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Measurement of dynamic characteristics of five stage proportional fluidic amplifier

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MEASUREMENT OF DYNAMIC CHARACTERISTICS OF FIVE STAGE PROPORTIONAL FLUID AMPLIFIER

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ABSTRACT

Experimentally determined frequency characteristics of a five stage proportional fluid amplifier are presented as a preliminary step to the design of a fluidic operational amplifier. Steady state and dynamic impedences at the input and the output are included as well as the forward gain, over the range of zero to 1000 Hz. Phase as well as magnitude is presented.

Cross talk between the two inputs and between the two outputs is less than 2% permitting one-sided excitation and measurement rather than full push-pull operation. Thus the characteristics obtained are complete for any application using the equilibrium conditions assumed.

The two admittances are seen to have a lead of less than 90^0 over the frequency range tested. The gain is roughly constant in amplitude but the phase can be approximated by a pure delay with 180^0 lag at about 900 Hz.

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Chapter I

INTRODUCTION

A fluid device in which the change in output differential pressure exceeds the causative change in input differential pressure, particularly if it has no mechanical parts, is a fluidic amplifier. If this change of the output is proportional to the change of the input, the amplifier is said to be proportional.

The purpose of this thesis is to measure the dynamic characteristics of a commercially available five-stage proportional fluidic amplifier [General Electric model AM-12]. So it subsequently can be incorporated as the heart of an optimally designed fluidic operational amplifier. An operational amplifier employs feedbacks around a high gain amplifier to achieve greater linearity, insensitivity of the gain to supply pressure changes, sharper and flatter saturation, and lower output impedence, at the expense of power and source complications. Noise characteristics may or may not be improved.

Several stages of amplification are usually needed in fluidic amplifiers to achieve a high overall gain, which in our case is about 2500. The five stages of the G. E. model AM-12 are shown in Fig. 1a. All stages are identical geometrically, and employ the jet deflection principle with two symmetrically placed input or control ports, two symmetrically placed output ports, and several vents or bleed ports. The five supply pressures which produce the power jet are markedly different from each other, however, only the output stage has the full 10 PSig supply, while the input stage has a very low supply pressure. In consequence, each first-stage control pressure has to be quite small, less than $\pm$ 0.01 PSig, for normal operation.

The gain block is fabricated from fifteen laminations of etched metal sheets which alternate between the two types shown in Fig. 1a and Fig. 1b, plus facing blocks and supply pressure manifolding laminations. External screws press the sheets together, presenting leakage but permitting disassembly for cleaning, etc. The complete assembly, with special Lehigh cover plates substituted (described later) is shown in Fig. 3. The only parts which breach the cover plate are a single supply (10 PSig), the two push-pull input or control ports, and the two push-pull output ports. No internal feedback is provided.

An operational amplifier results by placing feedback around a multistage gain block. The virtues of the circuit require an exceedingly high loop gain at low frequencies. The phase lag at high frequencies would produce violent instability, however, unless dynamic compensation is used.

The usual approach employed is to sharply reduce the amplitude of the feedback at high frequencies by inserting resistances and very large volumes (capacitors to ground) in the feedback channels as shown in Fig. 2 [Ref. 1]. The use of the flow resistances immediately to the left of the capacitances is not necessary but gives a derivative effect which can extend the closed loop response with smaller volumes than would otherwise be needed.

The worst limitation of the circuit is the rate limiting effect due to saturation of the amplifier coupled with feedback volumes. To understand this, presume a step change in the differential control pressure of 0.1 psi is imposed in a circuit that has a steady state gain of 10. The change in the steady state output differential pressures thus is 1 psi, well within the saturation limits of the amplifier. Momentarily, however, the feedback has no effect, and the output tries to become $0.1 \times 2500 = 250$ psi. Only if the linearity extended this far (it actually extends only to about 5 psi) would the overall response be as fast as it would be for an input step of less than about $\frac{5}{2500} = 0.002$ psi. Saturation of larger and more typical signal can be seen to slow down the response nearly by a factor of $\frac{250}{5} = 50$, a truly significant limitation.

The feedback volumes also present the linearized behavior from approaching the idealized optimum. The most significant conclusion, however, is that virtually all rate-limiting (saturation) effects can be eliminated by proper design. Dynamic elements are removed entirely from the feedback paths.

The most important characteristics needed for optimization are the input and output impedences of the gain block and its transfer characteristics which include gain and phase information.

Chapter II

CONCEPT OF EXPERIMENTS

In order to use a fluidic device in a circuit its input, output and transfer characteristics must be known. These are discussed under the following three headings:

1.1 Steady state self-impedences (input and output impedences of the amplifier)

1.2 Dynamic self-impedences (input and output impedences for sinusoidal excitation)

1.3 Transfer characteristics (gain and phase lag between input and output at various frequencies).

The dynamic characteristics describe only the linearized behavior. The steady state characteristics serve partly to check the linearized results at very low frequencies, when biased linearity is presumed.

The four variable pressures (two outputs and two inputs) for a given supply pressure can be related to the four associated flows with a 4 x 4 matrix of impedence or admittance parameters, plus four null values. Because of symmetry the number of independent parameters is reduced to half, i.e. ten. If we presume the usual push-pull operation, in which the sum of the two central and the sum of the two output pressures are held constant, the number of parameters is reduced to four. These can be represented in an impedence or admittance matrix [Ref. 2]

$$\begin{bmatrix} \Delta P_c \\ \Delta P_o \end{bmatrix} = \begin{bmatrix} Z_c & Z_{oc} \\ Z_{co} & Z_o \end{bmatrix} \begin{bmatrix} \Delta Q_c \\ \Delta Q_o \end{bmatrix} \quad (2a)$$

$$\text{or} \quad \begin{bmatrix} \Delta Q_c \\ \Delta Q_o \end{bmatrix} = \begin{bmatrix} Y_c & Y_{oc} \\ Y_{co} & Y_o \end{bmatrix} \begin{bmatrix} \Delta P_c \\ \Delta P_o \end{bmatrix} \quad (2b)$$

To measure the output impedence, Z_o, one sets $\Delta P_c = 0$ so that

$$Z_o = \left(\frac{\Delta P_o}{\Delta Q_o} \right)_{\Delta P_c = 0} \quad (2c)$$

For the input impedence, Z_i one sets $\Delta P_o = 0$ (no change in output pressures):

$$Z_c = \left(\frac{\Delta P_c}{\Delta Q_c} \right)_{\Delta P_o = 0} \quad (2d)$$

In practice it was determined that the ratio is completely insensitive to whether or not $\Delta P_o = 0$

The transfer impedence from output to input, Z_{oc}, was found to be immeasurably small, as would be expected from the cascading of the five stages. The final impedence, the transfer impedence from input to output, Z_{co}, could be measured using the same approach employed for Z_c and Z_o .

It was more convenient, however, to measure the transfer gain

$$g = \left(\frac{\Delta P_o}{\Delta P_c} \right)_{\Delta d = 0} = \frac{Z_{co}}{Z_c} \tag{2e}$$

which can be seen from equations (2a) - (2c) plus the statement $Z_{oc} = 0$, to be the ratio of impedences given in equation (2e).

To see the cross talk (effect of excitation at one part on the other) one port (input or output) was excited and its effect (magnitude) on the other corresponding port was seen with the help of spectrum analyzer. It was found that the cross talk between the two control ports and between the two output ports was less than 2%. Since other error exceeded 2% anyway, this meant that one-sided rather than push-pull excitation would be satisfactory. This is a considerable simplification since the nearly perfect asymmetricl balance required of push-pull excitation is difficult to achieve, and incidentally requires more equipment.

2.1 Steady-state Self Impedences

To determine the output static impedence the outputs are closed and the inputs (at virtually zero pressure) are adjusted to balance the outputs. Then the output loads are adjusted to give the desired operating point, for which the output pressures are 2 psi (Section 3.4). The output pressures and flows are noted. Then the output loads are unbalanced so as to raise one output pressure by a slight amount (0.1 psi) and to lower the other by the same amount. Again the output pressures and flows are noted. Output differential pressures and differential flows are plotted to give output static impedence. This is, of course, full push-pull excitation.

The input static impedence test was not run in a push-pull fashion, since the pressures and flows were exceedingly small. A water manometer and an inverted beaker (full of water) were employed for pressure and flow measurements, respectively (Fig. 8).

The output impedence for parallel rather than push-pull load changes also was determined for a wide range of load pressures. Because of the small cross-talk this impedence should be essentially equal to the push-pull impedence, and is primarily useful to show how this impedence changes with output pressure.

2.2 Dynamic Self-impedence

Unsteady flow in a small channel is difficult to measure directly. Hot wire measurements are possible, but are awkward and unreliable due partly to frequency-dependent velocity profiles. Instead, we chose the traditional idea of inserting calibrated flow resistances, and measuring pressure at both ends of the resistances. Equipment details are discussed in Chapter 3.

Either an input or output port can be conceptually represented as shown in Fig. 3. Since $P_i = Z_A Q$ and $P_o = (Z_A + Z) Q$

$$Y_A = \frac{1}{Z_A} = \frac{1}{Z}\left(\frac{P_o}{P_i} - 1\right) \qquad (2f)$$

Since the cross talk is less than 2% we need not run this experiment in a push-pull manner; rather only one side need be excited.

A. C sinusoidal pressures have a magnitude read from peak to peak. The phase angles between P_o and P_i are read from a Lisajor diagram, displayed on an oscilloscope, in the standard fashion.

Because of an electrical grounding problem between the two pressure transducers we could not use them together. Rather, we used only one at a time, referring magnitudes and phase angles to a common electrical signal from the driving frequency oscillator. A dual beam display also was used to make sure that the phase angles were interpreted in the proper quadrant. Noise often obscured the Lisajors patterns, particularly at low frequencies. In these cases the ratio of the magnitudes of the signals were determined using a spectrum analyzer. Phase angle information is lost in such cases.

The input dynamic impedence was measured in the same way, except that the outputs were kept open to atmosphere (it made no difference if they were blocked), and both input pressures were kept below 0.01 psi, as required for high-gain operation.

2.3 Transfer characteristics

Since the gain of the model was over 2000, the amplitudes of the signals at input were so small that they got nearly lost in the noise. Larger values would saturate the output, although the input impedence remained linear. This suggested using three signals: the oscillator voltage, the input pressure, and the output pressure. The ratio of the first two found using large amplitudes (producing saturation for the third), and the ratio of the first and the third was found using small (unsaturated) amplitudes. The ratio of the ratios then gave the desired answer. A fourth signal from a third pressure transducer was used to check the linearity of the driving system (See details in Section 3.8).

Here again there is no need of running the experiment in a push-pull fashion.

2.4 Need for Dynamic Correction

Since there are some volumes between the amplifier and the calibration resistances, a dynamic correction needs be applied to the results of the preceding sections. This correction, as derived by Mr. T. Sheikh in his thesis, for input and output impedences is given in the following equation:

$$Y = \frac{1}{R}\left[\frac{1}{1+\tau_1 D}\left(\frac{P_o}{P_i}-1\right)-\tau_2 D\right]$$

where $\tau_1 = \frac{I}{R}$ and $\tau_2 = R_C$, are time constants, "I" is inertance, "C" is compliance, "R" is resistance and "D" is operator.

A dynamic correction is applied to Transfer gain also, for which Mr. T. Sheikh's thesis also can be referred.

Chapter III

DESIGN OF EXPERIMENTS

The construction of the model is shown in Fig. 4. The four calibration resistors are each composed of a bundle of hyperdynamic tubes, held in position by tongs which are pressed inward. Dummy transducers (pins) were inserted in those transducer mountings in which no active transducers were used. Special care was taken to prevent leakage between the gain block and the main body of the model. Leakage was prevented by using Epoxy cement, pipe paint, vacuum grease, bath tub seal and seallastic rubber. A gasket was also used to prevent leakage between the main body of the model and the cover plate as shown in Fig. 4. The main body of the model has transducer mounting holes on both sides of the resistors, in a direction perpendicular to them. To reduce compressibility effects these holes are made very close to the both ends of the resistors.

3.1 Selection of Pressure Transducers

Two semiconductor strain gage pressure transducers [Kulite SemicondctorProducts Inc.] were used because of their small size [0.093" diameter], response from D.C. to high frequencies, sensitivity and resolution (about 0.01 psi). Two Tektronix Q-plug in units (Serial No. 000722 and 001961) performing the exitation, balancing, and amplification functions were used with each of these pressure transducers.

3.2 Design of Resistors

Considering the input and output requirements of the gain block we require a resistor of approximately 20,000 sec/in^{-2}. Hyper-dynamic tubes were chosen because parallel shear flow results in greater linearity than the flow through an irregular passage and is easily predictable.

For air at 72°F and 14.7 PSia,

$$\rho = 0.0745 \text{ lb/ft}^3 = 4.33 \times 10^{-5} \text{ lb/in}^3$$

$$\nu = \frac{\mu}{\rho} = 2.24 \times 10^{-2} \text{ in}^2/\text{sec}$$

Now Reynald's # $N_r = \frac{Vd}{\nu} = \frac{4Q}{n\pi d^2}\frac{d}{\nu} = \frac{4Q}{\pi d \nu n}\left(\frac{\text{in}^3}{\text{sec in}}\frac{\text{sec}}{\text{in}^2}\right)$

We want the flow to be fully developed over most of the length of the tubes, in order to achieve the desired linearity. The condition for fully developed flow is $\frac{L}{d} = \frac{1}{4} N_r$ [Ref. 3].

i.e. $\frac{L}{d} = \frac{1}{4} N_r = \frac{1}{4}\frac{4Q}{\pi d \nu n}$ or $L = \frac{Q}{\pi \nu n}\left(\frac{\text{in}^3}{\text{sec}}\frac{\text{sec}}{\text{in}^2}\right)$

Assume L = 0.2'' and $\Delta P = 4$ psi

Now $Q = \frac{\Delta P}{\rho R} = \frac{4}{20{,}000 \times 4.33 \times 10^{-5}} = 4.62 \text{ in}^3/\text{sec}$

$$n = \frac{Q}{\pi L \nu} = \frac{4.62}{\pi \times 0.2 \times 2.24 \times 10^{-2}} = 328$$

According to Hagen Poiseville's equation [Ref. 4]

$$\mu = \frac{\Delta P d^2 g}{32 V L} = \frac{\Delta P d^2}{32 L}\frac{\pi d^2 n g}{4Q} = \frac{\pi}{128}\frac{\Delta P d^4 n g}{L Q}$$

$$\text{or } d = \sqrt[4]{\frac{128}{\pi}\,\frac{\mu L Q}{\Delta p\, n g}} \quad \left(\sqrt[4]{\frac{lb}{in^2\, sec}\,\frac{in}{lb}\,\frac{in^2\, in^3}{sec}\,\frac{sec^2}{in}}\right)$$

$$= \sqrt[4]{\frac{128}{\pi}\,\frac{2.24\times10^{-2}\times0.2\times4.62\times4.33\times10^{-5}}{4\times328\times386}} = 0.00293''$$

$$\therefore\ d \simeq 0.003''; \ A = \frac{\pi}{4}d^2 = 7.065\times10^{-6}\ in^2$$

$$N_R = \frac{4Q}{\pi d \gamma n} = \frac{4\times4.62}{\pi\times0.003\times2.24\times10^{-2}\times328} = 264$$

For no turbulence the Reynald's number should be less than 2000 [Ref. 5]. So we are quite safe as far as turbulence is concerned.

Now the total area left by the spacings between the tubes is about 110% of the total area through the tubes, but taking into account the boundary layer (in the spacings between the tubes) effects we can reduce the number of tubes by about 60%. So now we need only $\frac{328}{1.6} = 205$ tubes. If we put these tubes in a square section for 14x14 = 196 tubes ($\simeq$ 205) we require 0.084"x0.084" Section, since the tubes available are 0.003" I.D. and 0.006" O.D. Now the sensing diameter of pressure transducer is 0.08", which is pretty close to 0.084". Four such resistors are put, two at the inputs and two at the outputs as shown in Fig. 4.

