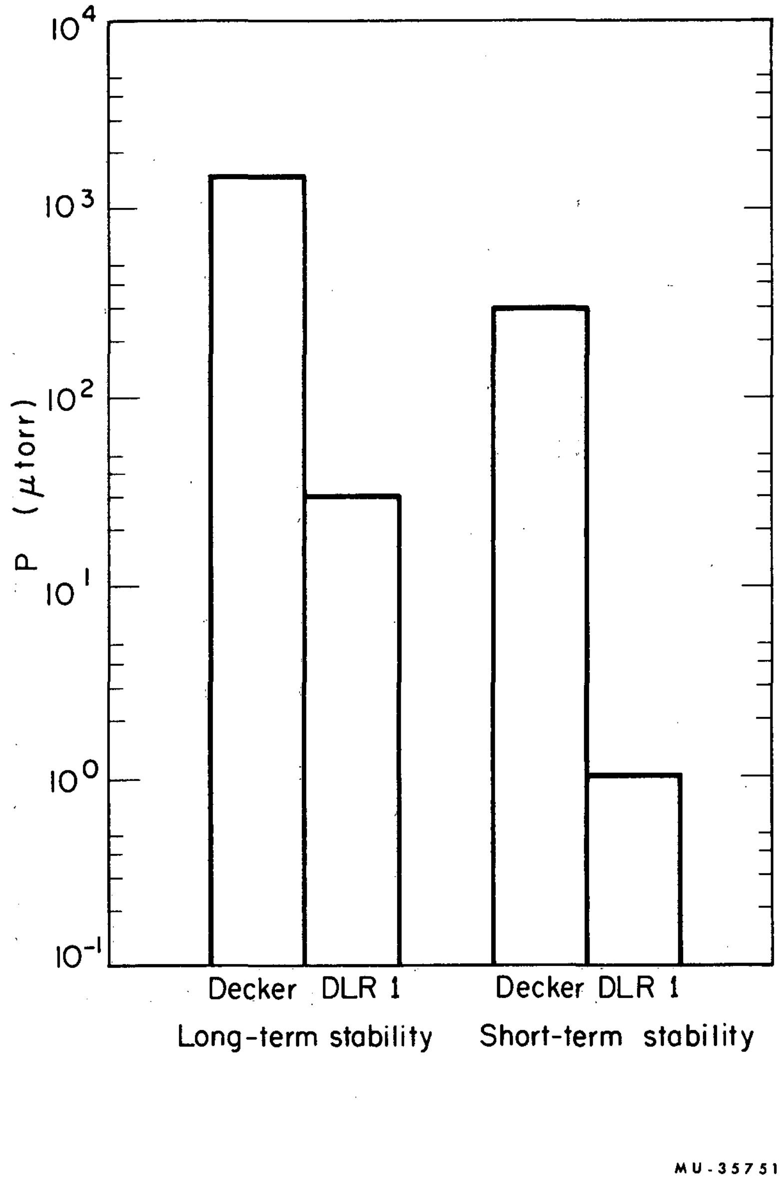


Fig. 36. Long-term and short-term stability of Decker and DLR No. systems.

aa. Capacitive displacement transducer coefficient, α: $2 \cdot 10^{-6}$ cm,

bb. Bridge coefficient, γ: 100-V pp/cm,

cc. Feedback-loop coefficient, β: 0.064 mtorr/V dc,

dd. Amplification factor, A: 62,000-V dc/V pp,

ee. Closed-loop gain: 0.8,

ff. Open-loop gain with amplifier signal-attenuation factor of 1: 6.2-V dc/mtorr,

gg. Same, with attenuation factor of 0.1: 620-mV dc/mtorr,

hh. Same, with attenuation factor of 0.02: 124-mV dc/mtorr,

ii. Same, with attenuation factor of 0.002: 12.4-mV dc/mtorr,

jj. Same, with attenuation factor of 0.0003: 1.86-V dc/torr.

The measured closed-loop gain of between 1 and 2 agrees quite well with the value given in item ee. The open-loop gain is also higher, having a value between 2.0 and 2.5-V dc/mtorr with an amplifier-signal attenuation factor of 0.1. Nevertheless, the agreement between the measured and calculated results is very satisfactory and represents a partial experimental verification of the validity of Eqs. (32) and (34).

Finally, the electrostatic constants for both sides of the transducer were measured according to the procedure given in Sec. VI.D:

kk. Electrostatic constant, right side: $4.8 \cdot 10^{-4} \pm 2\%$ mtorr/V^2,

ll. Electrostatic constant, left side: $3.9 \cdot 10^{-4} \pm 2\%$ mtorr/V^2,

mm. Calibration voltage: 127.0 V,

nn. Calibration potentiometer: 100 kΩ, 10-turn, wire wound,

oo. Recorder output potentiometer: 100 kΩ, 10-turn, wire wound.

For some unexplainable reason, the value of R calculated from the capacitance measurements and the electrostatic constant was lower by about 20% than the stated value of R, 1 in. This inconsistency was not pursued because the capacitance measurements were in doubt and the transducer was an early model. I had no desire to disassemble the nicely working gauge just to check this one remaining detail. If the value of R is lower than 1 in., then the agreement between the measured and calculated values of the open- and closed-loop gains would be better.

3. Measurements and Calculations

The calibration procedure for the DLR system is given in Sec. VI.D. The output from the Decker meter was passed through a calibrated resistance divider (Fig. 37 and Table IV). An identical McLeod gauge (CVC GM 100A) at the Laboratory was experimentally shown to be correct to within 0.5% of the scale constants calculated from the bulb volumes and the cross-sectional area of the closed capillary.[25]

When calibrated against the McLeod gauge, the Decker micromanometer (transducer serial number 161) showed a definite nonlinearity, in excess of the company specifications of ± 2%. The nonlinearity remained despite changes in the method of using the McLeod gauge or the ambient temperature of the trap (Table V).

The calibrations of the DLR No. 1 system against the McLeod gauge were not too satisfactory. This was undoubtedly due to the nonzero pressure reference level of the Kinney KC-5 pump and perhaps to problems with trap pumping by the McLeod gauge trap[26] (Fig. 30 and Table VI).

Much more uniform calibration values were obtained by calibration of the DLR No. 1 system against a previously calibrated Decker sensor. Unaffected by the reference level pressure, most of the experimental values of the electrostatic constant for the right side of the transducer were easily within 2% of the finally chosen one, $4.8_0 \cdot 10^{-4}$ mtorr/V^2 (Fig. 31 and Table VII).

In Tables VI and VII, the electrostatic constant k was calculated according to the formula

$$k = \frac{\Delta P_{measured}(f\text{-}s)}{pot^2(f\text{-}s) \cdot V_0^{\,2}} \qquad (39)$$

where $\Delta P_{measured}(f\text{-}s)$ was the equivalent full-scale reading for the DLR No. 1 output recorded on the 10 mV-Speedomax recorder, V_0 was the voltage applied to the ten-turn calibration potentiometer (Fig. 27), and pot(f-s) was the fractional setting of the calibration potentiometer (1.000 = ten turns) needed to produce a full-scale "electrostatic pressure" identical to $\Delta P_{measured}(f\text{-}s)$.

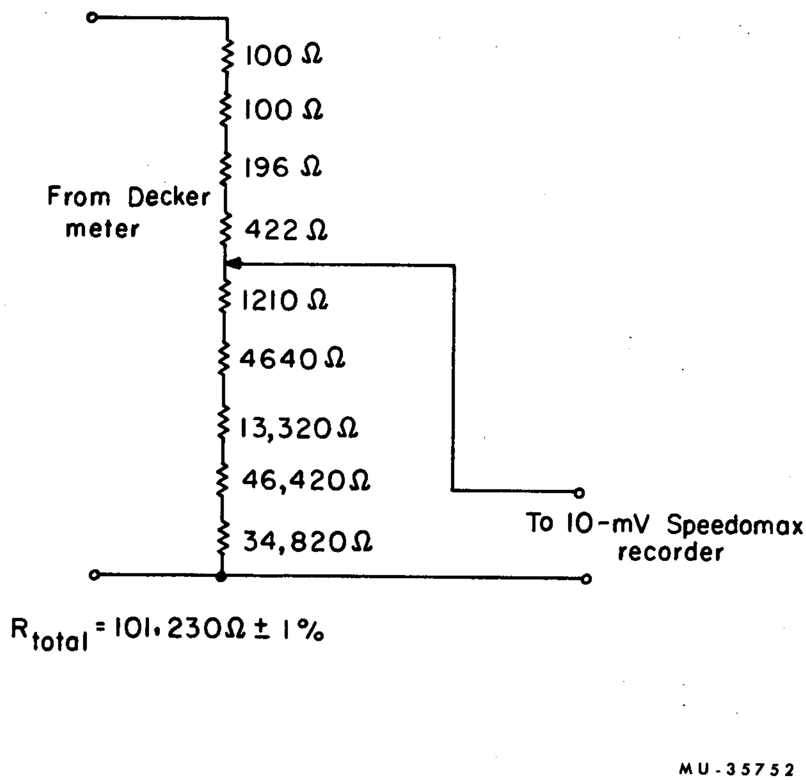


Fig. 37. Calibrated resistance divider for Decker micromanometer output.

Table IV. Measured resistance ratios for calibrated resistance divider.