3.3 Calibration of Resistors

The inside (closer to gain block) pressure transducer is removed to ensure that pressure downstream of the resistor is atmospheric (and now we will have to measure only one pressure). The gain block may or may not be attached (if the inside pressure transducer is removed) but if this is removed the inside pressure transducer need not be removed.

Now some measured pressure and flow is given through the resistor with one side of resistor open to atmosphere. The flow is corrected for different (than atmospheric) pressure at output of flowmeter. D. C. pressures measured by pressure transducers are proportional to deflections of trace on scope and are known from calibration of pressure transducers already known. These pressures and flows are drawn to give calibration of resistors.

MOUNTING: See Fig. 5

APPARATUS:

i) Pressure transducer, ii) flowmeter (very sensitive), iii) water flowmeter and 5 psi pressure gage, iv) Q-plug-in unit and scope, v) T-joint and air supply, etc.

PROCEDURE:

i) Set up the apparatus as shown.

ii) Apply some pressure and take the readings of flowmeter, manometer and deflection of trace on scope.

iii) Increase pressure and take the same readings again. A number of readings were taken in this way. At higher pressures a 5 psi gage was used in place of water manometer.

iv) Correct the measured flow for different (than atmosphere) output pressure since $Q_{act} = Q_{obs.} \sqrt{\frac{14.7 + \text{Manometer reading}}{14.7}}$

v) Calibration of pressure transducer being known a curve can be drawn between Q_{act} and actual pressure (measured by pressure transducer), giving calibration of resistor "o", which is shown in Fig. D.

From Fig. D the resistance at about 2 psi (operating point as seen in Section 3.4) is 15,900 sec/in^{-2} which is quite different from the values assumed (20,000 Sec/in^{-2}). This much error can be expected since the ends of the hyperdynamic tubes are spoiled and are bent where they are cut from one long tube.

Calibration of other resistors (input and output) was drawn in the same way but after being sure about the calibration of pressure transducers at the position under use.

3.4 Output Pressure Flow Characteristics

The operating point is seen from output pressure flow characteristics which are drawn as follows:

MOUNTING: See Fig. 6

APPARATUS:

i) 5 psi balance, ii) flowmeter, iii) Four restrictions, iv) Model, v) two T-joints, vi) Tubing, etc.

PROCEDURE:

i) Supply 10 psi after making connections as shown.

ii) Block R_{o1} and R_{o2} and adjust R_{c1} and R_{c2} to balance outputs.

iii) Measure gage pressure on one leg by disconnecting the other leg.

iv) Connect the leg again and open R_{o1} little bit to give some reading on flowmeter.

v) Again remove one leg and take gage pressure.

vi) Repeat till whole of R_{o1} is open.

vii) Plot a curve between gage pressure and flow which gives pressure flow characteristics.

viii) Since characteristics of resistor are known we can find pressure flow characteristics inside the resistor also by just adding the pressure drop to above characteristics. From Fig. F the operating point is seen at 2 psi and 0.031 CFM flow for resistor O_2. In the same way these characteristics for other resistors can be drawn.

SPECIMEN CALCULATIONS:

For resistor O_1

Flow meter reading = 99 div.

Pressure gage reading = 2.7 psi

From calibration of flowmeter, flow at 99 div. = 0.0108 CFM

So 2.7 psi and 0.0108 CFM are plotted.

From calibration of resister O_1 (Fig. D) pressure drop = 0.175 psi

∴ point, 2.7 + .175 = 2.875 and 0.0108 CFM is on the plot (Fig. F)

3.5 Static Output Impedence

APPARATUS:

i) Model, ii) Two pressure transducers and Q-block, iii) Four restrictions (adjustable), iv) a sensitive flowmeter and v) Air supply, etc.

MOUNTING: See Fig. 7

PROCEDURE:

i) Calibrate the pressure transducers in position as shown.

ii) Make connections as shown (Fig. 7) and supply a pressure of 10 psi. Close R_{o_1} and R_{o_2} fully and adjust R_{c_1} and R_{c_2} to balance the outputs for equal pressure shown by pressure transducers.

iii) Open R_{o_1} and R_{o_2} to get 2 psi (Shown by each of pressure transducers at output) which is the operating output pressure as seen from output pressure flow characteristics.

iv) Measure flow from each of output port.

v) Increase pressure on one output (say o_1) by about 0.1 psi and decrease it on other port (o_2) by same amount. Measure flow through each of outputs.

vi) Repeat the same thing by taking 2-3 increments like this. Repeat the same experiment by going on reverse side, i.e., now start decreasing pressure in the output where it was increased previously.

vii) A graph between output pressure and flow differentials gives the static output impedence. (Fig. 11)

SPECIMEN CALCULATIONS

Pressure P_{io_1} = 1.7 psi

Pressure P_{io_2} = 2.3 psi

$\therefore \quad \Delta P = P_{io_2} - P_{io_1} = 2.3 - 1.7 = 0.6$ psi

Now Flow Q_{o_1} = 125 div. = 0.0162 CFM

Flow Q_{o_2} = 62 div. = 0.0215 CFM

$\Delta Q = Q_{o_2} - Q_{o_1} = 0.0215 - 0.0162 = 0.0053$

Point 0.6 psi and 0.0053 CFM lies on the static output curve (Fig. H)

3.6 Static Input Impedence

Since pressures and flows are very small we can't use pressure transducers and flowmeter and therefore we have to go for some other technique to measure flows and pressures.

APPARATUS:

i) Model, ii) water manometer, iii) T-joint, iv) restriction, v) graduated cylinder (1000 ml), some container, vii) stop watch, etc.

MOUNTING: See Figs. 8a and 8b

PROCEDURE:

Supply 10 psi

i) Take reading of water manometer with R_{c_2} fully closed.

ii) Open R_{c_2} little bit, but taking care that pressure shown by manometer is a small fraction of .01 psi (Allowable control pressure).

iii) Take manometer reading and pass the same flow in an inverted (in a tub of water) graduated cylinder for a particular time which will give us the flow used for the experiment.

iv) Repeat the same experiment for a number of different pressure and flow increments.

v) A curve between input pressure's and flow's differentials gives static input impedence (Fig. G)

SPECIMEN CALCULATIONS:

Manometer readings

i) 33.075" of water   ii) 33.2" of water

$\Delta P = 33.2 - 33.075 = 0.125"$ of water $= 0.0045$ psi

Flow readings

i) 0.0001945 CFM   ii) 0.0002 CFM

$\Delta Q = 0.0002 - 0.0001945 = 0.0000155$ CFM

Point 0.0045 psi and 0.0000155 CFM lies on the curve (Fig. G)

3.7 Output Dynamic Impedence

MOUNTING: See Fig. 9

APPARATUS

i) Four restrictions, ii) Three T-joints, iii) A Hi-Fi driver iv) Power amplifier, v) frequen cy generator, vi) Q-block, vii) CA plug-in, viii) flowmeter.

The Hi-Fi driver is connected with two G.E. barb fittings, as shown, so that pressure on each side of its diaphragm is equal. This helps protect it from higher pressure changes on both sides of it.

PROCEDURE:

i) Supply 10 psi. Block R_{o_1} and R_{o_2}. Adjust R_{c_1} and R_{c_2} to balance the outputs for equal pressures (Both the outputs can be connected to a pressure gage to show the balance).

ii) Open R_{o_1} and R_{o_2} to get 2 psi at outputs of gain block, i.e., pressures between gain block and feedback resistors should be 2 psi. (One pressure is seen by pressure transducer while other pressure can be calculated once pressure and flow after the resistor are known since characteristics of the resistor are known).

iii) Now frequency oscillator is switched on. Magnitudes of amplitude P_i and P_o are noted in two steps so are phase angles ϕ_{Ro} and ϕ_{Ri} giving phase angle between P_i and P_o.

At low frequencies we have to use some other oscillator (with flip flop valve) instead of Hi-Fi driver. Technique is the same except there is a little change in setup as shown in Fig. 10.

Here since we are connecting the oscillator to a pressure source we see some pressure, downstream the oscillator. To come across this the restriction R_{o2} is opened wider apart to get 2 psi at inside pressure transducer again. Everything else is exactly the same. Zero frequency point is taken in exactly the same way with the help of spectrum analyzer at about 50 Hz. In this case phase information is lost. Output admittances corrected (for dynamics) and uncorrected are shown in Fig. J.

SPECIMEN CALCULATIONS:

Signal from oscillator (E_1) is taken as reference and sign of signal E_2 from pressure transducer depends on its lead (positive) or lag (negative). Leajor-U is read as shown in Fig. 11.

f (frequency) = 714 Hz (from scope)

Pressure Magnitude P_i = 1.97 cm (at 200 st./div.)

$\Phi_{Ri} = \sin^{-1}\frac{B}{A} = \sin^{-1}\frac{D}{C} = 90^o$ (From shape of Leajor - U)

Pressure Magnitude P_o = 3.8 cm (at 200 st./div.)

$\Phi'_{Ro} = \sin^{-1}\frac{54}{5.85} = 67.5^o$; $\Phi''_{Ro} = \sin^{-1}\frac{3.15}{3.4} = 67.9$;

$$\Phi'''_{Ro} = \frac{\Phi'_{Ro} + \Phi''_{Ro}}{2} = 67.7^o$$

From shape of Leajor - U $\Phi_{Ro} = -(\Phi'''_{Ro} + 180) = -(180+67.7)^o$

$$\Phi = \Phi_{Ro} - \Phi_{Ri} = -(180+67.7) - 90 = 22.3^o$$

Pressure ratio = $\frac{P_o(cm.)}{P_i(cm)}$ x ratio of calibrations of pressure transducers = $\frac{3.8}{1.97} \times 0.707 = 1.36$

Now $YR = \frac{P_o}{P_i}\angle\Phi - 1 = 1.36(\cos 22.3 + j\sin 22.3) - 1 = 0.26 + j0.516$

3.8 Input Dynamic Impedence

Apparatus and experiment is exactly the same as at output. Here outputs are kept open to atmosphere. It is to be noted that the signal should be such that pressure at input to gain block (i.e. P_{c_i}) should be less than 0.01 psi as desired by the characteristics of the gain block. Input admittance curve corrected and uncorrected are shown in Fig. I.

Specimen Calculations:

$f = 758$ Hz (from scope)

Pressure Magnitude $P_i = 2.6$ cm (at 10 St./div.)

$\phi_{Ri} = \sin^{-1}\frac{B}{A} = \sin^{-1}\frac{D}{C} = 0^\circ$ (From shape of Leazer-U)

Pressure Magnitude $P_o = 3.5$ cm (at 10 St./div.)

$\phi'_{Ro} = \sin^{-1}\frac{.45}{1.3} = 20.2^\circ$; $\phi''_{Ro} = \sin^{-1}\frac{.4}{1.25} = 18.65^\circ$; $\phi'''_{Ro} = \frac{\phi'_{Ro} + \phi''_{Ro}}{2} = 19.43^\circ$

FROM Leazer-U $\phi_{Ro} = \phi'''_{Ro} = 19.43^\circ$

$\phi = \phi_{Ro} - \phi_{Ri} = 19.43 - 0 = 19.43^\circ$

Pressure ratio $= \frac{P_o(\text{cm.})}{P_i(\text{cm.})}$ x ratio of calibrations $= \frac{3.5}{2.6} \times \frac{1}{1.036} = 1.3$

Now $YR = \frac{P_o}{P_i}\angle\phi - 1 = 1.3\ (\cos 19.43^\circ + j \sin 19.43^\circ) - 1 = 0.228 + j0.433$

3.8 Transfer Characteristics

MOUNTING: See Fig. 11

APPARATUS:

i) model, ii) Four adjustable restrictions, iii) 1 psi pressure gage, iv) Hi-Fi driver, v) power amplifier, vi) frequency oscillator, vii) Two Q-plug-in units, viii) Special fitting for bigger pressure transducer P_t, etc.

PROCEDURE:

i) Set up the experiment as shown in Fig. 11 and apply a small pressure P_{st} and adjust R_{st} so that pressure P_{it} is less than 0.01 and balance the outputs with R_{o_1} and R_{o_2} blocked.

ii) Block the outputs completely after removing all kinds of tubing, etc. This is done since higher gains are expected with blocked loads.

iii) Switch on frequency generator, adjust R_{bt} and electrical magnitude so that P_{ot} is about 2 psi. Measure P_t and P_{ot} and phase angle (Φ_{ot}) between references and P_{ot}.

iv) Increase the amplitude (electrical amp. at frequency generator) and measure P_t and P_{it}. Measure phase angle (Φ_{it}) of P_{it} with reference from frequency generator. Now difference between Φ_{ot} and Φ_{it} gives phase angle between output and input whereas gain can be found as mentioned earlier.

Here again at low frequencies we have to use flip flop frequency oscillator; since a big resistor R_{bt} is in downstream of oscillator we won't come across any trouble we had earlier. The way of connecting this oscillator is exactly the same as used earlier.

SPECIMEN CALCULATIONS:

frequency f = 834 Hz (from scope)

P_{t_i} = 4.4 cm. (at 50 st./div.)

P_{ot} = 3.6 cm. (at 200 st./div.)

P_{t_2} = 3.75 cm (at 500 st./div.)

$\therefore$ Magnification ratio = $\frac{P_{t_2}}{P_{t_1}} = \frac{3.75\ (500\mu\ st.)}{4.4\ (50\mu\ st.)} = \frac{37.5}{4.4}$

P_{it} = 1.5 cm (at 10 st./div.)

$\phi_{it} = \phi'_{it} - \phi''_{it} = 0^\circ$ (From shape of Leajor - U)

$\phi = \phi_{it} - \phi_{ot} = 0 - 57.78 = -57.78^\circ$

But since we are not running this as push-pull and we are measuring output angle on reverse side we must add 180° to "ϕ" to get actual angle between input and output.

$\therefore \phi = -57.78 + 180 = 122.22^\circ$

Now gain = $2\frac{P_{ot}}{P_{it}}$ x ratio of calibration of pressure transducers' x Magnification ratio = $2 \times \frac{3.6\ (200\mu)}{1.5\ (10\mu)} \times 1.482 \times \frac{37.5}{4.4}$

$= 1230$

Chapter 4

CONCLUSION

Noise was the main problem in reading the data, especially at high and very low frequencies. At the input, the noise was much less than at the output, so the input data is more accurate. Other sources of error in the data could be the pressure transducer calibrations, which sometimes changed when a transducer was remounted or otherwise disturbed, and error in the operating point coupled with nonlinearities. Most raw data is believed to be accurate within $\pm$ 10% and after magnification in the data reduction some results could be $\pm$ 30% erroneous.

As seen, the two self admittances have a lead less than 90° over the frequency range tested. There is only a small variation in the input admittance after correction, and the gain is roughly constant in amplitude (after correction) with 180° lag at about 900 Hz.

A significant consequence of these results is that virtually all rate limiting (saturation) effects of an operational amplifier potentially can be eliminated by proper design. Dynamic elements are removed entirely from the feedback paths.