Recorder scale	Calculated from value of resistance (Fig. 37)	Measured Resistance Ratios Run No. 1	Run No. 2	Run No. 3	Run No. 4	Run No. 5	Best values
2000	0.000988	0.000987	0.000989	0.000988	0.000990	0.000990	0.000988
1000	0.001976	0.001978	0.001978	0.001978	0.001974	0.001983	0.001978
500	0.003912	0.003914	0.003912	0.003909	0.003910	0.003928	0.003911
250	0.008081	0.008089	0.008092	0.008082	0.008083	0.008117	0.008083
100	0.02003	0.02001	0.02003	0.02000	0.02002	0.02006	0.02002
30	0.06587	0.06558	0.06586	0.06580	0.06583	0.06590	0.06583
10	0.1975	0.1970	0.1972	0.1970	0.1971	0.1972	0.1971
3	0.6560	0.6548	0.6544	0.6548	0.6545	0.6542	0.6546
2	1.0000[a]	1.0000[a]	1.0000[a]	1.0000[a]	1.0000[a]	1.0000[a]	1.0000[a]

[a]Reference value—no attenuation.

Table V. Summary of calibration measurements for the Decker micromanometer.

McLeod-gauge reading (mtorr)	Calculated full-scale recorder readings (mtorr)[a]				
	30	100	250	500	1000
A. McLeod gauge tapped and vibrated; trap filled with liquid nitrogen (11-4-64)					
29.5	31.4	103.2			1045
29.7	31.6	103.8			1051
65.2		106.7			1079
65.5		107.3			1086
84.3		104.9	262	537	1062
85.1		106.0	264	543	1073
89.5		107.4	268	550	1087
90.4		108.5	271	555	1098
100.0		107.3	268	550	1086
103.8		108.1	270	553	1094
168.0			273	564	1116
206.0			272	563	1112
259.0			273	563	1114
264.0			275	568	1124
351.0				572	1124
355.0				568	1124
558.0				572	1131
853.0					1128
967.0					1125
1016.0					1125
1020.0					1129
B. McLeod gauge not tapped or vibrated; trap filled with liquid nitrogen (11-15-64)					
30.3	31.5	103.5			1048
101.3		109.4			1107
102.0		109.6			1109
982.0					1144
990.0					1142
C. McLeod gauge not tapped or vibrated; trap filled with ice water (11-15-64)					
24.8	32.3	106.1			1073
30.1	32.4	106.6			1078
30.1	32.7	107.5			1088
40.9		106.5			1077
41.0		107.1			1084
55.5		107.6			1089
69.8		107.6			1089
69.8		108.4			1097
85.2		108.2			1095
95.3		109.1			1104
95.9		109.3			1106
100.5		108.4			1097
101.3		108.9			1102
1100.0					1133
1102.0					1137

[a] Decker Corporation's 306-2 meter and 306-2A sensor.

Table VI. Summary of McLeod-gauge calibration measurements for the DLR No. 1 micromanometer.

McLeod-Gauge reading (mtorr)	DLR No. 1 Recorder reading	Calculated f-s pressure	pot^2(f-s)	k (eq. 39) (10^{-4} mtorr/V^2)
A. McLeod gauge vibrated but not tapped. Trap filled with liquid nitrogen. DLR No. 1 system. Amplifier signal-attenuation factor of 0.0003. Recorder-output potentiometer at 5.00 turns. Right side of the transducer. V = 354 V. (11-6-64)				
32.4	0.792	40.9	0.694	4.70
30.9	0.762	40.9	0.694	4.70
32.2	0.753	42.8	0.694	4.92
32.0	0.753	42.5	0.694	4.89
31.6	0.758	41.7	0.694	4.79
31.5	0.758	41.6	0.690	4.81
31.6	0.756	41.8	0.690	4.83
34.1	0.817	41.7	0.677	4.92
34.2	0.824	41.6	0.673	4.93
B. McLeod gauge vibrated but not tapped. Trap filled with liquid nitrogen. DLR No. 1, with attenuation factor of .002 and output potentiometer at 2.00 turns. Right side of transducer. V_o = 354 V. (11-6-64)				
14.7	0.722	20.4	0.351	4.63
14.7	0.722	20.4	0.351	4.63
14.7	0.729	20.2	0.351	4.59
C. McLeod gauge not tapped or vibrated. Trap filled with liquid nitrogen. DLR No. 1 with attenuation factor of .0003 and output potentiometer at 5.00 turns. Right side of transducer. V_o = 354 V. (11-6-64)				
28.5	0.753	37.8	0.647	4.66
28.4	0.753	37.7	0.647	4.65
28.7	0.749	38.3	0.647	4.72
28.6	0.752	38.0	0.647	4.69
28.6	0.742	38.6	0.647	4.75
18.3	0.494	37.1	0.647	4.57
18.3	0.495	37.0	0.647	4.56
8.76	0.248	35.4	0.647	4.36

Table VII. Summary of Decker calibration measurements for the DLR No. 1 micromanometer

Decker recorder reading	DLR No. 1 recorder reading	pot^2(f-s)	k (10^{-4} mtorr/V^2)
A. Decker micromanometer, + 30 scale (32.6 mtorr f-s), used to calibrate DLR No. 1 system. Amplifier signal-attenuation factor of 0.0003. Recorder-output potentiometer set at 5.00 turns. Right side of the transducer. V_o = 355 V. (11-14-64)			
0.866	0.717	0.647	4.83
0.853	0.712	0.647	4.79
0.854	0.710	0.647	4.81
0.846	0.703	0.647	4.81
0.843	0.699	0.647	4.82
0.838	0.695	0.647	4.82
0.828	0.690	0.647	4.80
0.835	0.690	0.647	4.84
0.823	0.685	0.647	4.81
0.818	0.679	0.647	4.82
0.678	0.574	0.647	4.72
0.687	0.573	0.647	4.80
0.664	0.560	0.647	4.74
0.661	0.557	0.647	4.75
0.663	0.553	0.647	4.80
0.655	0.549	0.647	4.77
0.667	0.551	0.647	4.84
0.664	0.548	0.647	4.85
0.649	0.547	0.647	4.75
0.661	0.547	0.647	4.83
0.655	0.541	0.647	4.84
0.646	0.541	0.647	4.78
0.543	0.459	0.647	4.73
0.549	0.453	0.647	4.85
0.552	0.458	0.647	4.82
0.553	0.456	0.647	4.85
0.548	0.455	0.647	4.82
0.542	0.453	0.647	4.79
0.391	0.328	0.647	4.77
0.389	0.327	0.647	4.76
0.389	0.326	0.647	4.77
0.389	0.320	0.647	4.86
0.385	0.317	0.647	4.86
		Average:	$4.80 \cdot 10^{-4}$ mtorr/V^2
B. Decker micromanometer + 10 scale (10.9 mtorr f-s) used to calibrate DLR No. 1 system. Attenuation factor is 0.002, output potentiometer is 3.50 turns, and the right side of the transducer is calibrated. V_o = 355 V. (11-14-64)			
0.940	0.845	0.199	4.83
0.949	0.847	0.199	4.86
0.951	0.865	0.199	4.77

Table VII. Continued.

Decker recorder reading	DLR No. 1 recorder reading	pot^2(f-s)	k (10^{-4} mtorr/V^2)
C. Same as A above (11-14-64)			
0.937	0.789	0.649	4.73
0.939	0.789	0.649	4.74
0.935	0.788	0.649	4.73
0.928	0.782	0.649	4.73
0.923	0.779	0.649	4.72
0.919	0.775	0.649	4.73
0.910	0.770	0.649	4.71
0.936	0.784	0.649	4.76
0.903	0.767	0.649	4.69
0.896	0.758	0.649	4.71
0.904	0.759	0.649	4.75
0.886	0.750	0.649	4.71
		Average:	$4.73 \cdot 10^{-4}$ mtorr/V^2
D. Same as A and C above (11-15-64)			
0.953	0.825	0.622	4.81
0.946	0.823	0.622	4.78
0.933	0.808	0.622	4.80
0.923	0.802	0.622	4.79
0.933	0.802	0.622	4.84
0.902	0.780	0.622	4.81
0.892	0.775	0.622	4.79
		Average:	$4.80 \cdot 10^{-4}$ mtorr/V^2
D. Same as D, but with one of the amplifier inductors retuned. (11-15-64)			
0.800	0.821	0.519	4.86
0.783	0.812	0.519	4.81
0.788	0.807	0.519	4.87
0.781	0.796	0.519	4.89
0.768	0.789	0.519	4.85
0.766	0.783	0.519	4.88
		Average:	$4.86 \cdot 10^{-4}$ mtorr/V^2
		Average of all figures:	$4.79 \cdot 10^{-4}$ mtorr/V^2
		Weighted average:	$4.80 \cdot 10^{-4}$ mtorr/V^2

When the amplifier-detector was used as a null detector, the ratio of the electrostatic constants for both sides of the same transducer was easily measured to ± 2% or better. With proper care and the use of decade voltage sources for V_o, this measurement could be made to perhaps ± 0.3% (Fig. 38).

Since R and R' were presumably the same, the ratio z_{oR}/z_{oL} was also obtained from such a measurement:

$$\frac{z_{oR}}{z_{oL}} = \frac{pot_R \cdot V_{oR}}{pot_L \cdot V_{oL}} \quad . \tag{40}$$

This ratio was compared to that experimentally determined from the capacitance ratio (with the assumption that R' is the same for both sides):

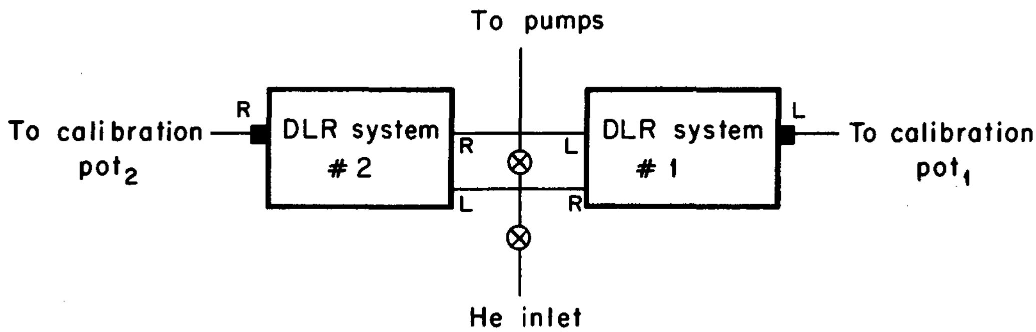
$$\frac{z_{oR}}{z_{oL}} = \frac{C_L}{C_R} \quad . \tag{41}$$

The agreement between the experimental values of the ratio determined by these two different methods was not as good as it should be. Values obtained by the electrostatic method were considerably more precise and reproducible (Table VIII).