NOMENCLATURE

ρ	Density of air at S. T. P.; (lb/in^3)
μ	viscosity coefficient $\left(\frac{lb}{in\ sec}\right)$
ν	kinematic viscosity, $\frac{\mu}{\rho}$
Nr	Reynold's #
V	Velocity of air; (in/sec)
Q	Air flow (in^3/sec)
d	Internal diamter of hyperdynamic tube; (in)
n	Number of hyperdynamic tubes per resistor.
L	Length of hyperdynamic tube; (in)
ΔP	Pressure drop across a resistor; (lb/in^2)
R	Resistance of a resitor; (sec/in^2)
g	Acceleration due to gravity; (in./sec^2)
A	Cross-section area of hyperdynamic tube, (in^2)
$Q_{obs.}$	Flow through a resistor as shown by flowmeter (ft^3/mt)
$Q_{act.}$	Flow through a resistor after applying correction for different output pressure of flowmeter; (ft^3/mt)
C. F. M.	cubic ft. per minute
ΔP_c	Differential control pressure; (lb/in^2)
ΔP_o	Differential output pressure (" ")
ΔQ_c	Differential control flow; (C. F. M.)
ΔQ_o	Differential output flow; (")

Z_c	Input impedence; $\frac{5}{144}$ $\frac{lb. sec}{in^5}$
Z_o	Output impedence; " "
Z_{co}	Impedence between control and output;
Z_{oc}	Impedence between output and control;
Y	Admittances; $\frac{144}{5}$ $\frac{in^5}{lb\ sec}$
R_{c_1}, R_{c_2}	Restrictions at input
R_{o1}, R_{o2}	Restrictions at output
C_1, C_2	Input resistors
O_1, O_2	Output resistors
S	Supply pressure; (lb/in^2)
Z_A	Impedence of amplifier (at input or at output); $\frac{5}{144}$ lb $\frac{sec}{in^5}$
Z	Impedence of resistor (Since this is not an ideal resistor)
P_i	Pressure at output of amplifier (between amplifier and resistor); (lb/in^2)
P_o	Pressure at output of resistor; (lb/in^2)
Φ_{Ri}	Phase angle between reference signal and P_i; (degrees)
Φ_{Ro}	Phase angle between reference signal and P_o; (")
Φ	Phase angle between P_o and P_i (difference between Φ_{Ro} and Φ_{Ri}); (degrees)
f	frequency; (cycle/sec)
A, B, C, D	Readings from Leazer-U; (cm)
Φ'_{Ri}, Φ'_{Ro}	Phase angles from readings A & B
Φ''_{Ri}, Φ''_{Ro}	" angles from readings C & D

$\phi'''_{Ri}, \phi'''_{Ro}$	Average phase angles between ϕ'_{Ri}, ϕ''_{Ri} and ϕ'_{Ro}, ϕ''_{Ro} respectively
P_{it}	Input (between resistor and gain block) pressure for transfer characteristics (lb/in^2)
P_{ot}	Output (between gain block and resistor) pressure for transfer characteristics; (lb/in^2)
P_{st}	Small input pressure for transfer characteristics
R_{st}	Small restriction to input pressure for transfer characteristics
P_t	Big input pressure for transfer characteristics
R_{bt}	Big restriction to big input signal.
P_{io1}, P_{io2}	Inside pressures at outputs; (lb/in^2)

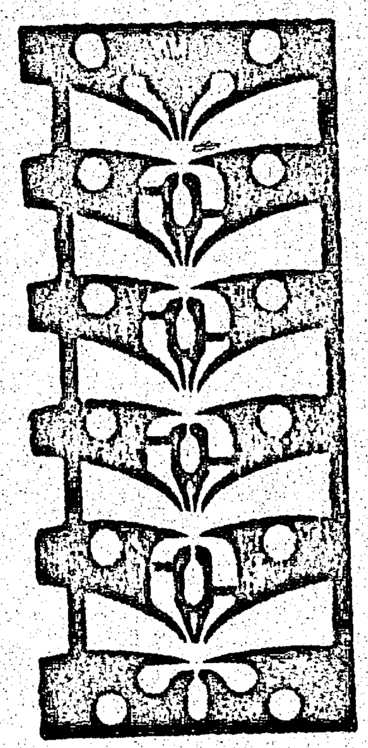


Fig.1a Five Stages of Gain Block

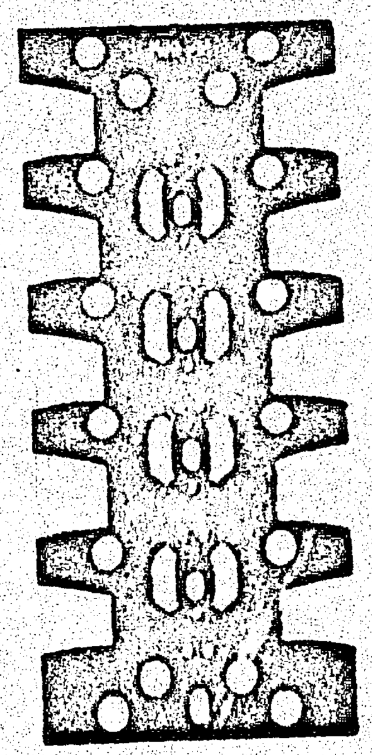


Fig.1b Alternating Plate

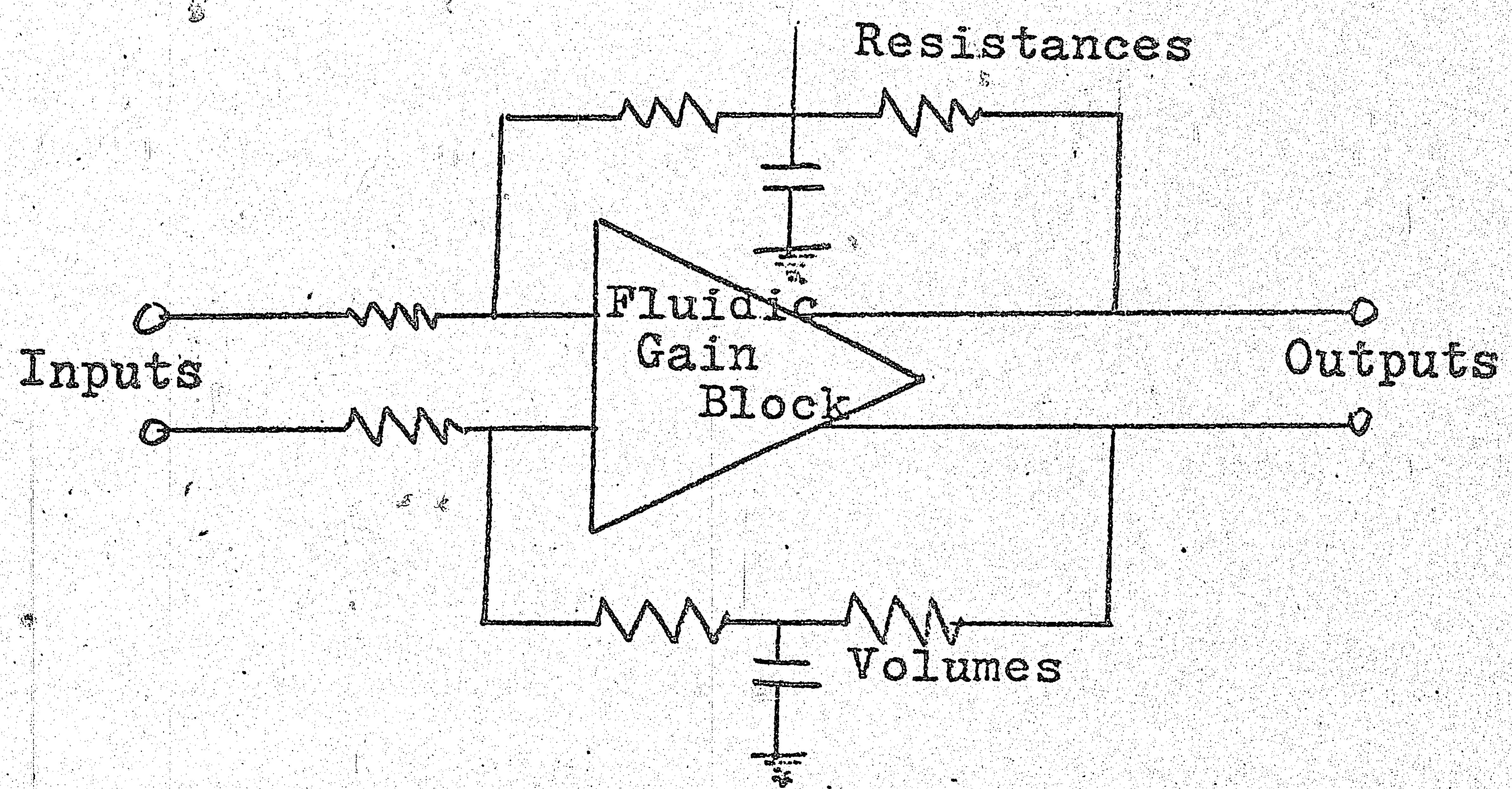


Fig.2 Fludic Operational Amplifier,Standard Type

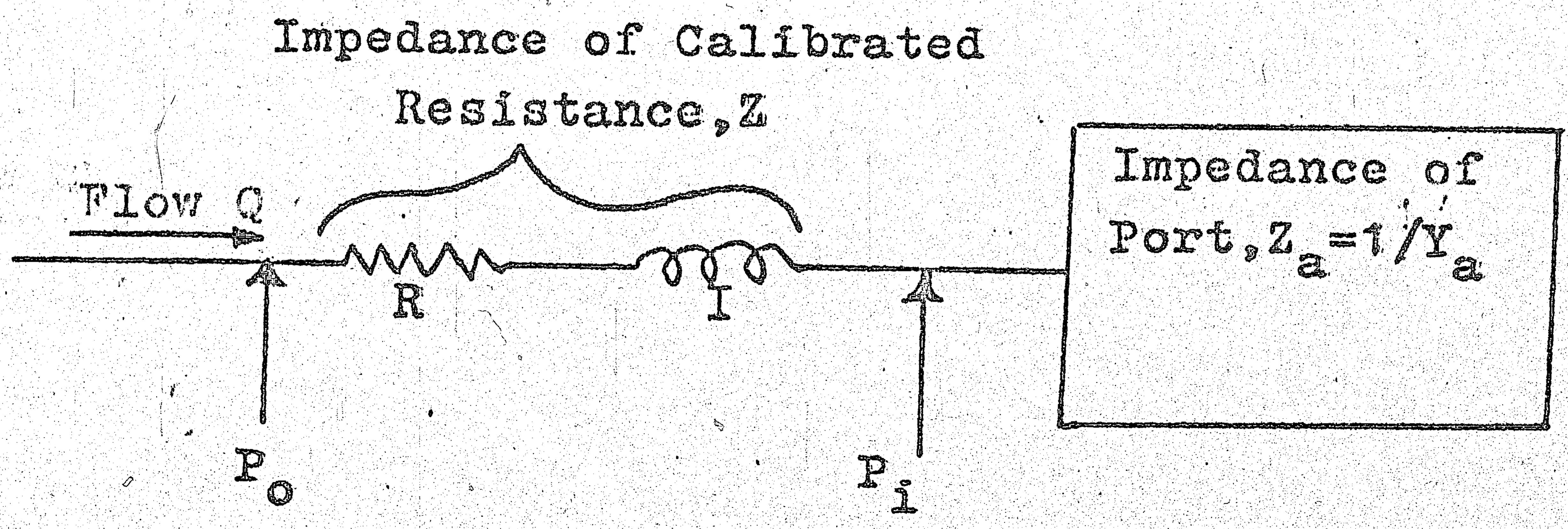


Fig. 3 Concept of Measurement of Dynamic Self-Impedance (Uncorrected)