The measurements were sufficient to enable me to compute the electrostatic constants for both sides of the No. 1 transducer to a conservatively estimated accuracy of ± 2% (Table IX).

Rather than repeat the above procedure with the DLR No. 2 system, I decided to simplify matters and to calibrate it directly against the DLR No. 1 system. This latter procedure had the additional advantage that it most closely approximated the experimental conditions when both micromanometers would be used as Wrede-Harteck gauges. Only relative ratios of readings would be required, so a relative calibration of one gauge against the other was perfectly acceptable.

I electrostatically calibrated both transducers by a null method to determine the ratio of the electrostatic constants for the opposite sides (items C and D in Table VIII). With a Speedomax 10-mV X1-, X2-vs-time Recorder (i.e., two inputs), the fractional setting of the calibration



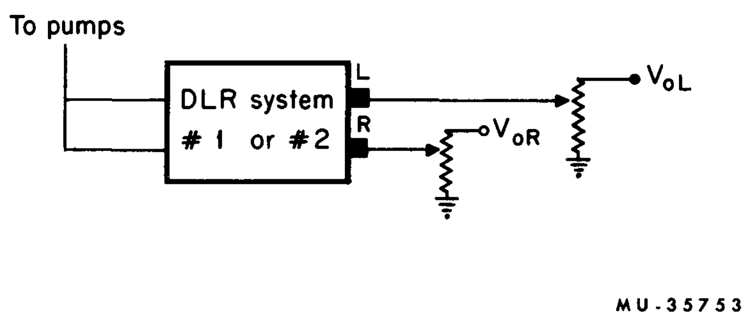


Fig. 39. Calibration apparatus for both DLR systems simultaneously.

Fig. 38. Electrostatic calibration apparatus for the DLR system.

Table VIII. Summary of measured diaphragm-to-electrode spacing ratios.

Measured ratios $\frac{z_{oR}}{z_{oL}} = \frac{pot_R}{pot_l} \cdot \frac{V_{oR}}{V_{oL}}$ for transducer in Decker-Lamers-Rony system.

z_{oR}/z_{oL}							pot_R/pot_L	
A		B	C	D	E	F	C	D
0.893	0.907	0.911	0.902	0.974	$\frac{13.135}{13.612} = 0.965$	$\frac{12.762}{13.066} = 0.977$	0.911	0.965
0.893	0.907	0.910	0.902	0.974			0.911	0.965
0.901	0.907	0.908 or 0.909	0.902	0.971			0.911	0.962
0.893	0.902	0.913		0.976				0.967
0.926	0.899	0.912						
0.885	0.895	0.910 or 0.911						
0.901	0.901	0.911 or 0.912						
0.901	0.902	0.914						
0.901		0.909 or 0.910						
0.901		0.910						
		0.913						

A. DLR system No. 1. Attenuation factor of 1. Recorder output potentiometer (10 kΩ) at either 0.50, 1.00, or 2.00 turns. V_{oL}, from a dry-cell battery, initially at 325.5 V. V_{oR} from another dry-cell battery, initially at 320.0 V. (9-22-64).

B. DLR system No. 1. Amplifier signal-attenuation factor of 0.002. Recorder output potentiometer set at 2.00 turns. $V_{oL} = V_{oR} = 127.9$ V. V_{oL} from DLR power supply and V_{oR} from Lambda Regulated Power Supply (11-16-64).

C. DLR system No. 1. Attenuation factor of 0.02. Output potentiometer at 3.00 turns. $V_{oL} = 127.0$ V. $V_{oR} = 125.8$ V. V_{oL} from DLR No. 1 power supply. V_{oR} from DLR No. 2 power supply (2-15-65).

D. DLR system No. 2. Attenuation factor of 0.02. Output potentiometer at 3.00 turns. $V_{oL} = 127.0$ V. $V_{oR} = 125.8$ V. V_{oL} from DLR No. 1 power supply and V_{oR} from DLR No. 2 power supply.

E. DLR system No. 1. Calculated value of z_{oR}/z_{oL} from measured capacitance values.

F. DLR system No. 2. Calculated value of z_{oL}/z_{oR} from measured capacitance values.

Table IX. Best electrostatic constants for DLR No. 1 and No. 2 systems.

Decker-Lamers-Rony system No. 1:		
Right side:	$P = 4.8_0 \cdot 10^{-4}\ V^2$	mtorr/V^2
Left side:	$P = 3.9_1 \cdot 10^{-4}\ V^2$	mtorr/V^2
If V = potentiometer reading $\cdot\ V_{o1}$ and V_{o1} = 127.0 V		
Right side:	$P = 7.7_4\ (pot_1)^2$	mtorr
Left side:	$P = 6.3_1\ (pot_1)^2$	mtorr
Decker-Lamers-Rony system No. 2:		
Right side:	$P = 3.3_3 \cdot 10^{-4}\ V^2$	mtorr/V^2
Left side:	$P = 3.5_1 \cdot 10^{-4}\ V^2$	mtorr/V^2
If V = potentiometer reading $\cdot\ V_{o2}$ and V_{o2} = 125.8 V		
Right side:	$P = 5.2_7\ (pot_2)^2$	mtorr
Left side:	$P = 5.5_5\ (pot_2)^2$	mtorr

potentiometer for each system needed to produce a full-scale recorder deflection was measured (Table X). Finally, with the side bypass valve closed, the ratio of the sensitivities of the two gauges to an actual pressure differential was determined by a method similar to that used to calibrate the DLR No. 1 system against the Decker micromanometer (Fig. 39 and Table X). A sample calculation is given below:

Known:

$$k_{1R} = 4.8_0 \cdot 10^{-4} \ \text{mtorr/V}^2$$
$$k_{1L} = (0.911)^2 \left(\frac{125.8}{127.0}\right)^2 k_{1R} = 3.9_1 \cdot 10^{-4} \ \text{mtorr/V}^2$$

Measured: (with the weighted average of the recorder reading ratios in Table X):

$\text{pot}^2_{1L}(\text{f-s})$ = square of fractional setting of calibration potentiometer in system No. 1 needed to produce a full-scale (f-s) recorder deflection, left-hand side, with $V_{oL} = 127.0$ V
= 0.315

$\text{pot}^2_{2R}(\text{f-s})$ = same for right-side of system No. 2, with V_{oR} = 125.8 V
= 0.322

$\frac{\text{s.r.}_2}{\text{s.r.}_1}$ = ratio of No. 2 to No. 1 scale readings (s.r.) for identical differential pressure applied across each transducer
= 1.172

Calculation:

$$P_{1L} = P_{2R}, \quad \text{for identical differential pressures}$$
$$\text{s.r.}_1 \, P_{1L}(\text{f-s}) = \text{s.r.}_2 \, P_{2R}(\text{f-s})$$
$$(0.315)(127.0)^2 \, k_{1L} = (1.172)(0.322)(125.8)^2 \, k_{2R}$$
$$(0.315)(0.911)^2 \, k_{1R} = (1.172)(0.322) \, k_{2R}$$
$$k_{2R} = 3.3_3 \cdot 10^{-4} \ \text{mtorr/V}^2$$

Table X. Summary of the simultaneous calibration measurements of the two DLR systems (2-15-65).

DLR No. 1 recorder reading, left side[a]	DLR No. 1 $pot^2_{1L}(f\text{-}s)$	DLR No. 2 recorder reading, right side[b]	DLR No. 2 $pot^2_{2R}(f\text{-}s)$	Ratio of recorder readings, No. 2/No. 2
0.707	0.315	0.831	0.322	1.175
0.599	0.315	0.720	0.322	1.202
0.697	0.315	0.831	0.322	1.192
0.593	0.315	0.715	0.322	1.206
0.627	0.315	0.754	0.322	1.203
0.589	0.315	0.691	0.322	1.173
0.616	0.315	0.725	0.322	1.177
0.599	0.315	0.712	0.322	1.189
0.658	0.315	0.770	0.322	1.170
0.747	0.315	0.881	0.322	1.179
0.749	0.315	0.873	0.322	1.166
0.726	0.315	0.843	0.322	1.161
0.740	0.315	0.865	0.322	1.169
0.743	0.315	0.871	0.322	1.172
0.746	0.315	0.874	0.322	1.172
			Weighted average:	1.172

[a]Decker-Lamers-Rony system No. 1: signal-attenuation factor, 0.02; recorder output potentiometer, 3.00 turns; V_{o1} = 127.0 V; $pot^2_{1L}(f\text{-}s)$ = 0.315; left side.

[b]Decker-Lamers-Rony system No. 2: signal-attenuation factor, 0.02; recorder output potentiometer, 3.00 turns; V_{o2} = 125.8 V; $pot^2_{2R}(f\text{-}s)$ = 0.322; right side.

4. Sample Recorder Readings and Calibration Curves

A prodigious number of short- and long-term stability recorder readings and calibration curves were obtained for a Decker 306-2A sensor and 306-2 meter combination and for the DLR No. 1 and DLR No. 2 differential micromanometer systems. To save space and avoid repetition, only two typical examples of the curves obtained are given here.

Figures 40 and 41 compare the short-term stability for the Decker system and the DLR No. 1 system (set at its most sensitive scale), respectively. The performance of the Decker pressure transducer, as shown by the two figures, was improved by a factor of about 100 with the electronics Kenneth W. Lamers designed! The stability of the DLR No. 1 system compares favorably to all other high-sensitivity differential micromanometers.

Figures 42 and 43 show the recorder data and Figs. 44 to 48 are the corresponding calibration curves for the DLR No. 1 system set at signal attenuation factors of 1.0, 0.1, 0.02, 0.002, and 0.0003, respectively. The right-hand part of Fig. 42 and the corresponding calibration curve in Fig. 46 show results for the DLR No. 2 system.

I would like to emphasize here that the step-like recorder readings took about two minutes to obtain and the calibration curve about five minutes to calculate and plot. The resulting calibration curve, which was linear to ± 1% and accurate to ± 2% or better, usually applied to the system for a period of several hours or longer.

In selecting the curves for this report, I did have a slight bias toward the nicer ones. Generally they are typical of what can be achieved with the DLR No. 1 system.

L. Other Systems

This survey of high-sensitivity differential micromanometer systems is representative, but not complete. Commercial micromanometers are also sold by the Granville Phillips Company, Atlaßwerke in Bremen, Germany, and perhaps by several other companies. Other differential

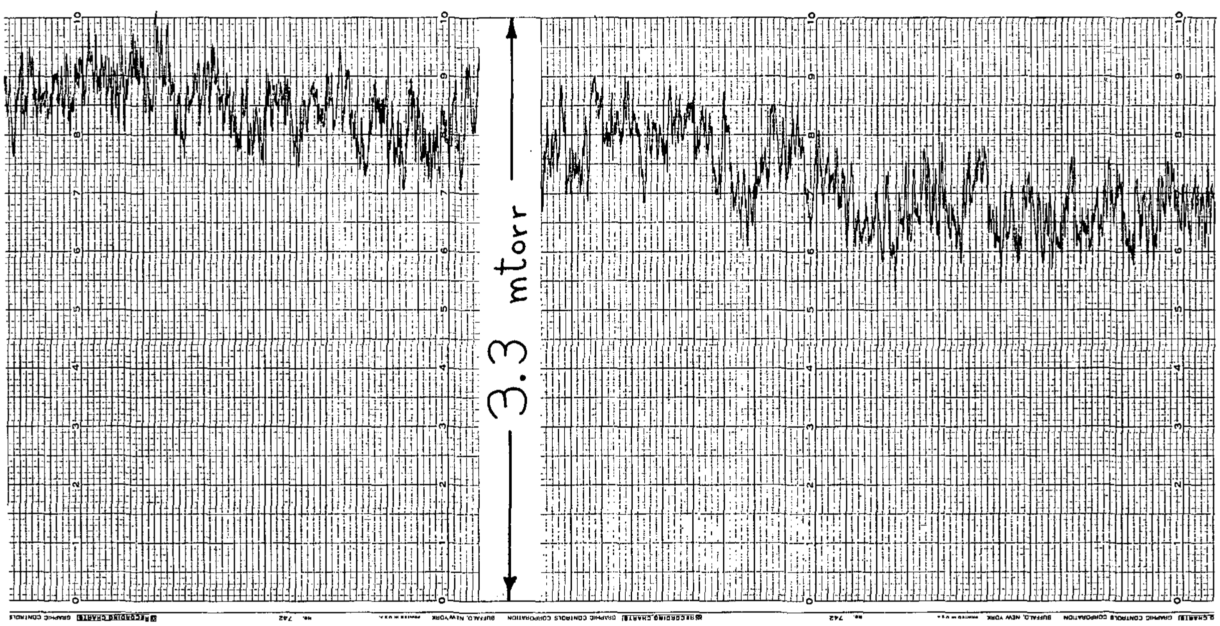


Fig. 40. Typical short term and long term stability curve for Decker 306-2A sensor and 306-2 meter (total time = one hour).

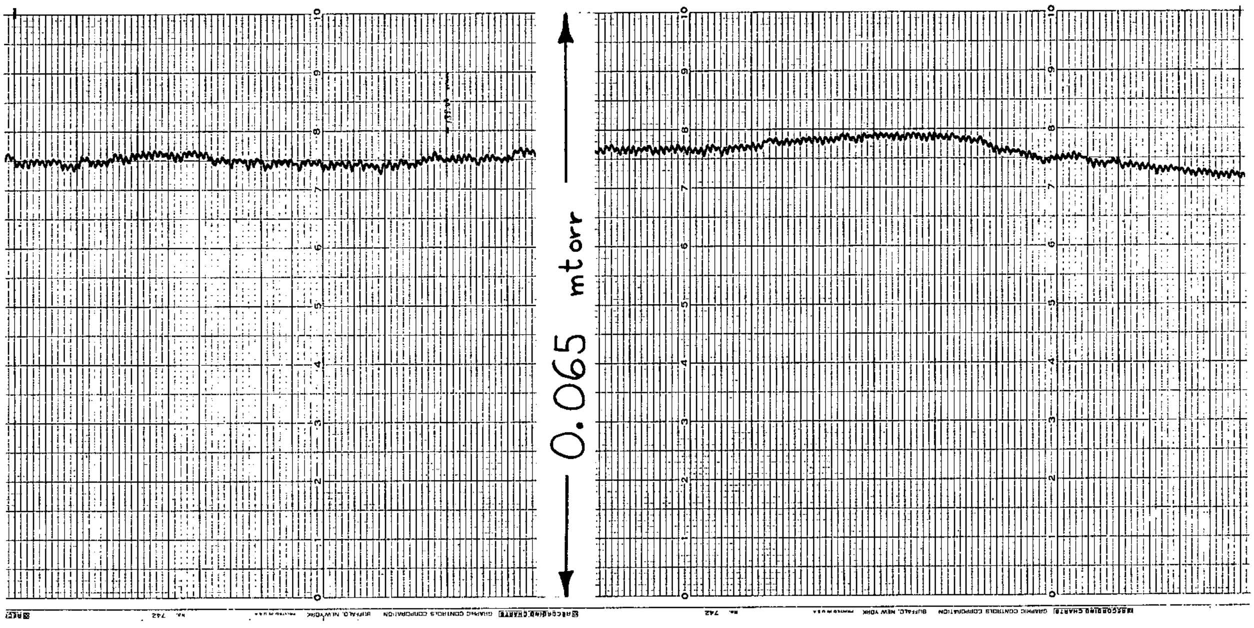


Fig. 41. Typical short term and long term stability curve for Decker-Lamers-Rony No. 1 system. Signal attenuation factor = 1.0 and recorder output potentiometer setting = 2.00 turns (total time = one hour).

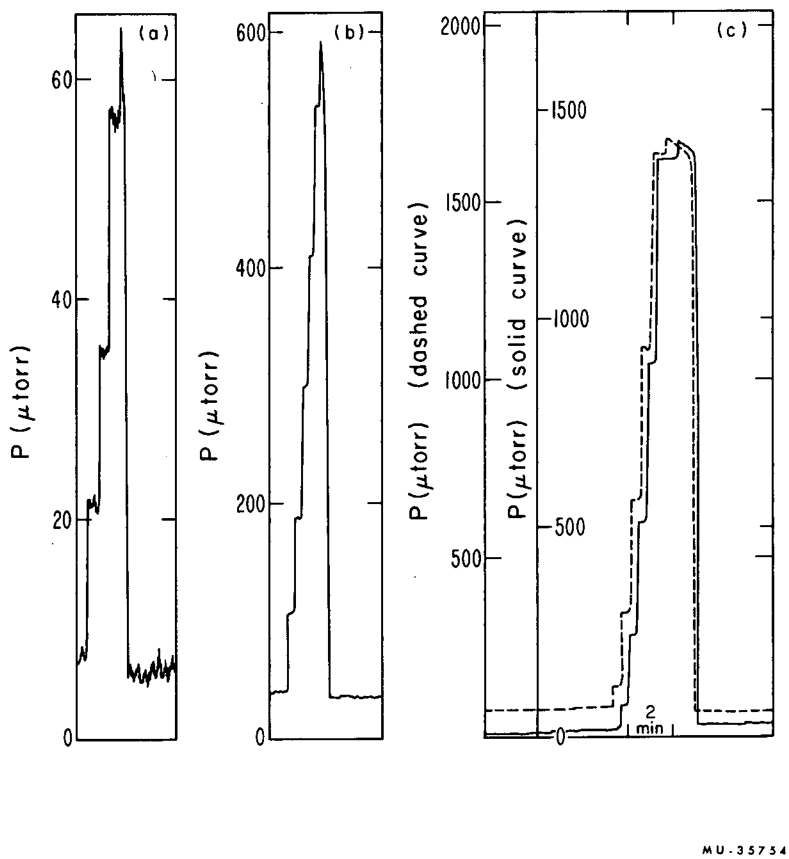


Fig. 42. Typical recorder-chart calibration data: (a) DLR No. 1, attenuation factor = 1.0, and recorder output setting = 2.00 turns; (b) DLR No. 1, attenuation factor = 0.1, and recorder output setting = 3.00 turns; (c) DLR No. 1 (solid curve) and DLR No. 2 (dashed curve), identical attenuation factors = 0.02, and identical recorder output settings = 3.00 turns.