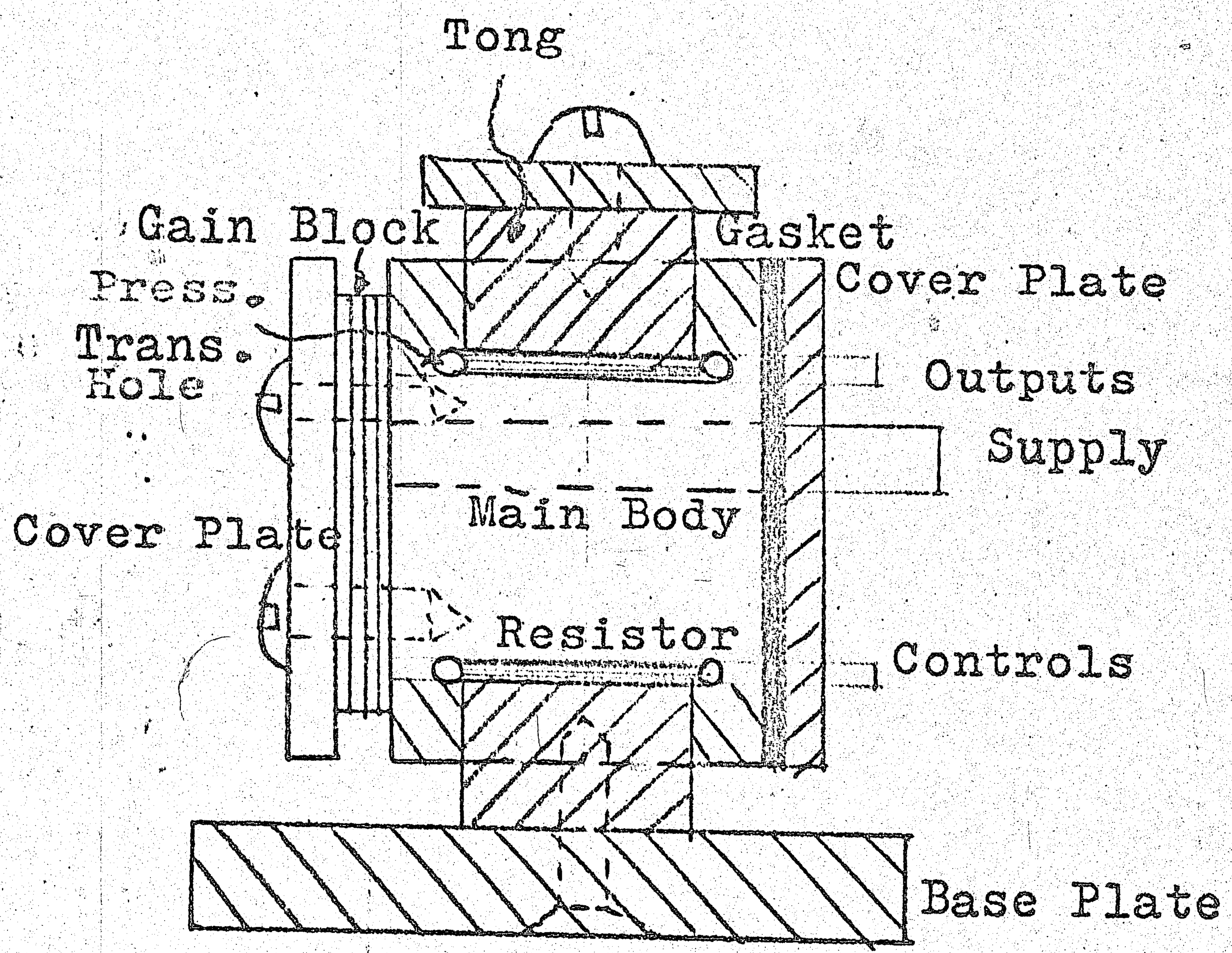


Fig.4 Sectioned View of the Assembly of Model

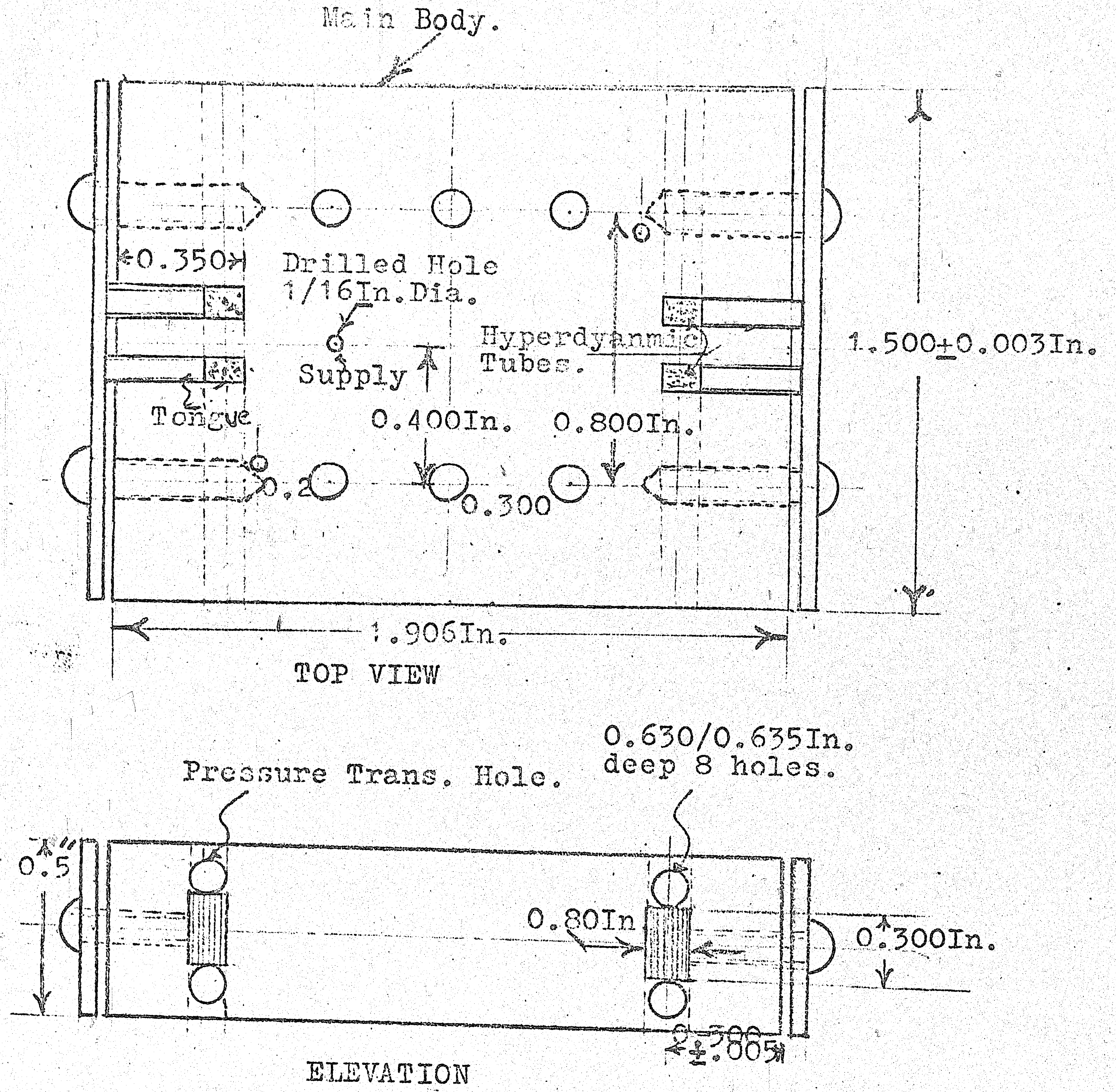

Main Body.
0.350
Drilled Hole
1/16In.Dia.
Supply
Hyperdyanmic
Tubes.
1.500±0.003In.
Tongue
0.400In.
0.800In.
0.2
0.300
1.906In.
TOP VIEW
0.630/0.635In.
deep 8 holes.
Pressure Trans. Hole.
0.5
0.80In
0.300In.
0.300
±.005
ELEVATION

FIGURE 4a,

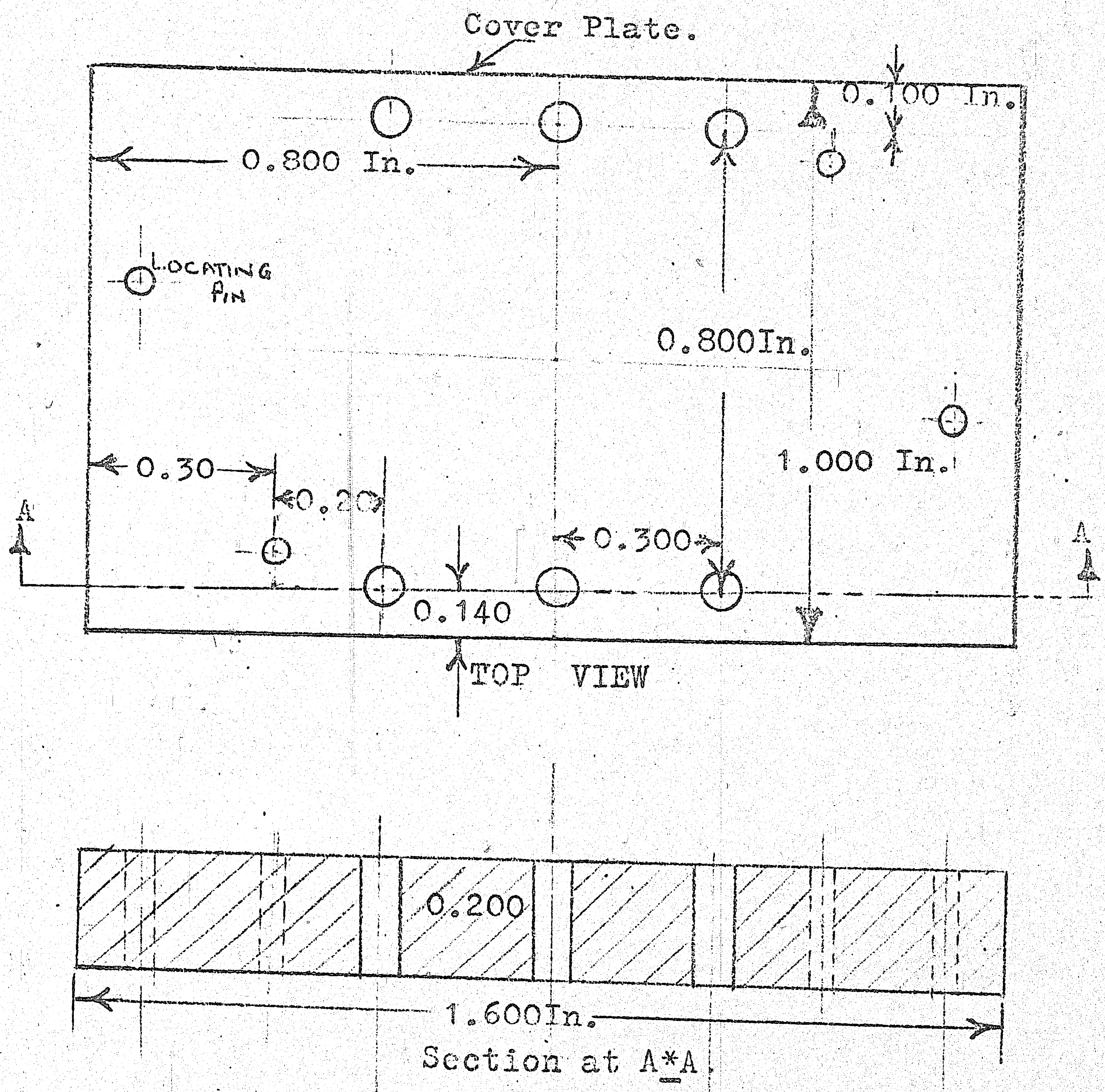

Cover Plate.
0.100 In.
0.800 In.
LOCATING PIN
0.800In.
1.000 In.
0.30
0.20
0.300
A
A
0.140
TOP VIEW
0.200
1.600In.
Section at A*A

FIGURE 4b.

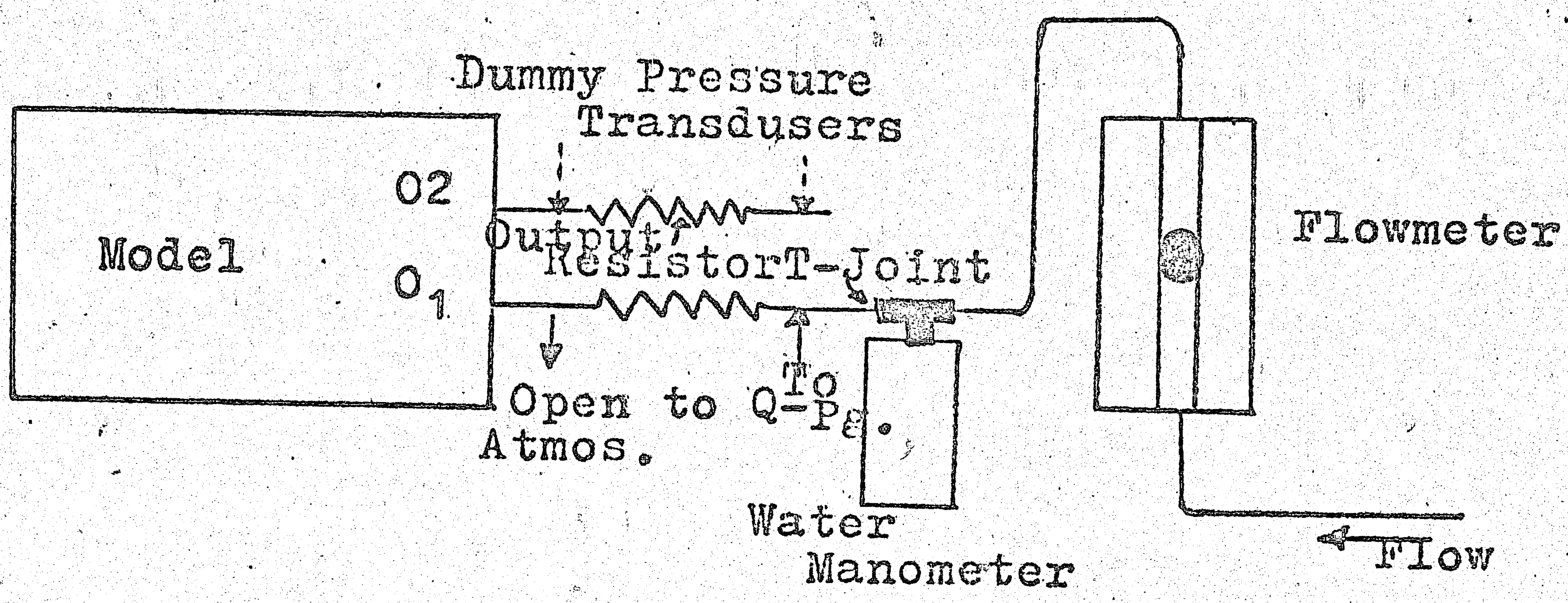


Fig.5 Experiment Setup For Calibration of Resistor
Resistor

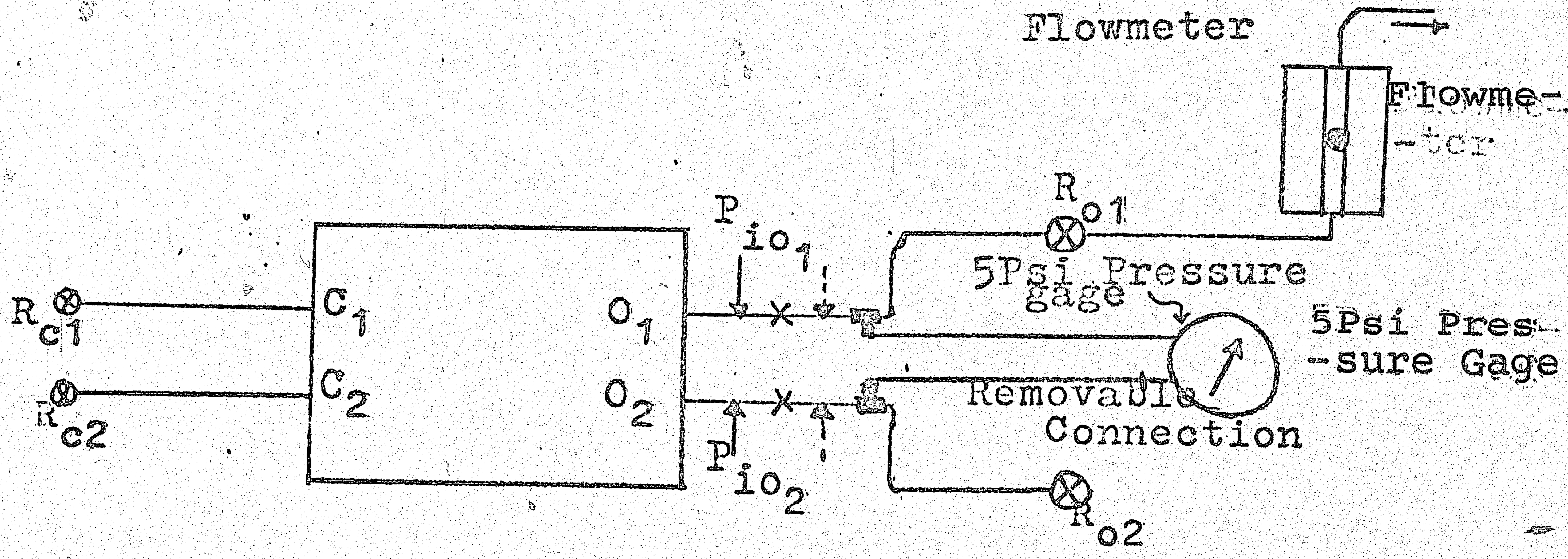


Fig.6 Output Pressure-Flow Characteristics Test

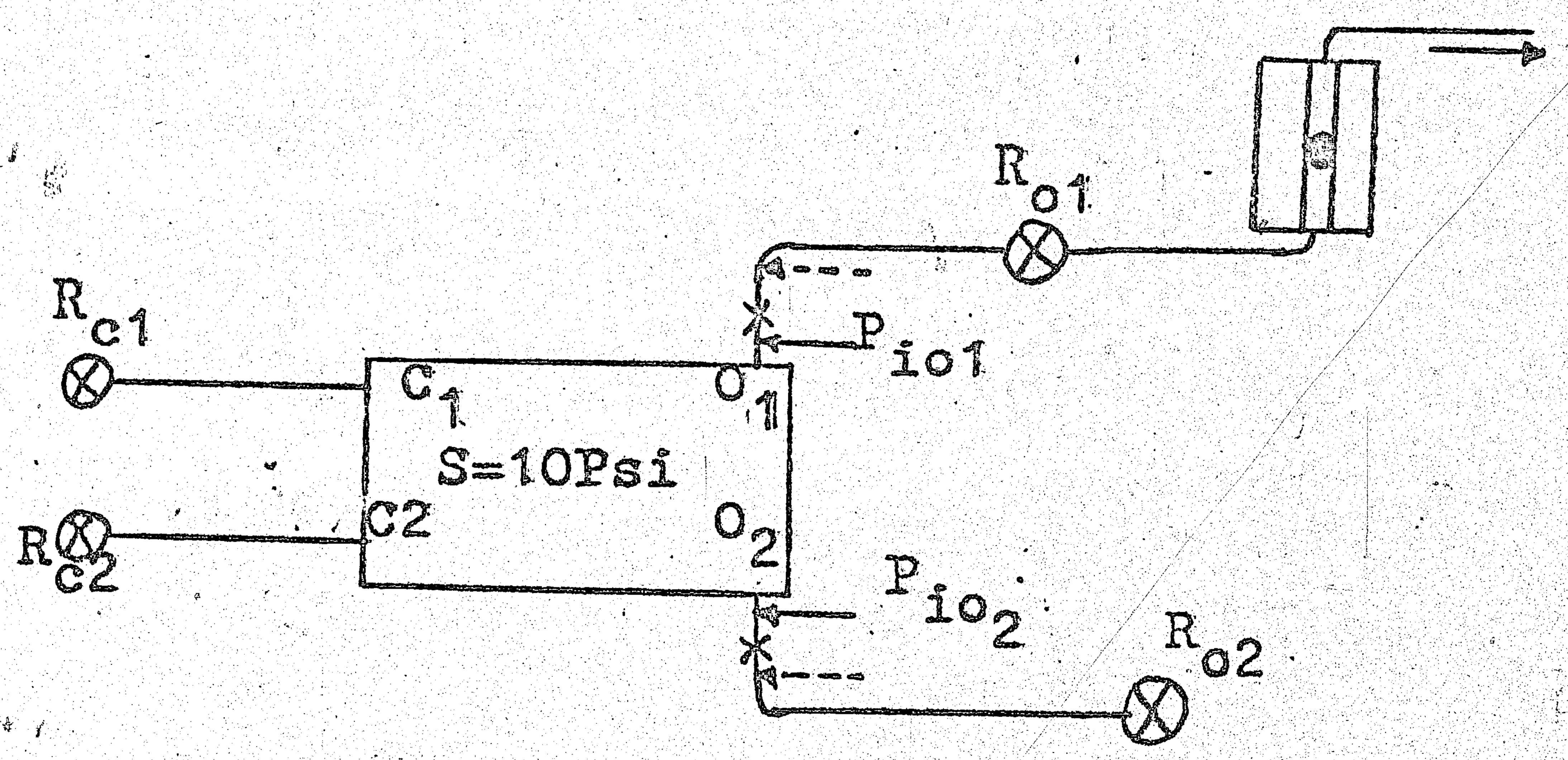


Fig.7 Steady State Output-Impedance Test

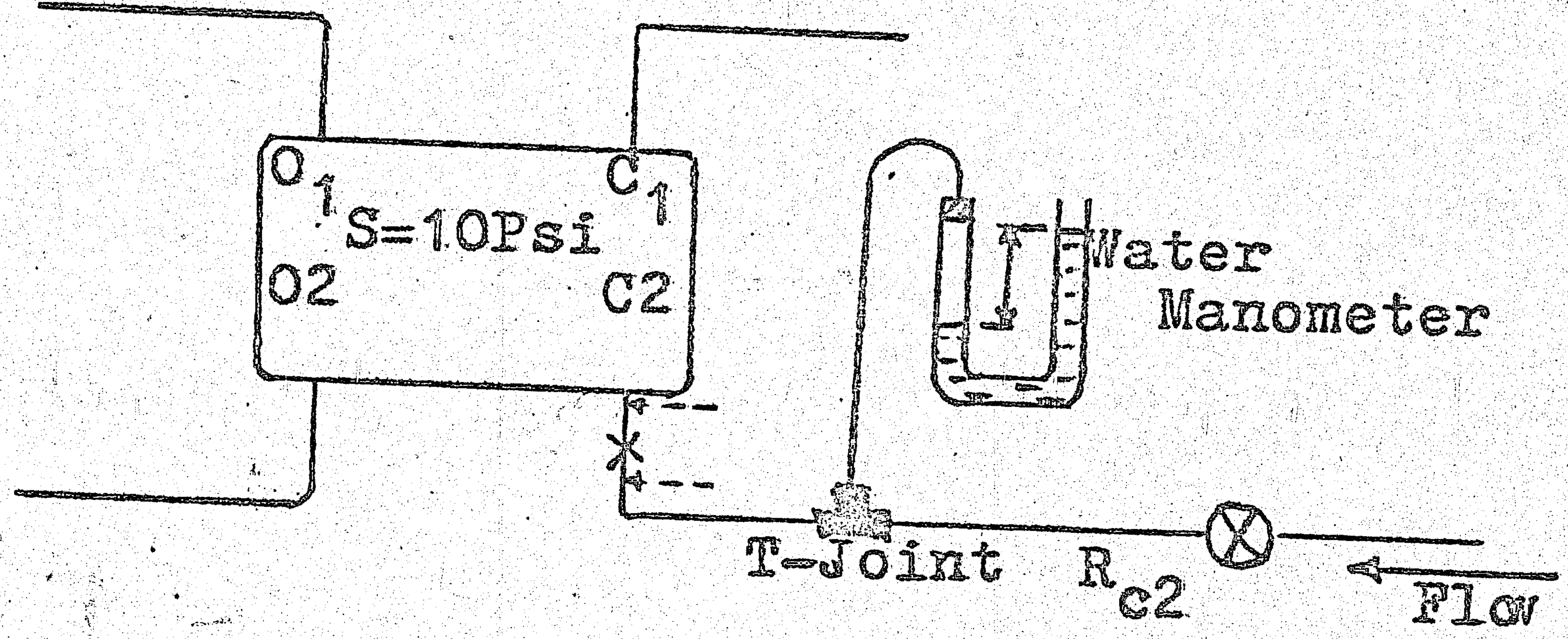


Fig. 8a

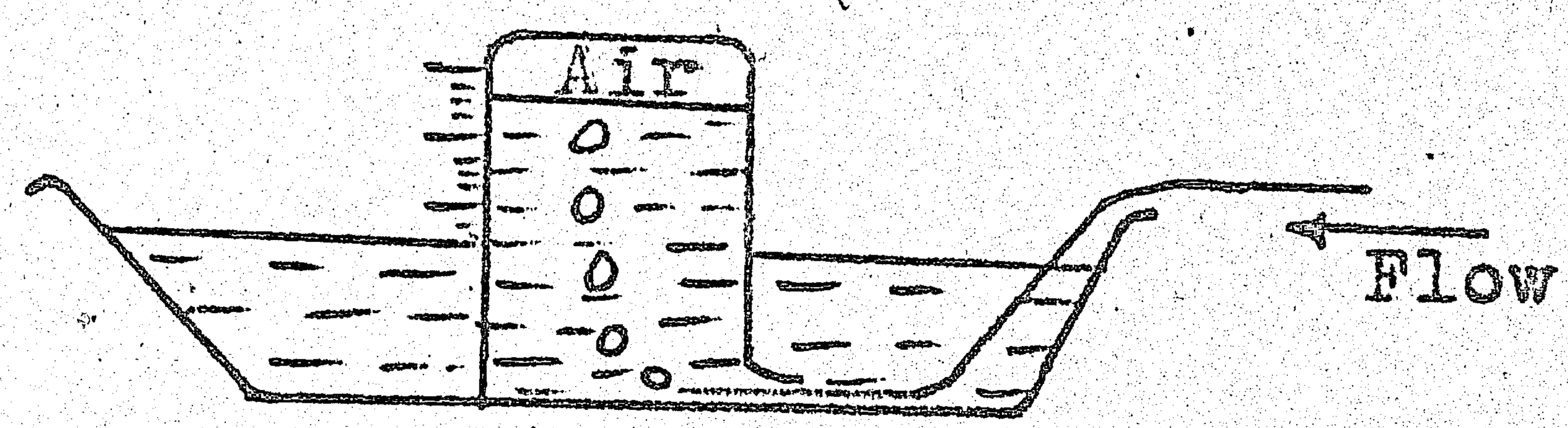


Fig. 8b

Fig. 8 Steady State Input Impedance Test

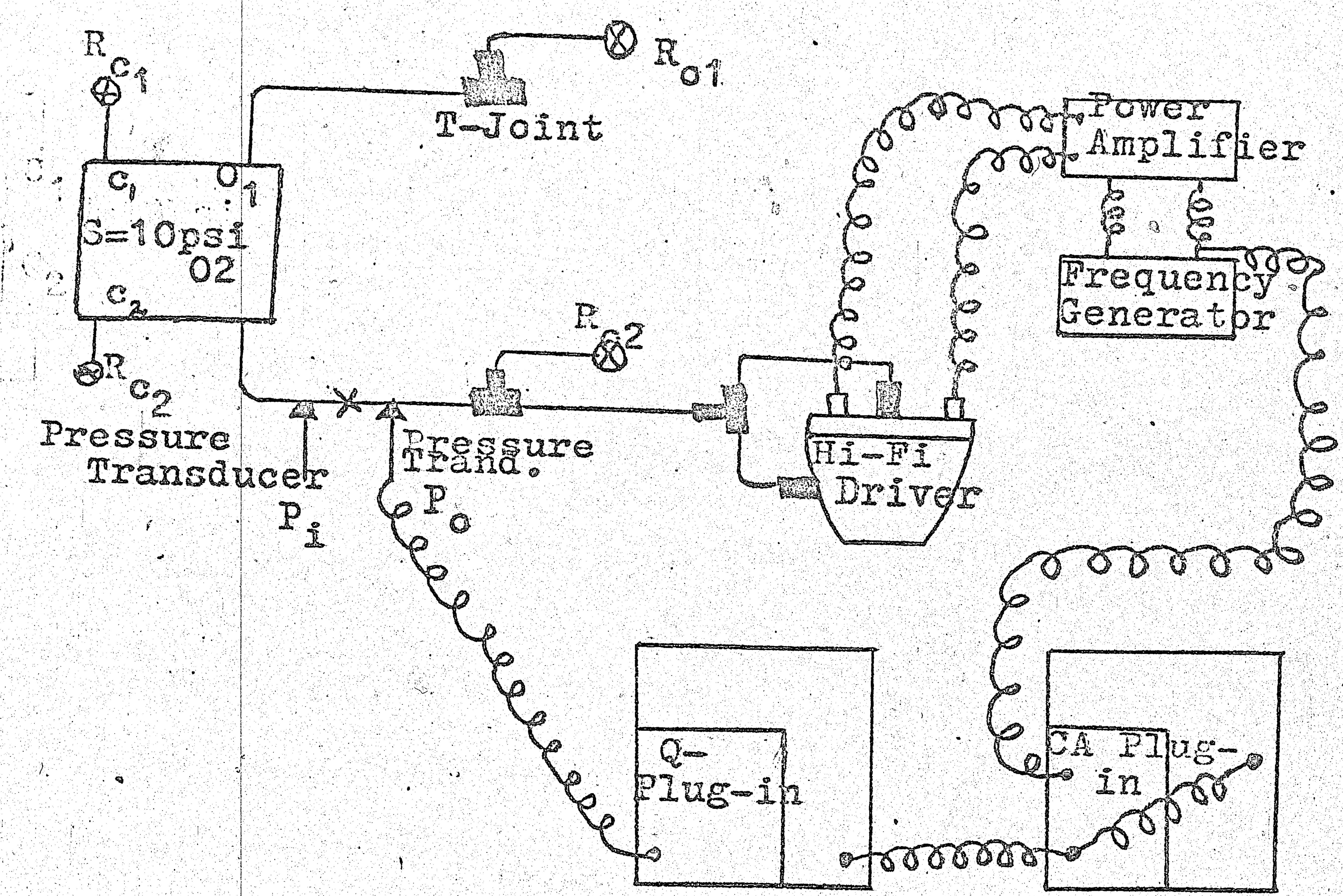


Fig.9 Output Dynamic Impedence Test(High Frequency)

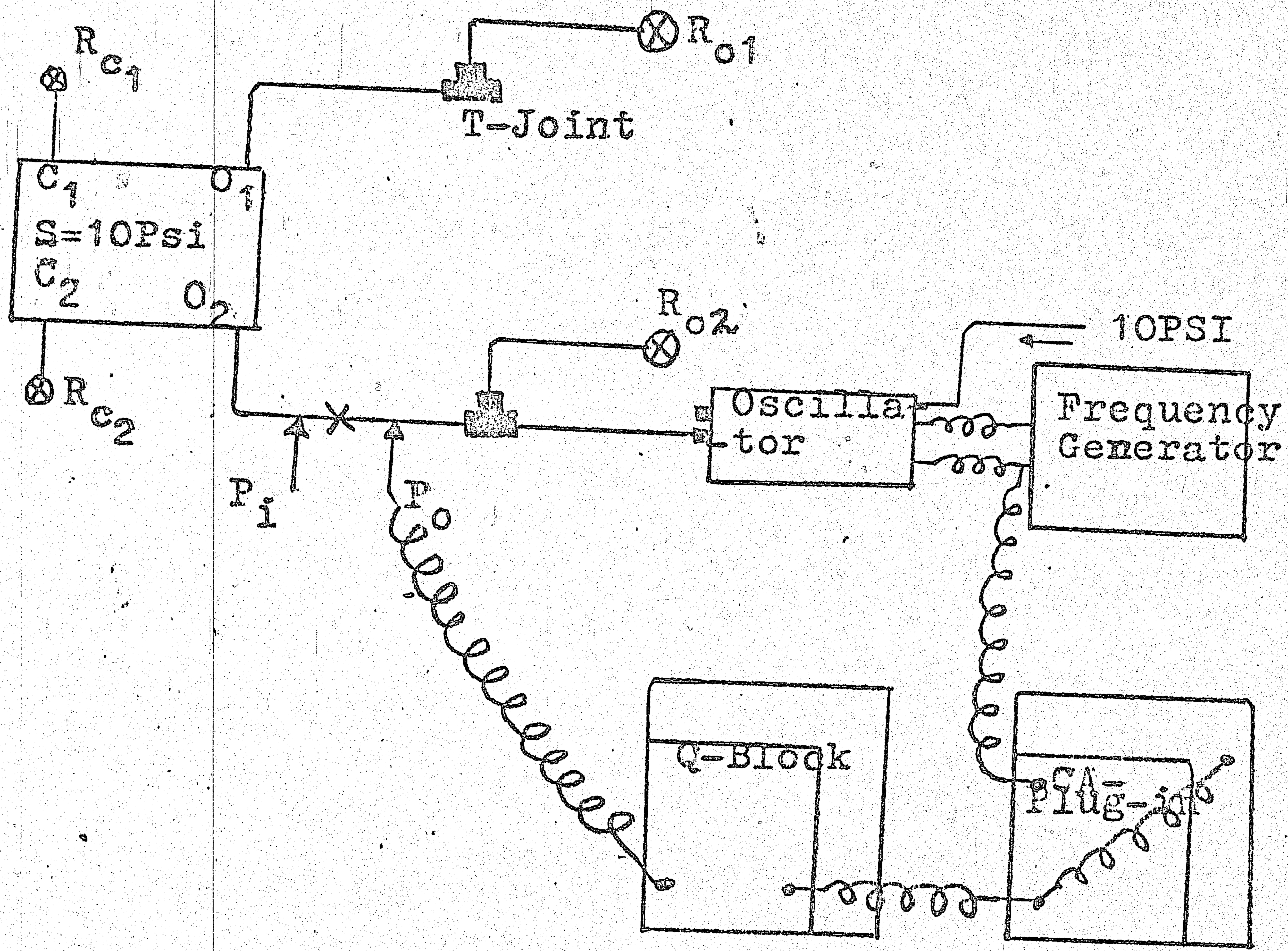


Fig.10 Output DynamicImpedance Test (low Freq.)