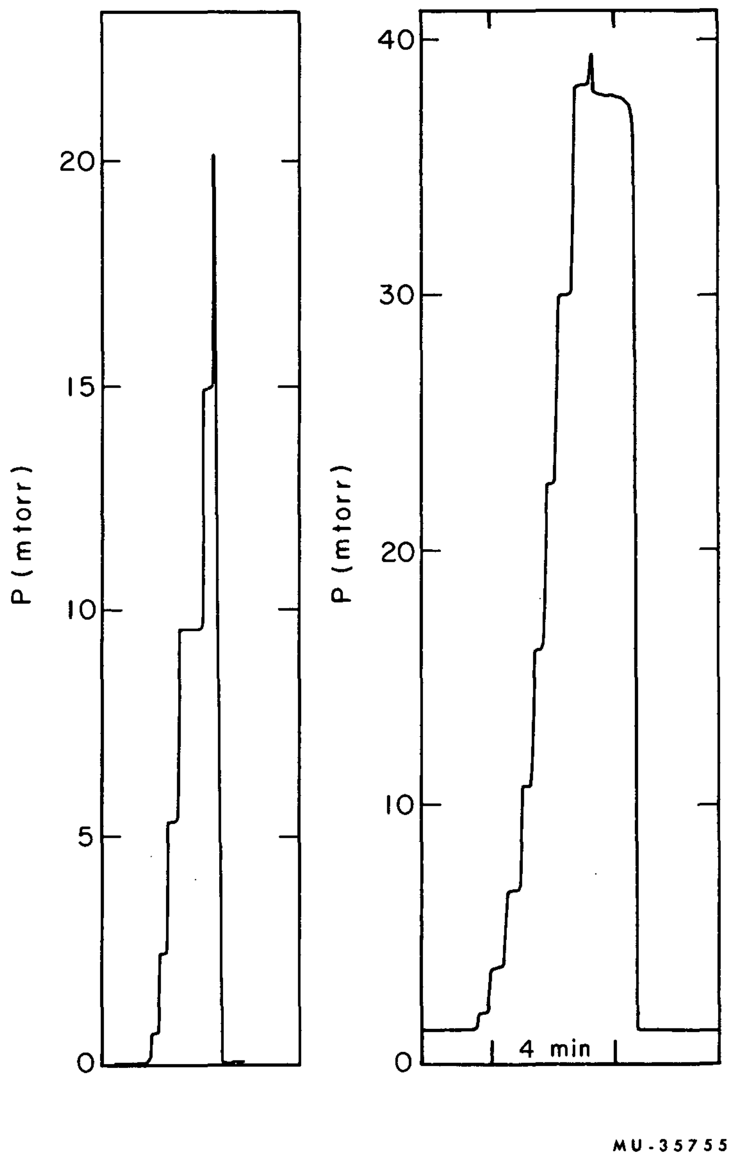


Fig. 43. Typical recorder-chart calibration data: (a) DLR No. 1, attenuation factor = 0.002, and recorder output setting = 2.00 turns; (b) DLR No. 1, attenuation factor = 0.0003, and recorder output setting = 5.00 turns.

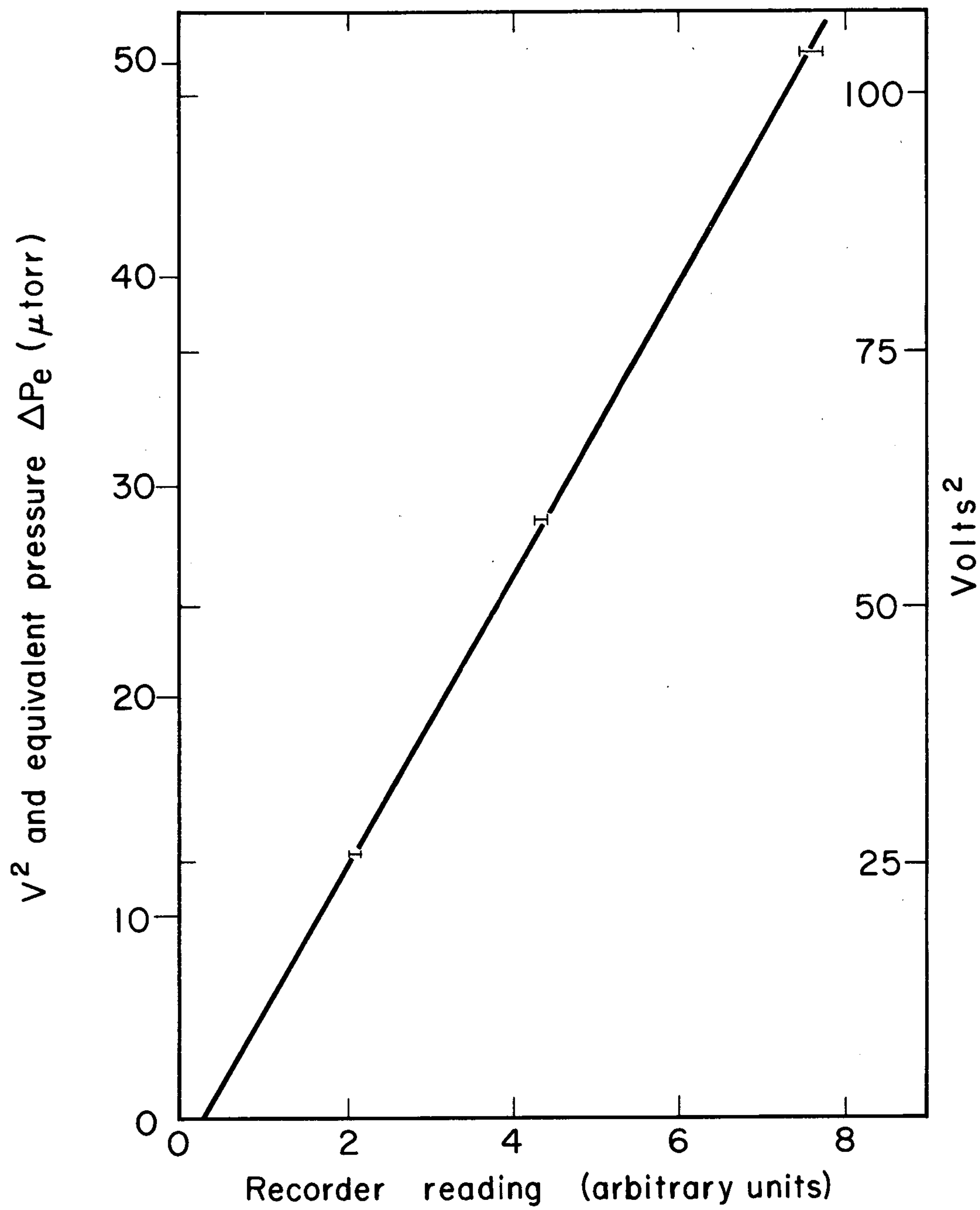


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Fig. 44. Calibration curve corresponding to chart (a) in Fig. 42.

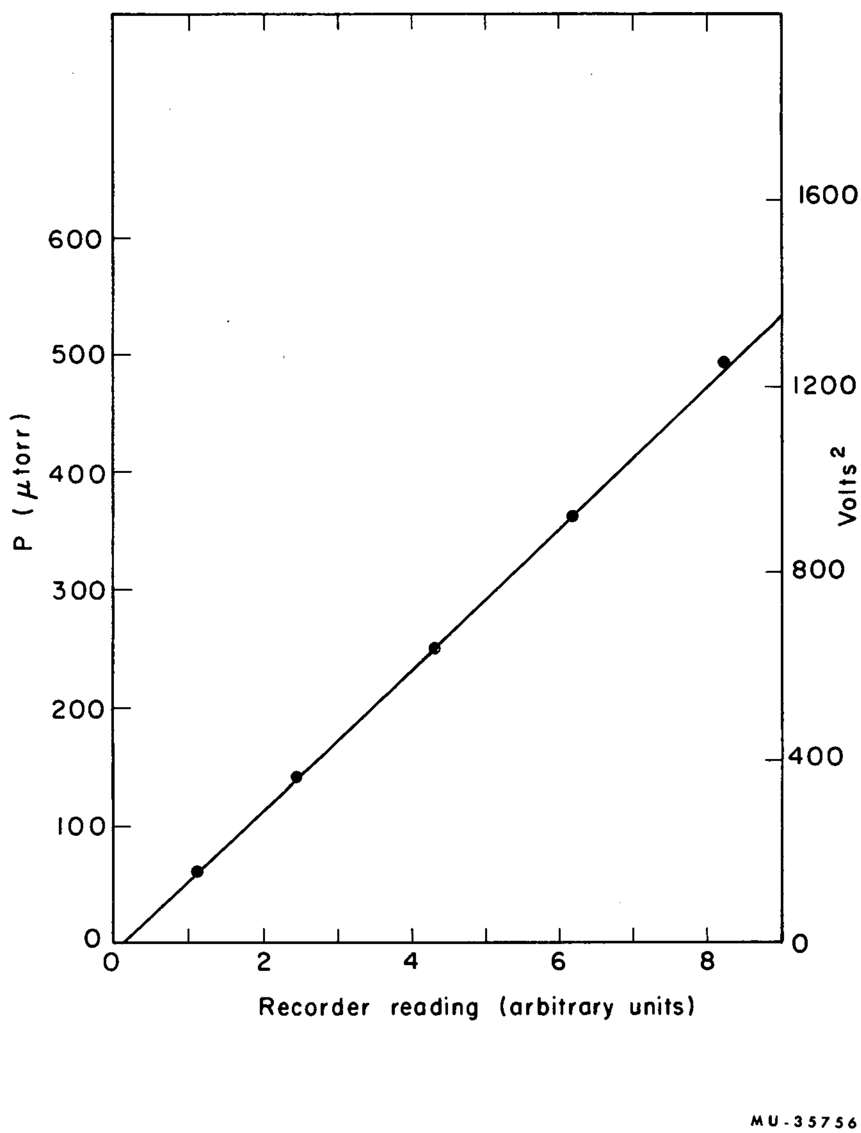

Fig. 45. Calibration curve corresponding to chart (b) in Fig. 42.