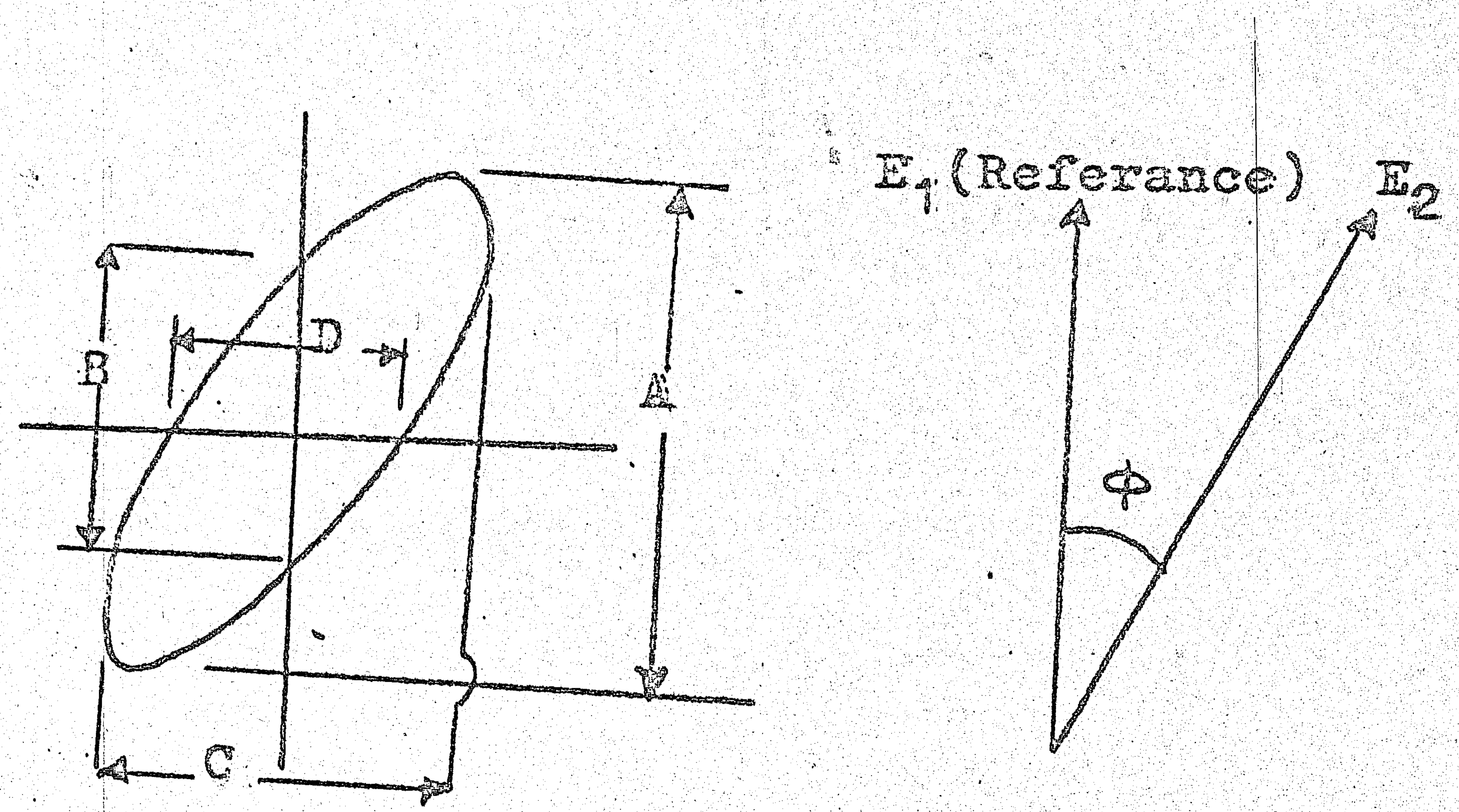


Fig. 11 Leajor-U Reading

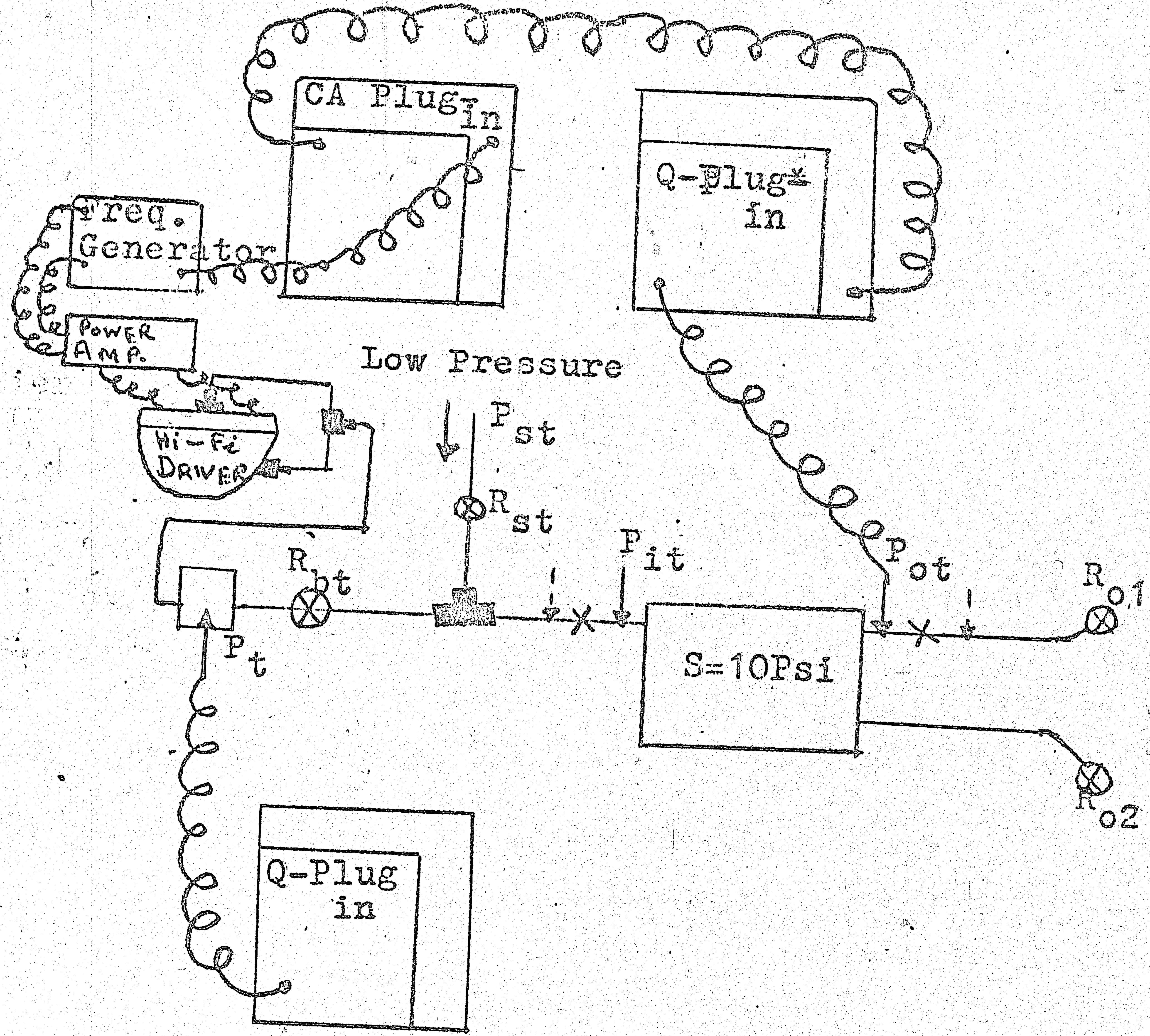


Fig.12 Transfer Characteristics Measurements

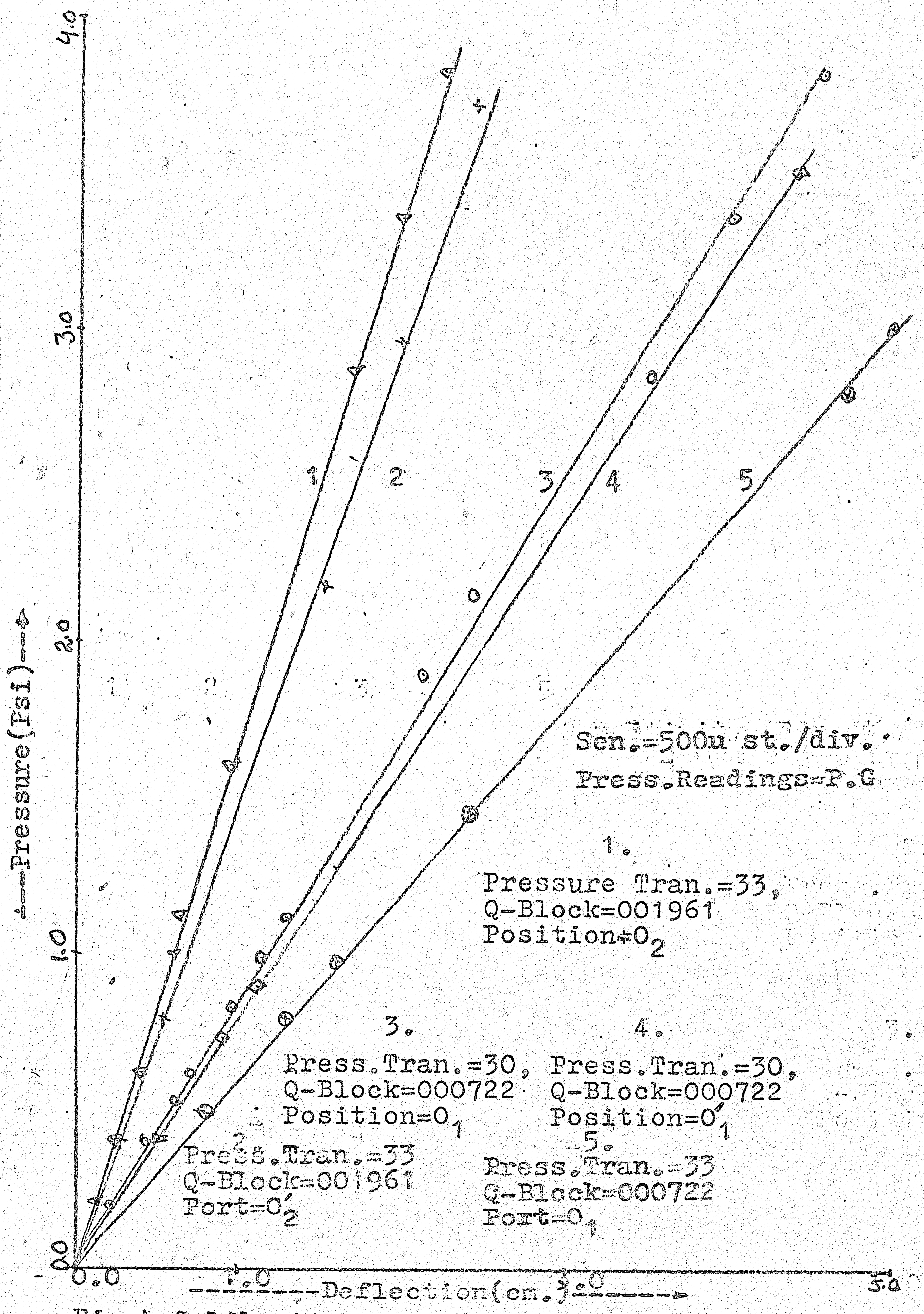


Fig.A Calibration of Press.Tran. at Output Ports

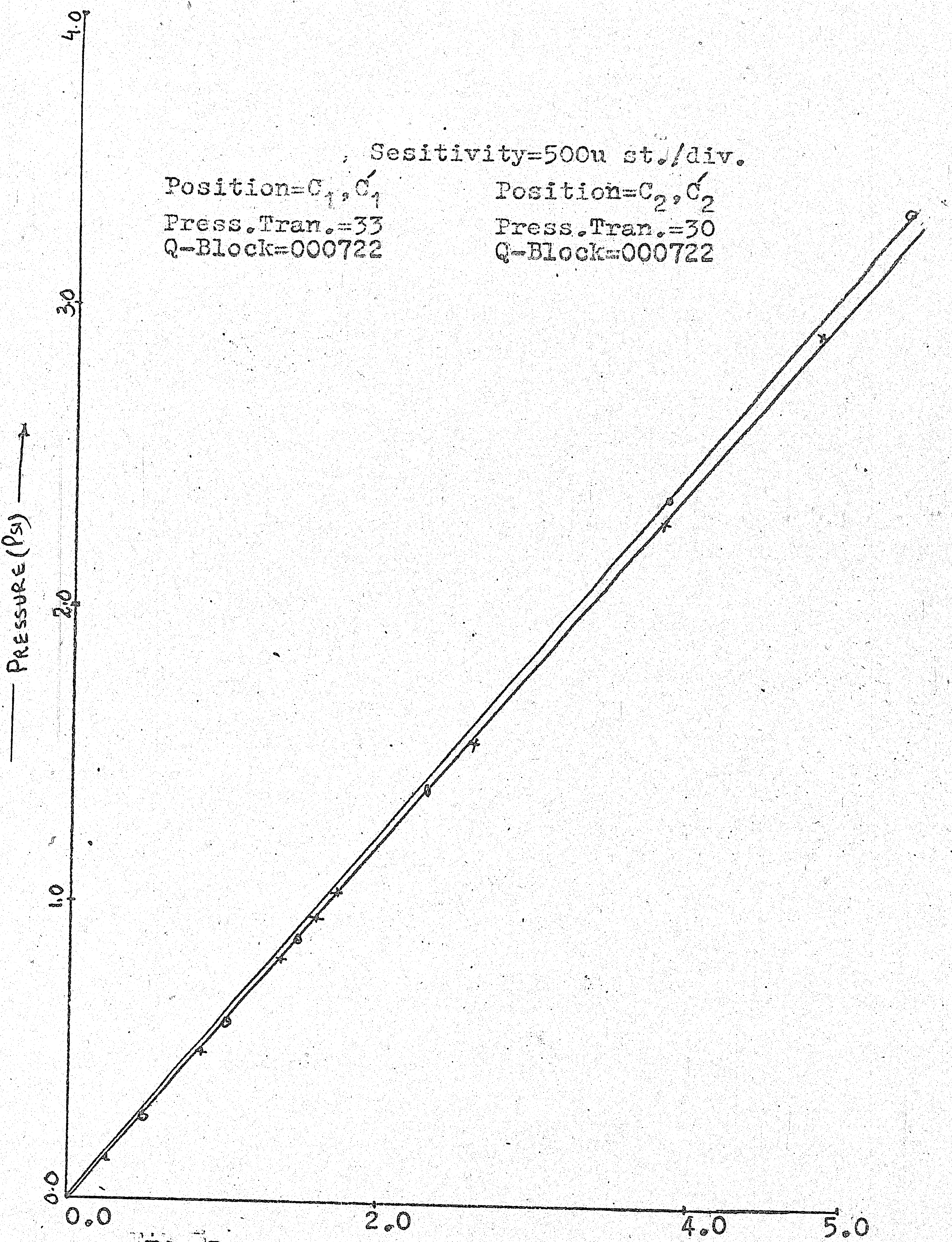


Fig.B Calibration of Pressure Transducer in control ports

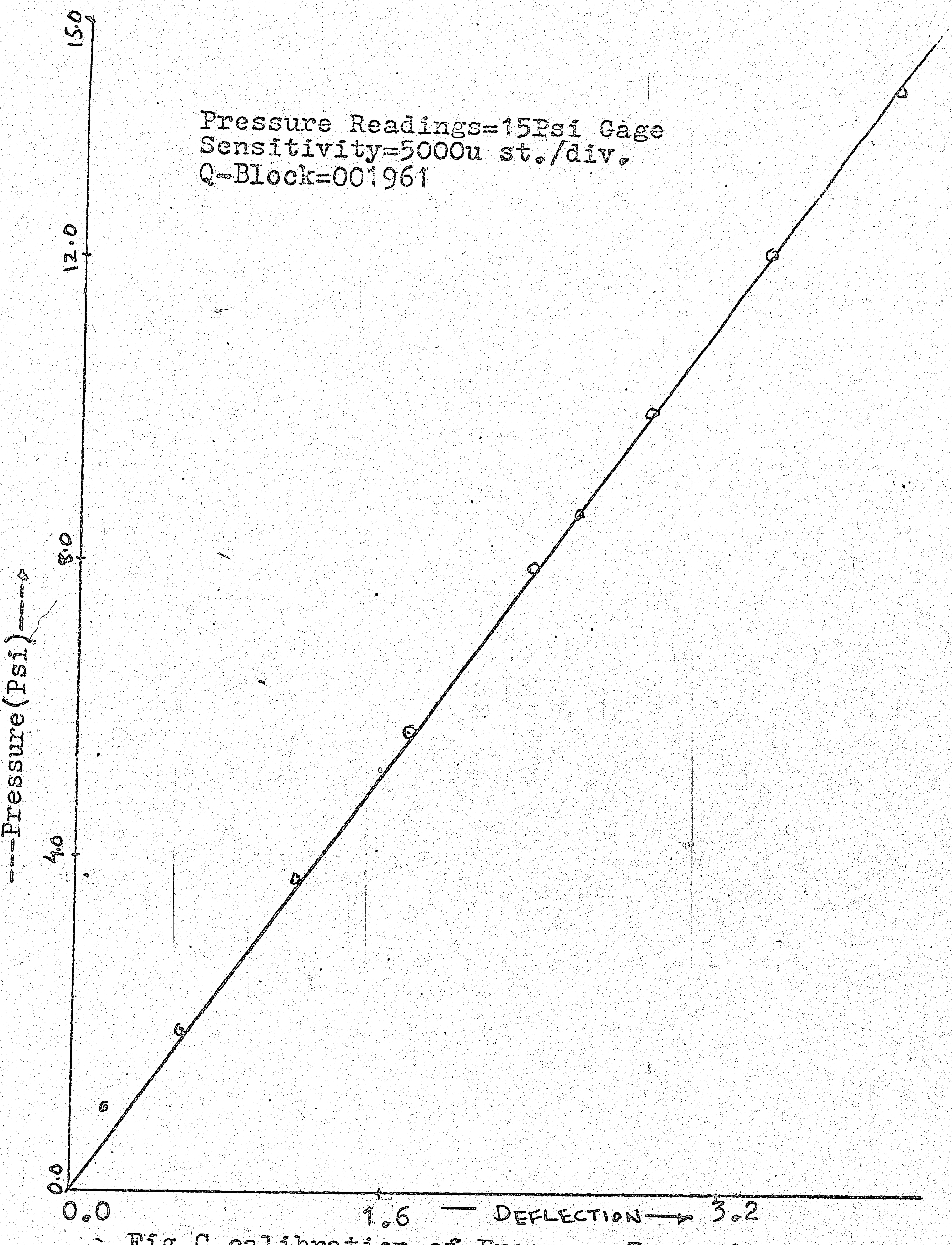


Fig.C calibration of Pressure Tran. in special fitting.

Sensitivity-200μ st/div.

1. Pressure Tran.=33
Q-Block=0001961
POSITION-O_2

2. Pressure Tran.=30
Q-Block=0000722
POSITION-O_1

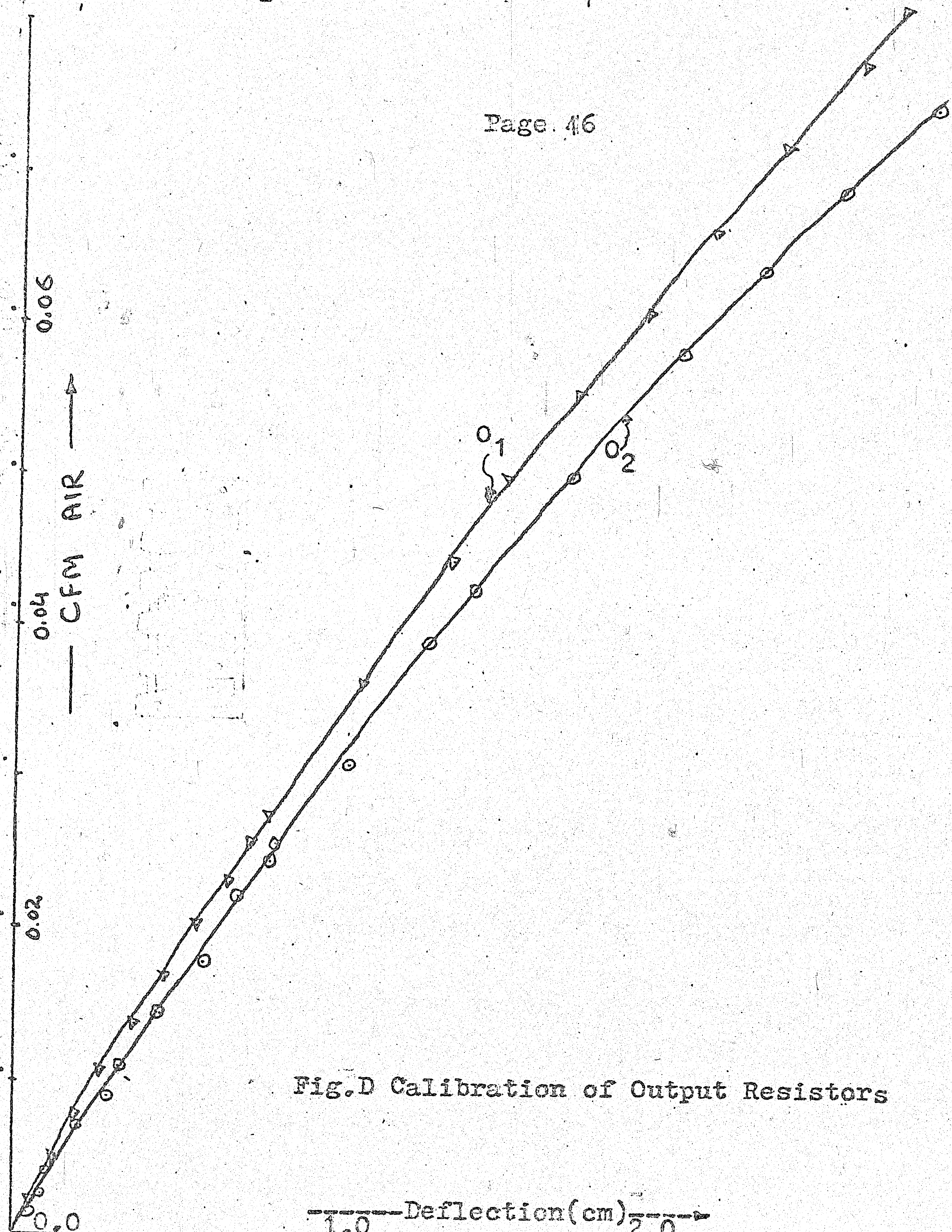


Fig.D Calibration of Output Resistors

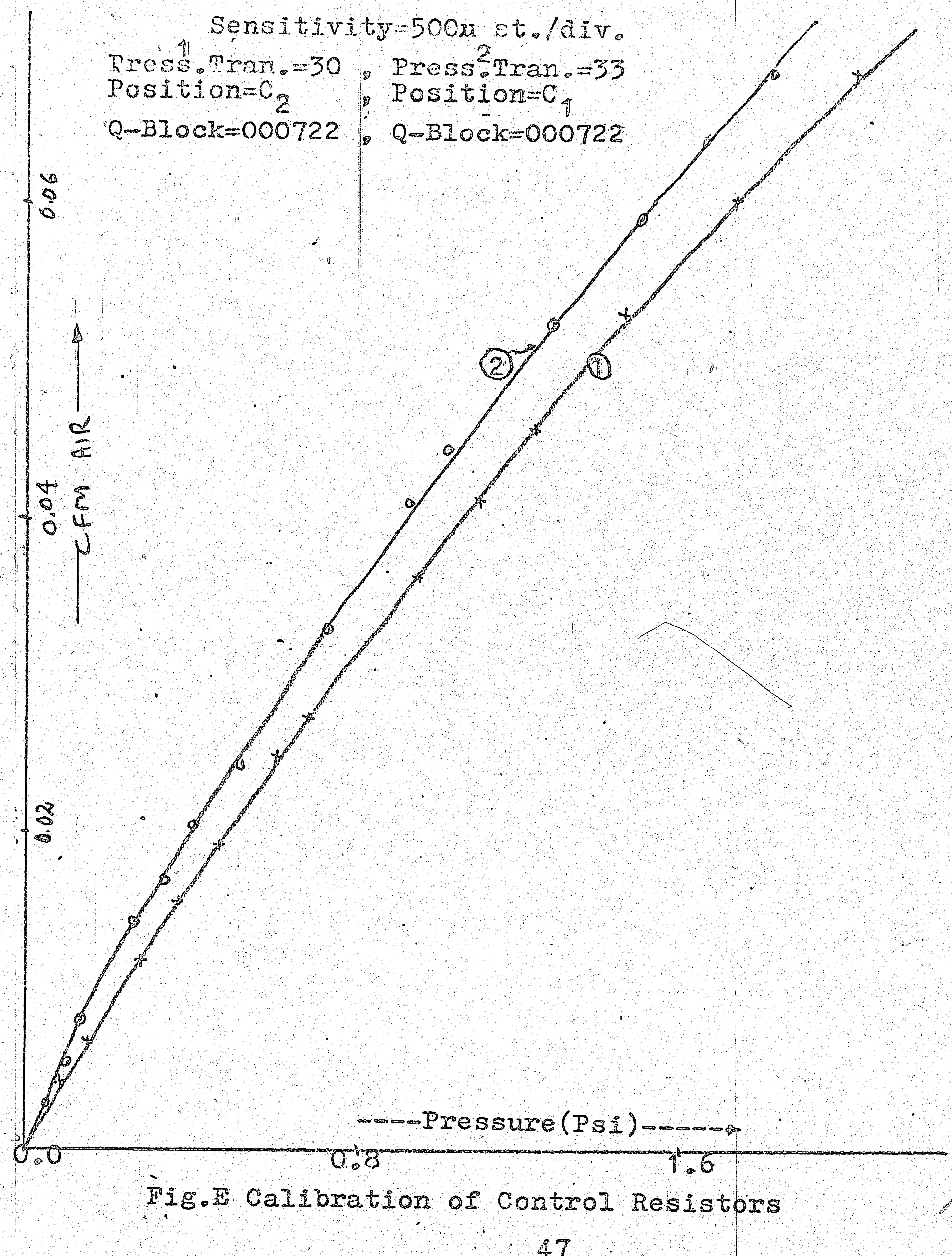
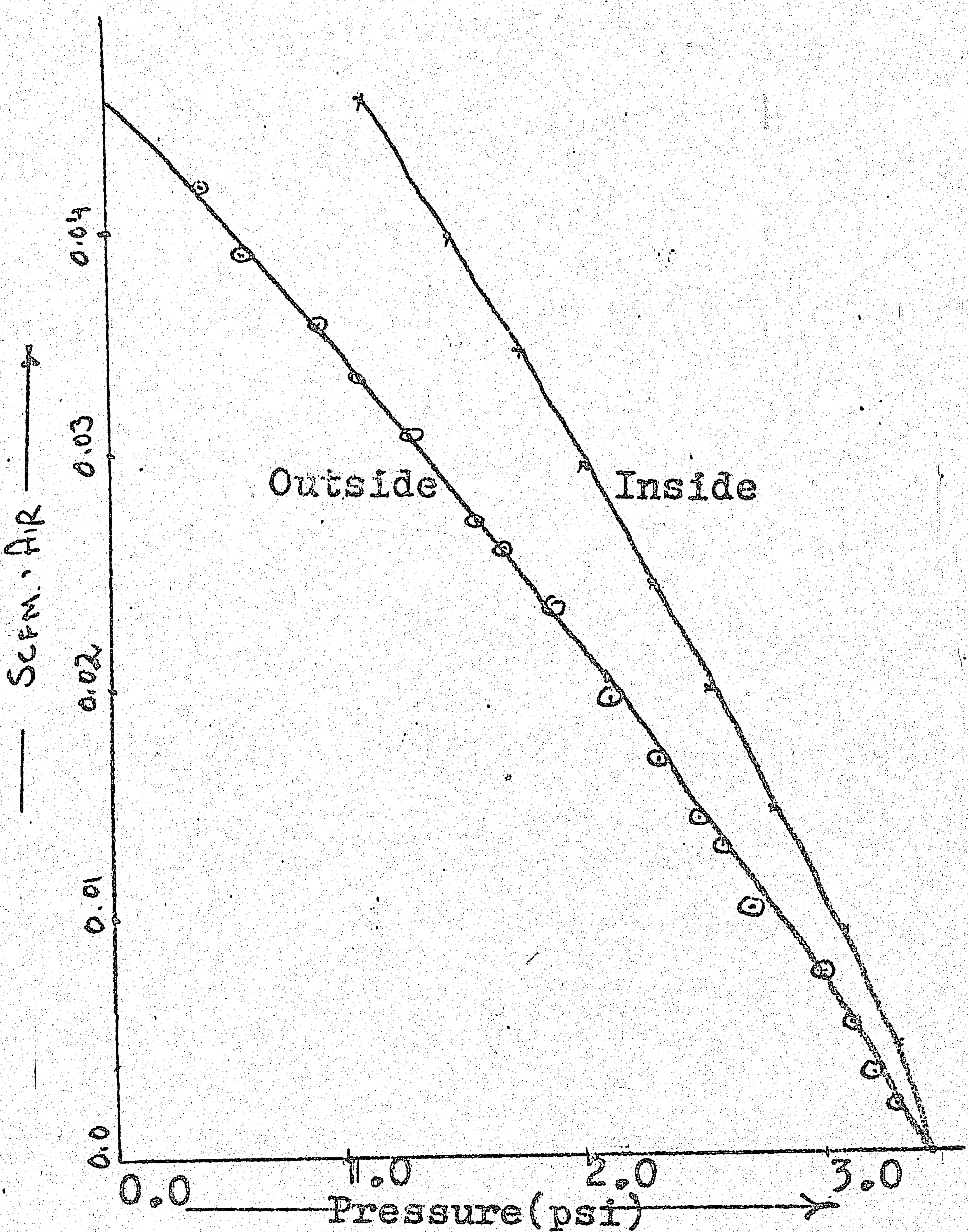