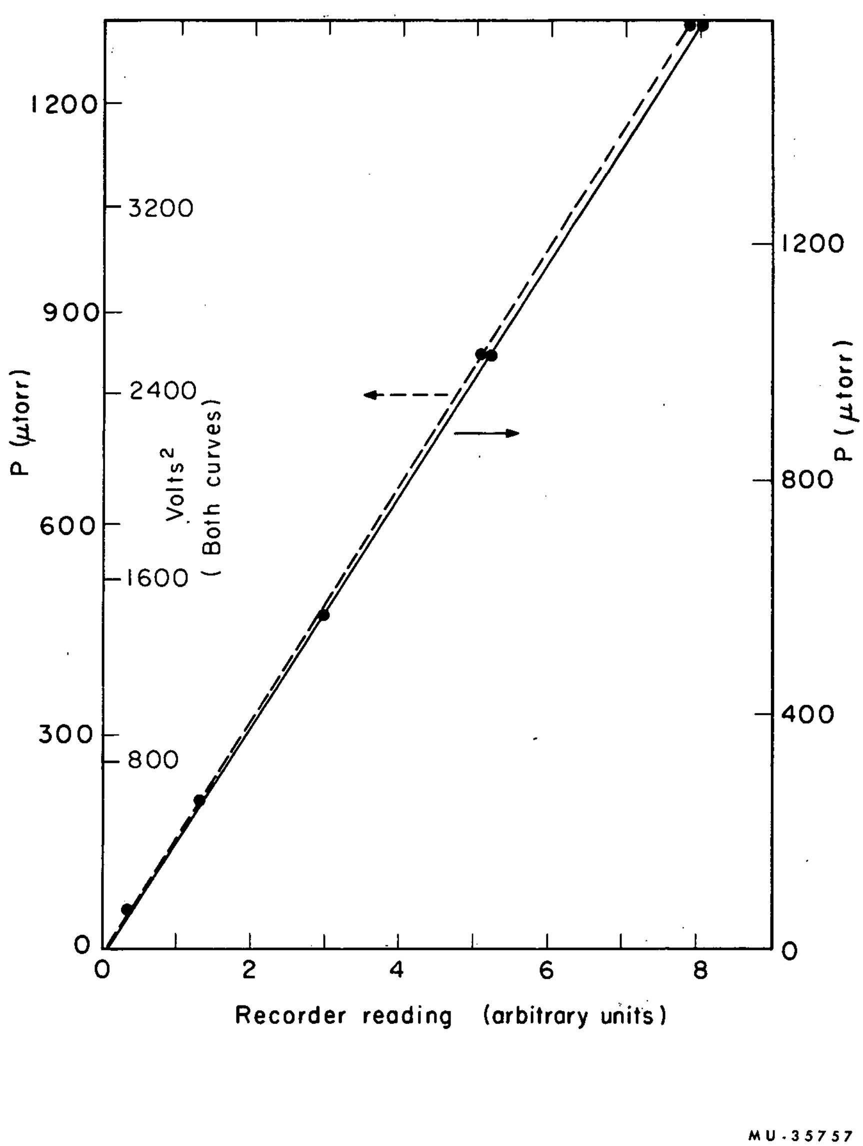

Fig. 46. Calibration curves corresponding to chart (c) in Fig. 42.

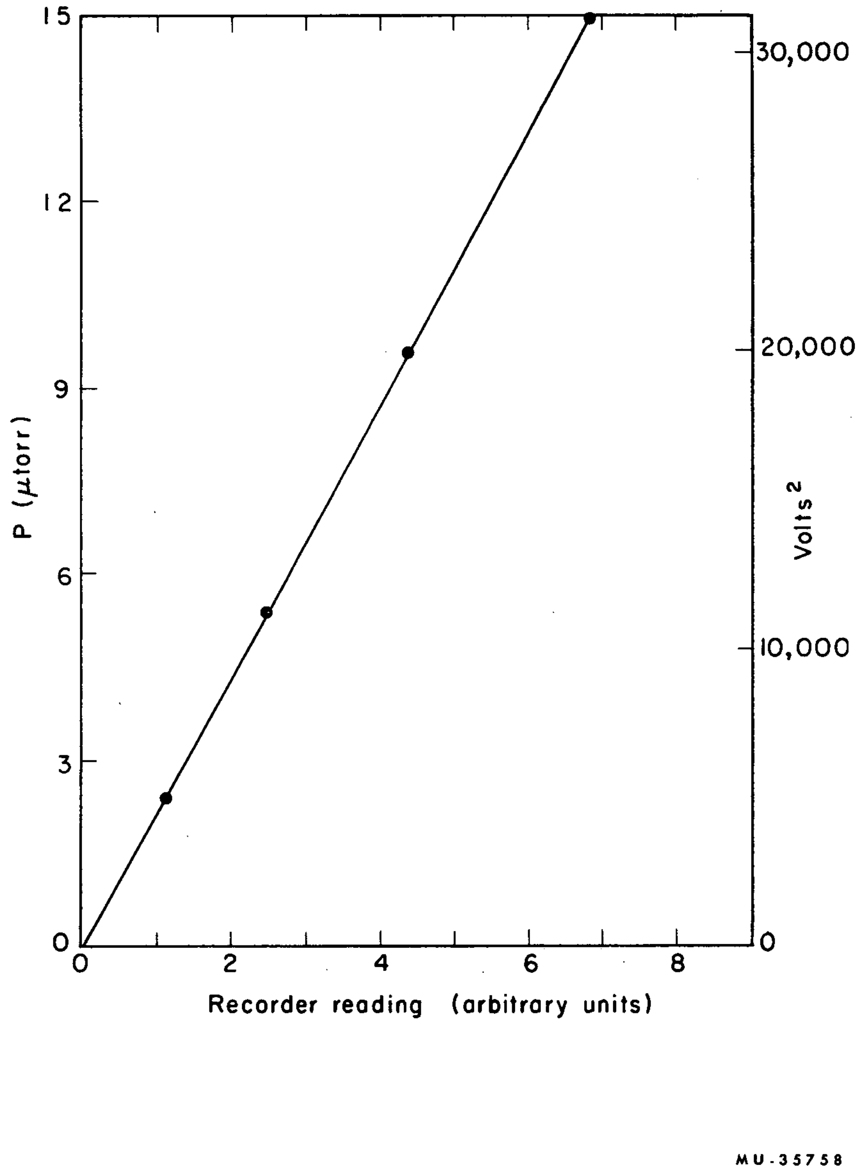

Fig. 47. Calibration curve corresponding to chart (a) in Fig. 43.

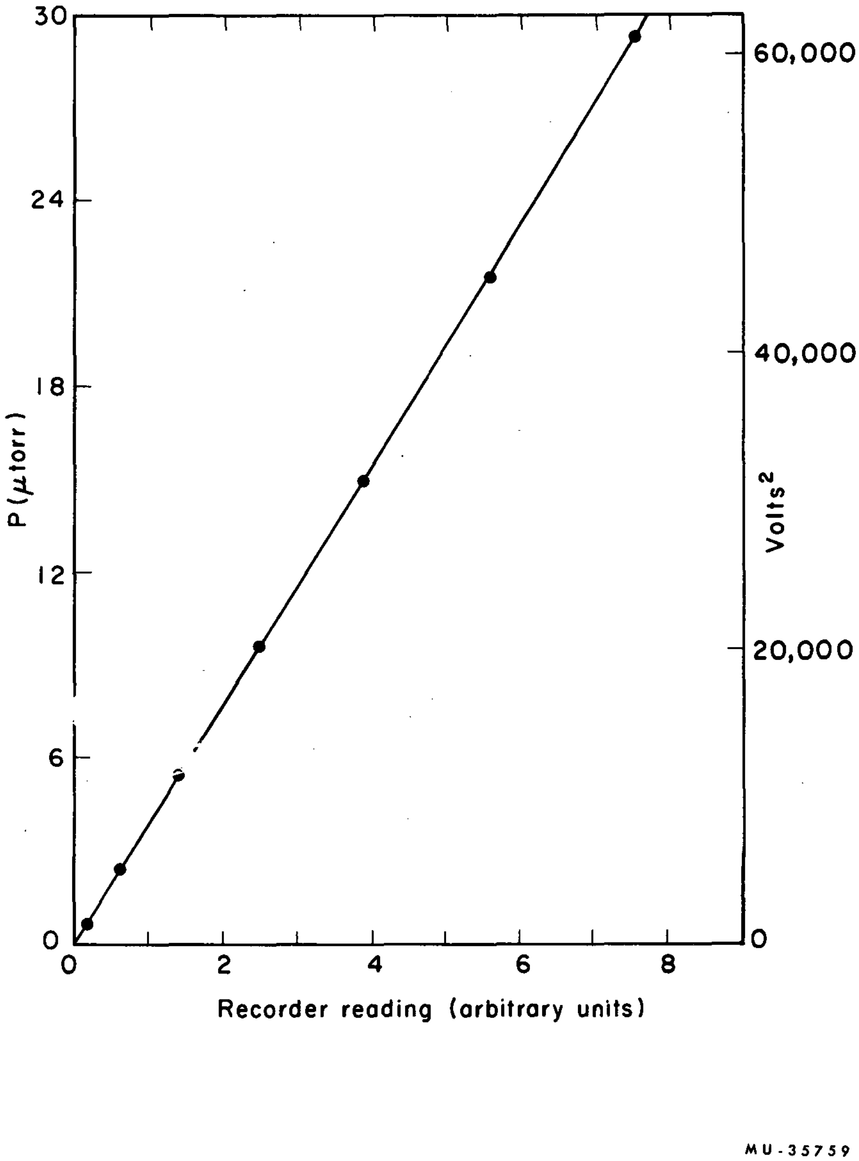

Fig. 48. Calibration curve corresponding to chart (b) in Fig. 43.

micromanometers based upon capacitance, inductance, resistance, optical, and other techniques are given in the books or articles by Leck,[27] Melville and Gowenlock,[28] and Steckelmacher.[29]

The Granville-Phillips advertisement sheet on the Series 212 Capacitance Manometer, which I have just received, is notable for its lack of many specifications on the transducer and the electronics.[30] Neglected are the long-term stability (per hour), short-term stability (30-sec interval), noise, bridge characteristics, frequency of operation, output impedance, response time, calibration stability, sensitivity to electromagnetic interference, necessity for line-voltage regulation, measured outgassing properties, and various characteristics of the capacitive transducer such as the static capacitance and the radius of the electrode and diaphragm. Like most other brochures of its type, it also fails to give typical zero-stability curves, calibration curves, or any comments on the factors limiting the stability and sensitivity of the gauge. Most of these characteristics cannot be classified as "exotic" or too specialized and should be available directly on the advertising sheet instead of through correspondence. Finally, the useful range ± 2% accuracy, 25 to 1000 mtorr, is not a very wide one for the 0 - 1 torr model.

IX. SUMMARY AND CONCLUSIONS

We developed a high-sensitivity differential micromanometer when we could find no commercial one that would meet our specifications. During the period of design, construction, and operation, improved commercial systems did appear. One of these, the Barotron (MKS Instruments, Inc.), is now as sensitive and stable as the system described in this report.

Of the various differential micromanometer systems described in the technical literature, we chose the system developed by Opsteltin, Warmoltz, and Van Zelst[9,10] and by Cope[11] because (a) it operated closed loop, (b) it had a linear relationship between pressure and output voltage, and (c) it had high sensitivity. We therefore designed and constructed a system that employed the features of the micromanometer described by the above authors. Our system eventually performed exactly to specifications, but the whole process of designing and constructing it proved to be a time-consuming and expensive operation.

In retrospect, only one of the advantages cited above was as important as it was thought to be—the sensitivity. In actual practice, the gauge designed and constructed by K. W. Lamers and me was operated open loop, but it did have a linear relationship between pressure and output voltage. Even the originally desired sensitivity, 0.1 mtorr to several percent, was not so necessary when the micromanometer was used as a Wrede-Harteck gauge. Certain limitations in the operation of the WHG made it necessary to measure 0.1 mtorr only to within 5 to 8% as the extreme lower limit.

The differential-micromanometer system we developed compares very favorably with all other micromanometers described in the technical literature for room-temperature operation. Realizing the difficulties we encountered in this research work, we have made a definite effort in Parts I and II to present as detailed and comprehensive a description as possible.

The advantages of the Decker-Lamers-Rony system are:

a. It is linear to ± 1% or better.

b. It uses an existing commercial capacitive transducer that is inexpensive.

c. The electronics are inexpensive to construct.

d. The existence of photographs, circuit diagrams, component listings, templates, tuning instructions, gain and voltage measurements, and a thorough discussion of calibration and operation makes it easier to construct than other systems.

e. It is very insensitive to electromagnetic interference.

f. The pressure transducer can be located remotely.

g. A complete mathematical description of its operation is available.

h. The micromanometer can be electrostatically calibrated to better than 2% over a range of 0.1 to 35 mtorr.

i. The calibration procedure takes two minutes, doesn't require any special equipment other than a source of regulated dc voltage and a ten-turn potentiometer, and can be done in situ without the need of special valves and duplicate manometers.

j. Careful temperature regulation of the system is not necessary. Such regulation may possibly improve the performance.

k. The system has been duplicated by a novice and operated successfully the very first time.

l. It takes only a few days to construct the bridge and electronics.

m. In principle, the upper range can be extended to 1.87 torr by desensitizing the bridge.

n. The upper range can be further extended by employing other Decker transducers. The use of such higher range transducers sacrifices the electrostatic calibration feature of the gauge, though.

o. The lower range, to 2% accuracy, can possibly be extended by employing more sensitive Decker transducers.

p. Other commercial transducers besides the Decker sensors can also be used.

The disadvantages of this system are:

a. The electronics and bridge still must be constructed rather than purchased.

b. The system has not been completely debugged.

c. The output impedance is high.

d. A double-input 5-Mc/sec oscilloscope is required for the initial tuning procedure. However, for normal operation it is not necessary.

e. The system is not trivial and thus takes time to get accustomed to.

f. It may no longer have any technical advantage over at least one commercial differential micromanometer, the MKS Instruments Barotron.

g. The transducer is not bakeable. However, a bakeable transducer can be employed easily as a substitute for the Decker sensor.

In addition to finally making two sensitive and stable differential micromanometers, the main benefits of this work came in the insights obtained during the calibration and operation of the gauge. The prinicpal benefit was the extreme utility of the electrostatic calibration technique, the advantages of which are:

a. It may eventually be an excellent primary pressure standard in the range 10 μtorr to 10 torr, superseding the McLeod gauge.

b. It is already an excellent secondary pressure standard in the same pressure range.

c. The technique can be used either as a null or an open-loop calibration method.

d. It is simple to perform.

e. It doesn't require elaborate equipment.

f. It can be done wherever the transducer is located without the use of special valves or piping, i.e., <u>in situ</u>.

g. The linearity can be easily made to be better than 0.5%.

h. The accuracy can be easily made to be better than 2%.

i. Since it is applied directly at the transducer, it eliminates changes in the bridge constant, diaphragm tension, amplification factor, detector operation, or recorder calibration.

X. FUTURE DEVELOPMENTS

As mentioned previously, the range of the Decker-Lamers-Rony system can be extended to higher or lower levels simply by use of Decker sensors 306-2B to E or 306-2F to G, respectively. Alternatively, capacitive transducers of other companies, such as MKS Instruments, Inc., Consolidated Engineering Corporation, or Granville-Phillips, can be procured. All of them are more expensive than the Decker sensors, though. I am not sure what improvement in the signal-to-noise ratio can be achieved with the more sensitive Decker 306-2F and G sensors. The use of higher range transducers requires other methods of calibration.

With the DLR system, a decade-null feature similar to that employed in the Barotron (MKS Instruments) can be easily incorporated. However, a new and improved Barotron may now meet or exceed the sensitivity and stability characteristics of the system described in this paper. Under such conditions, unless economy is very important, there is no longer any advantage to construction of the DLR system.

A typical electrostatic constant for the two Decker transducers used is approximately $4 \cdot 10^{-4}$ mtorr/V^2. This means that applied voltages of 10, 100, and 1000 V produce electrostatic "pressures" or 0.04, 4.0, and 400 mtorr, respectively. This is a wide calibration range and is well within the capabilities of modern regulated-voltage units. The only limitation to the use of high voltages is the possibility of electrical breakdown between the electrode and the diaphragm. This problem can be partially or completely eliminated by coating a thin insulating layer of high dielectric strength on the fixed electrodes. The contribution of the dielectric layer to either the capacitance or the thermal instability would be generally small.

Another way of extending the upper range of the electrostatic calibration technique is to employ capacitive transducers with larger electrode areas and smaller electrode-to-diaphragm spacings. The home-made capacitive transducer in the Lamers-Rony system, with C_o = 270 pF, R = 1 in., R' = 27/32 in., and z_o = 0.0047 cm (calc), has an electrostatic constant of about $1 \cdot 10^{-2}$ mtorr/V^2. With 1, 10, 100, and 1000 V, the electrostatic pressure in this system is 0.01 mtorr, 1.0 mtorr, 100 mtorr, and 10 torr, respectively—a range of 10^6! Provided that the diaphragm doesn't contact the fixed electrode, a system such as this would be ideal for all low-pressure studies.

The electrostatic deflection method can also be used in conjunction with a high-impedance differential lock-in amplifier to sumultaneously produce and detect electrostatic "pressures" in the ntorr region. In the case of the DLR No. 1 system, with an electrostatic constant of about $4 \cdot 10^{-4}$ mtorr/V^2, the application of a 100-cps electrostatic voltage of 0.2 V peak height produces a 200-cps signal from the DLR No. 1 system output equivalent to a peak-height "pressure" of 4 ntorr on the diaphragm. This signal can be in principle detected according to the block-diagram shown in Fig. 49.

I have stated previously that electrostatic calibration techniques are limited only to modifications of the capacitance bridge. Unfortunately, many of the commercial differential micromanometers are of the partial-capacitance-bridge type (F9g. 50). Actually, the stated limitation is not correct. The reason that the bridges shown cannot be used with an electrostatic calibration is the existence of a direct or partial dc short from one side of the differential capacitor to the other [Fig. 51(a)]. This limitation can be circumvented by placing a low-impedance capacitor in series with each side of the transducer in the lower legs of the bridge [Fig. 51(b)]. With this procedure it should be possible to adapt all existing high-sensitivity differential manometers to open-loop electrostatic-calibration systems or to closed-loop operation.

Finally, the prospects of using the electrostatic calibration technique as either a primary or secondary standard of pressure in the 10-μtorr or 10-torr pressure range should be very seriously considered. All properties of the capacitive transducer can be measured and computed probably to 0.1% or better. With a carefully designed transducer and with standardized voltages for the electrostatic calibration, there should be every reason to expect such a unit to rival or excel the McLeod

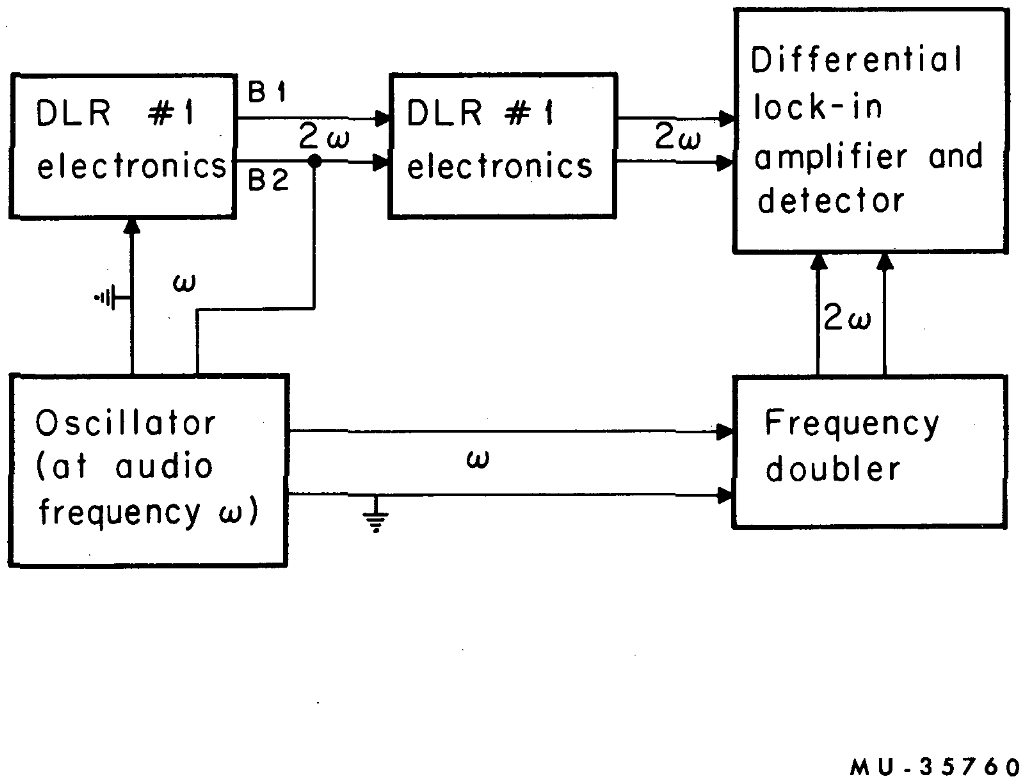

Fig. 49. Proposed block diagram for producing and detecting ntorr "electrostatic pressures".

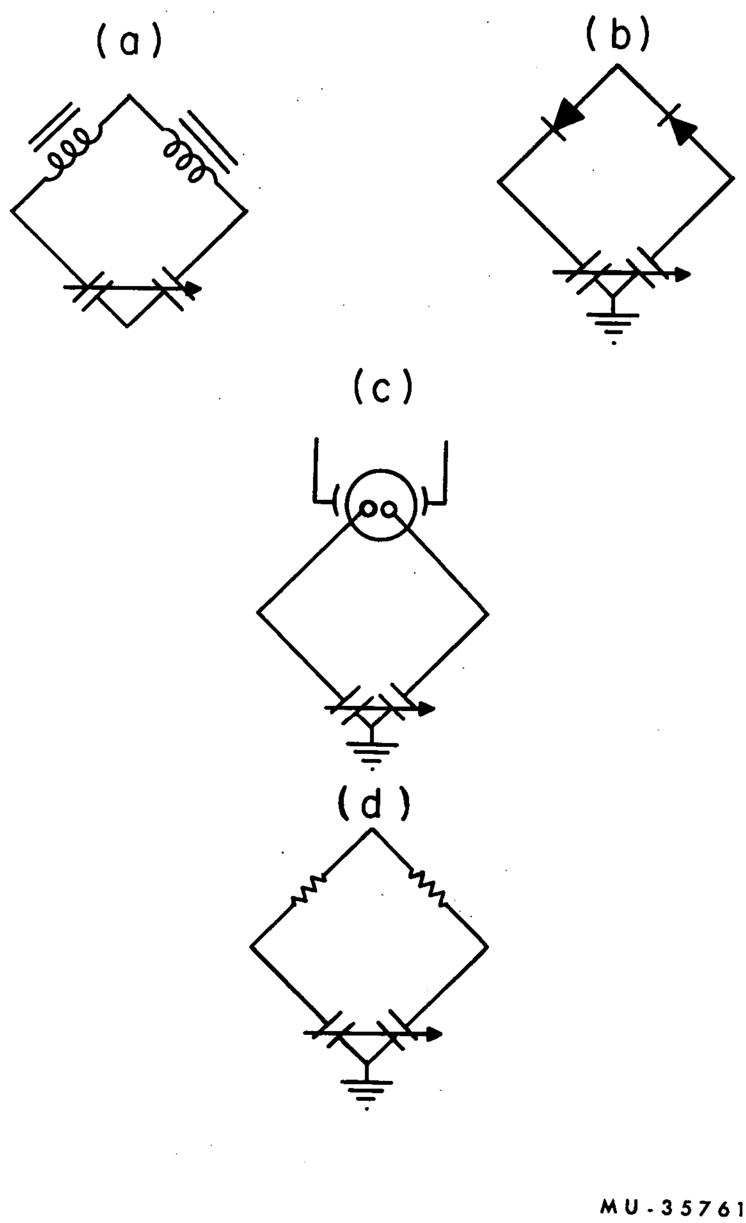

Fig. 50. Partial capacitance bridges used commercially: (a) transformer bridge; (b) diode bridge; (c) ionization-transducer bridge; (d) resistance bridge.

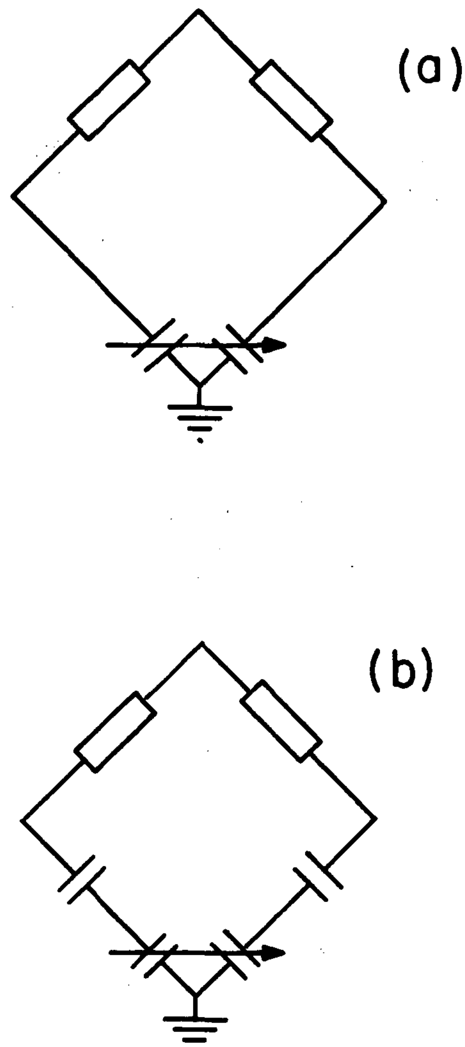

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Fig. 51. Schematic diagrams showing presence and absence of dc bypass between the differential capacitor sides: (a) with dc bypass between differential capacitor sides; (b) without dc bypass between differential capacitor sides.

gauge in this pressure region. Even if there are certain obstacles to adoption of the capacitive transducer as a primary standard, it is still a superb secondary standard and should be used widely in preference to the McLeod gauge.

SYMBOLS AND NOTATION

A	Amplification factor
C_o, C_L, C_R	Capacitance of one side of the differential micromanometer
C', C_1, C_2, C_3, C_4	Capacitances
$e = e_A - e_B$	Bridge voltage signal
E	Bridge exciting voltage
F	Force
$f(s/z_o)$	Function defined by Eq. (35)
g	Gravitational constant
h	Height
k, k_1, k_2	Electrostatic constants
K	Function of R and R' defined by Eq. (19)
L_1, L_2	Inductances
M_1	Constant defined by Eq. (25)
P	Pressure
r	Radius
R	Radius of diaphragm
R'	Radius of fixed electrode
R_1, R_2, R_c	Resistances
T	Stretching force per unit length of membrane edge
v	Signal voltage after amplification
V_o, V_{oR}, V_{oL}	Electrostatic voltages applied to fixed electrode of transducer
V_P	Polarizing voltage applied to fixed electrode of transducer
z_o, z_{oR}, z_{oL}	Diaphragm-to-electrode spacing; the subscripts R and L refer to left and right
Δz	Differential diaphragm-to-electrode spacing
α	$R^2/4T$
β	$\left(\frac{R'}{R}\right)^2 \frac{2\epsilon V_o}{z_o^2}$

ϵ	Permittivity of free space
γ	$\frac{EC'K}{C_o z_o}$
η	$\rho g h M_1$
θ	Angle with respect to vertical [Eq. (24)]
ρ	Density
ω	Radian frequency
ζ	Diaphragm displacement

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FOOTNOTES AND REFERENCES

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