Fig.E Calibration of Control Resistors

Position=o$_1$

Flow Readings=Rotometer
Pressure Readings=5 psi gage



Figf Output Pressure Flow Chracteristics

Position=O_2
Flow Readings=Rotometer
Pressure Readings=5 psi gage

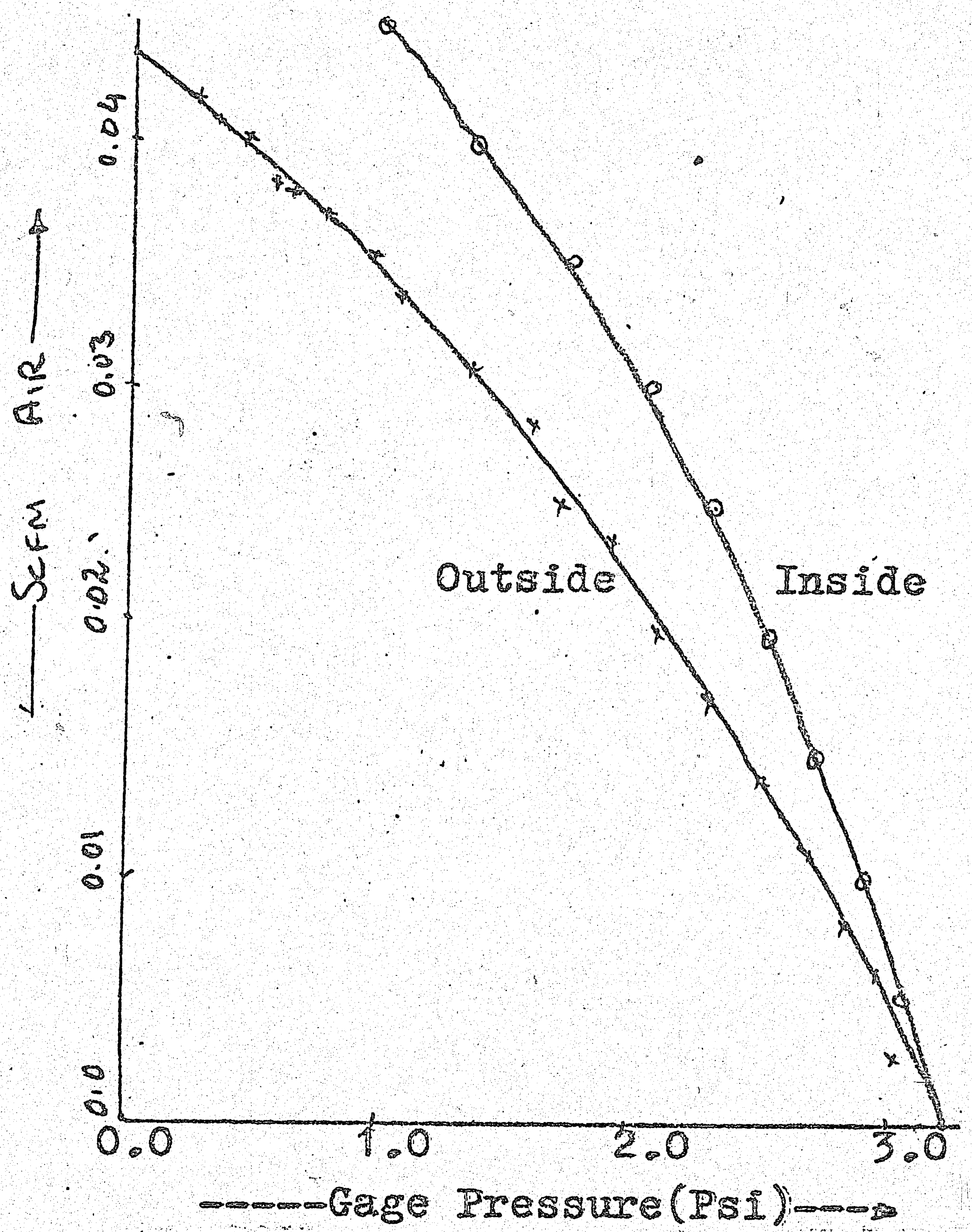


Fig. F Output Pressure Flow Chracteristics

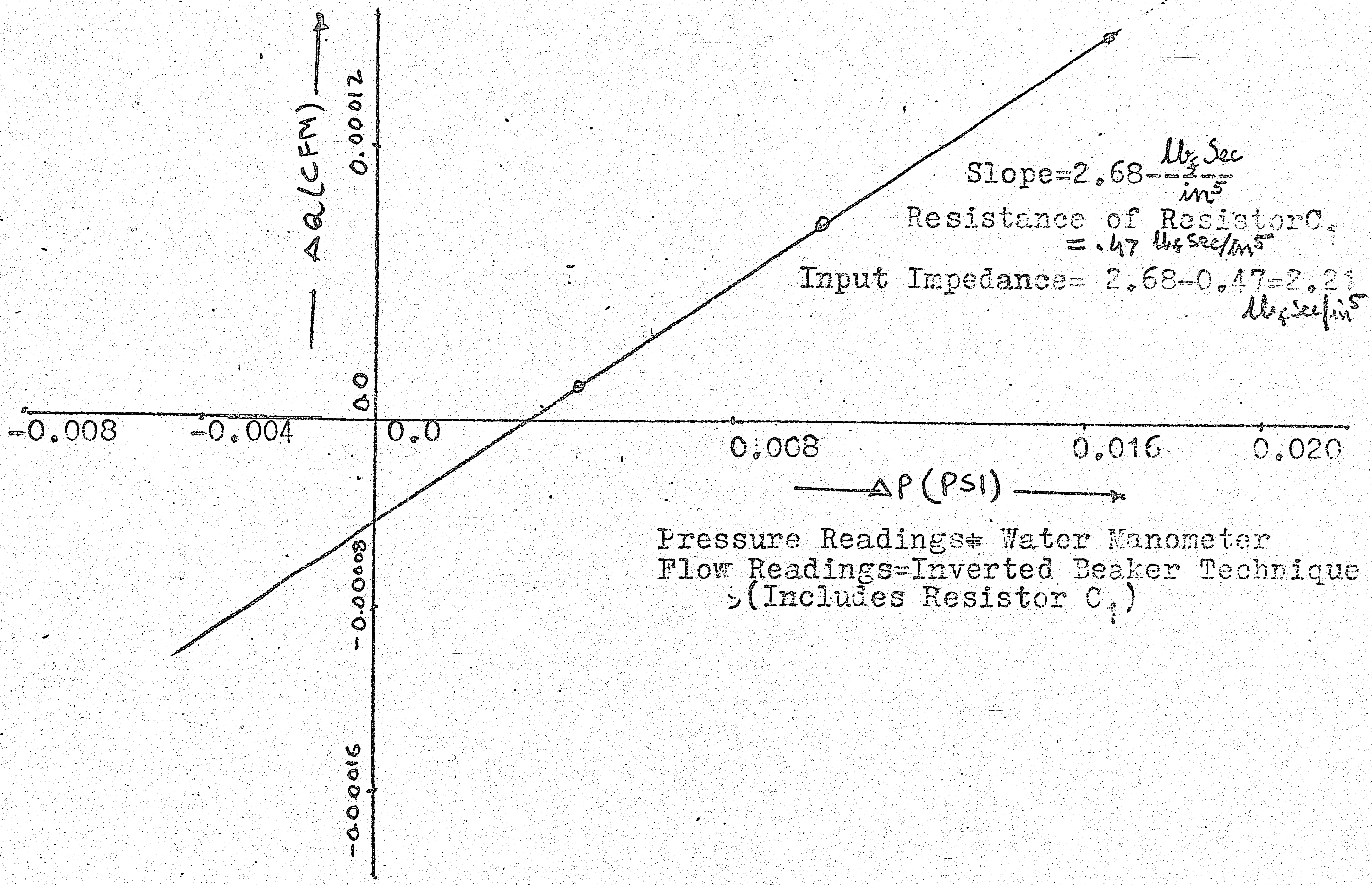


Fig.G Steady State Input Impedance

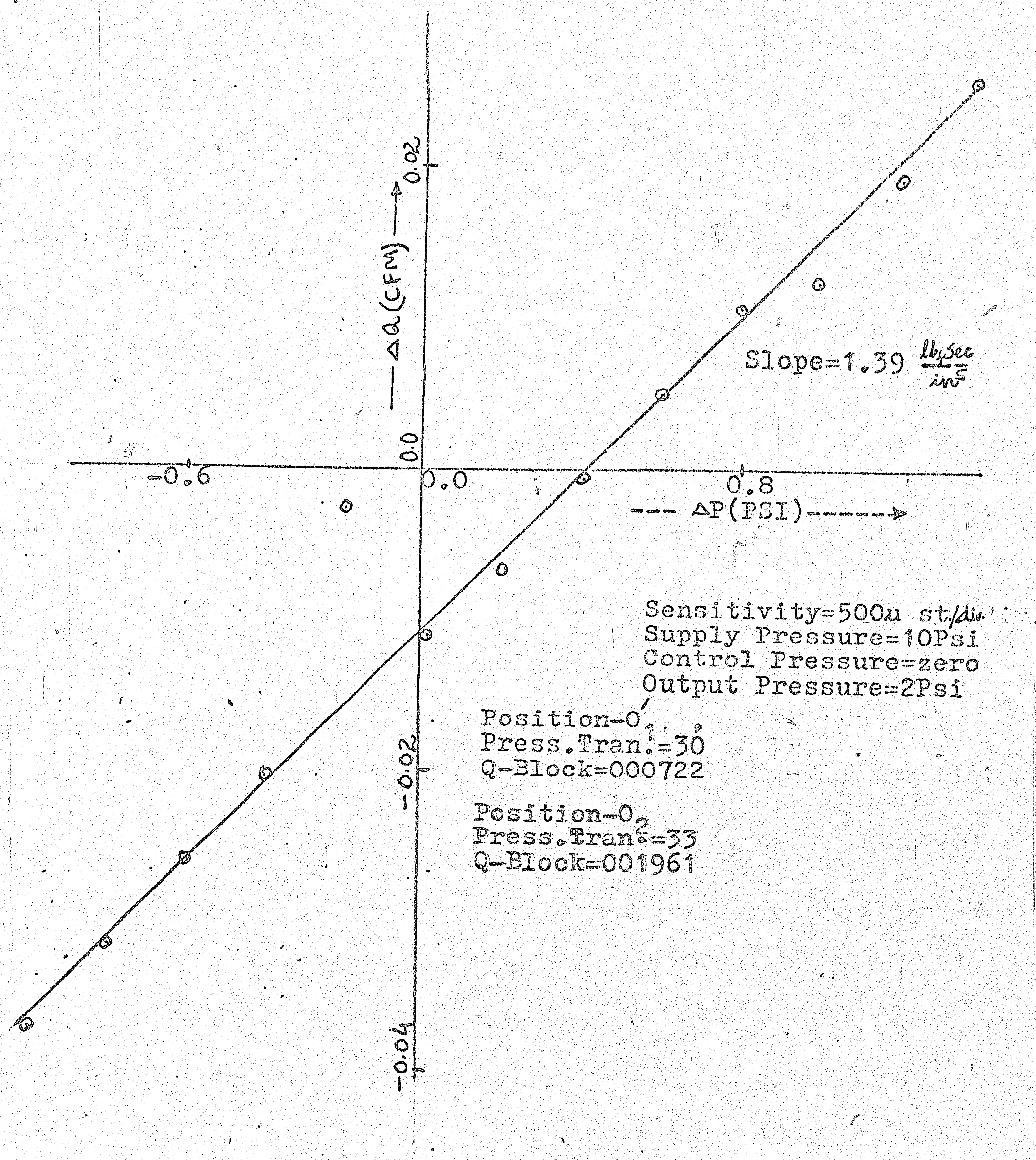


Fig.H Steady State Output Impedance(Push Pull)

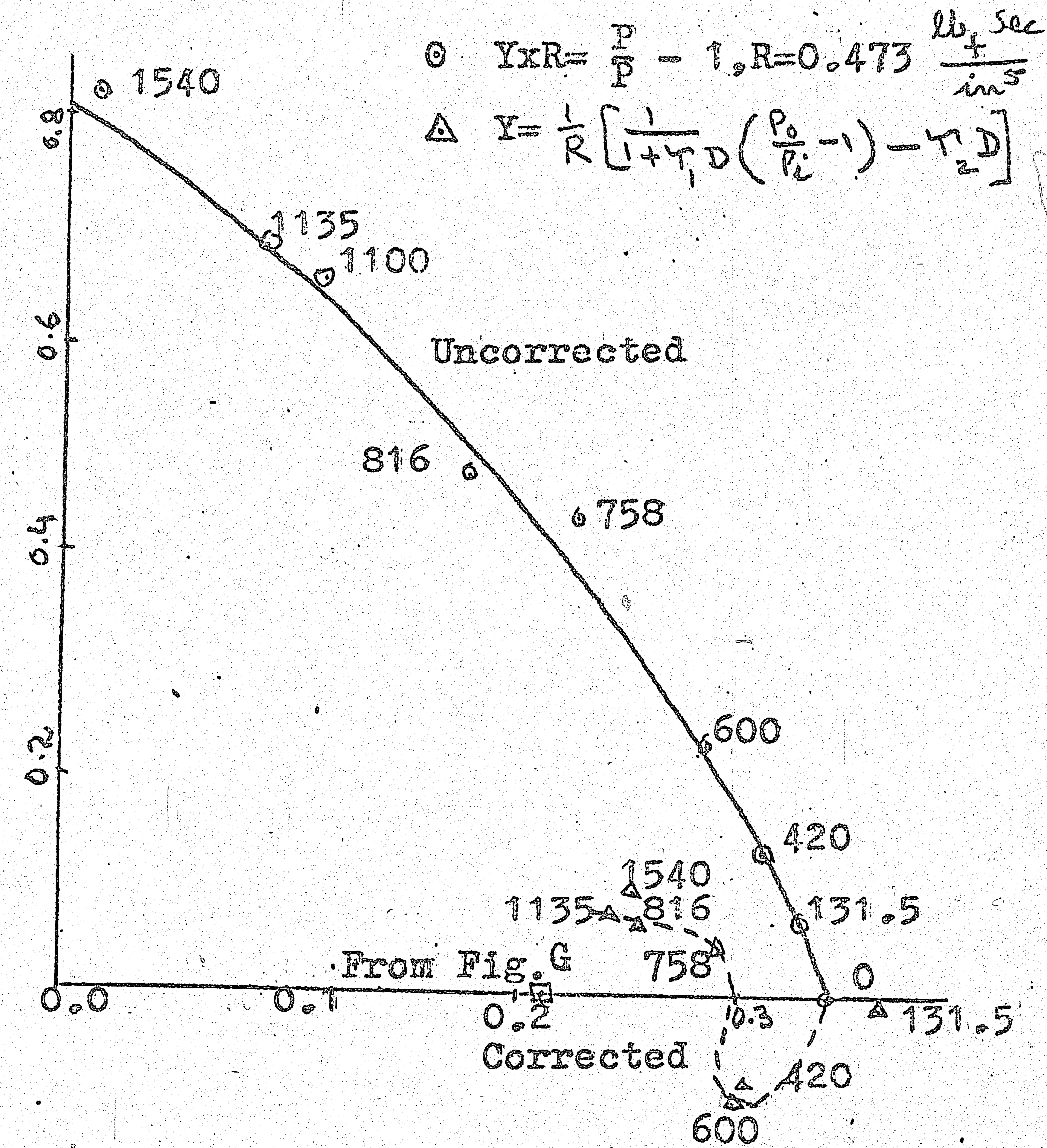


Fig. I Input Admittance (Corrected&Uncorrected)

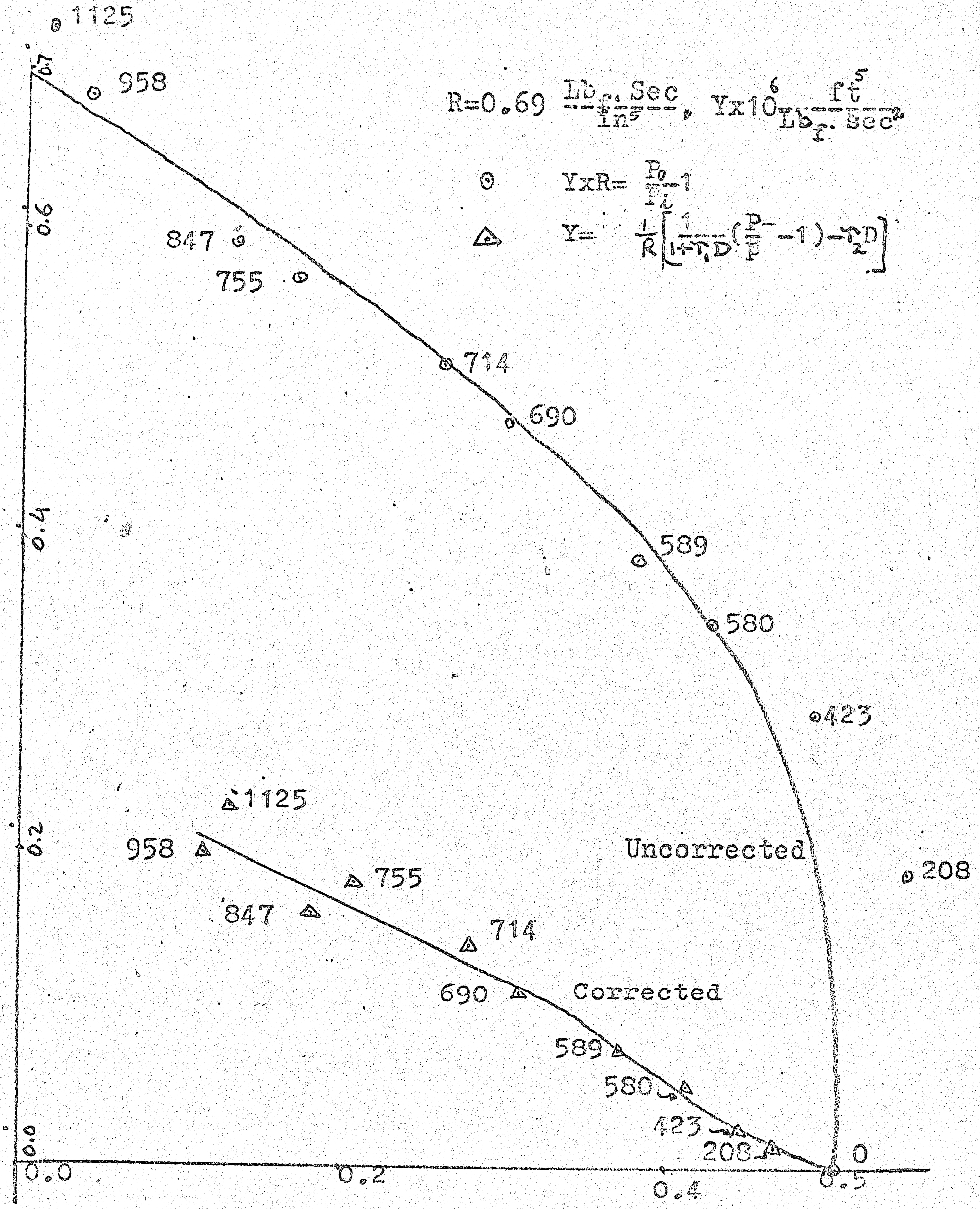


Fig.J Output Admittance(Corrected&Uncorrected)

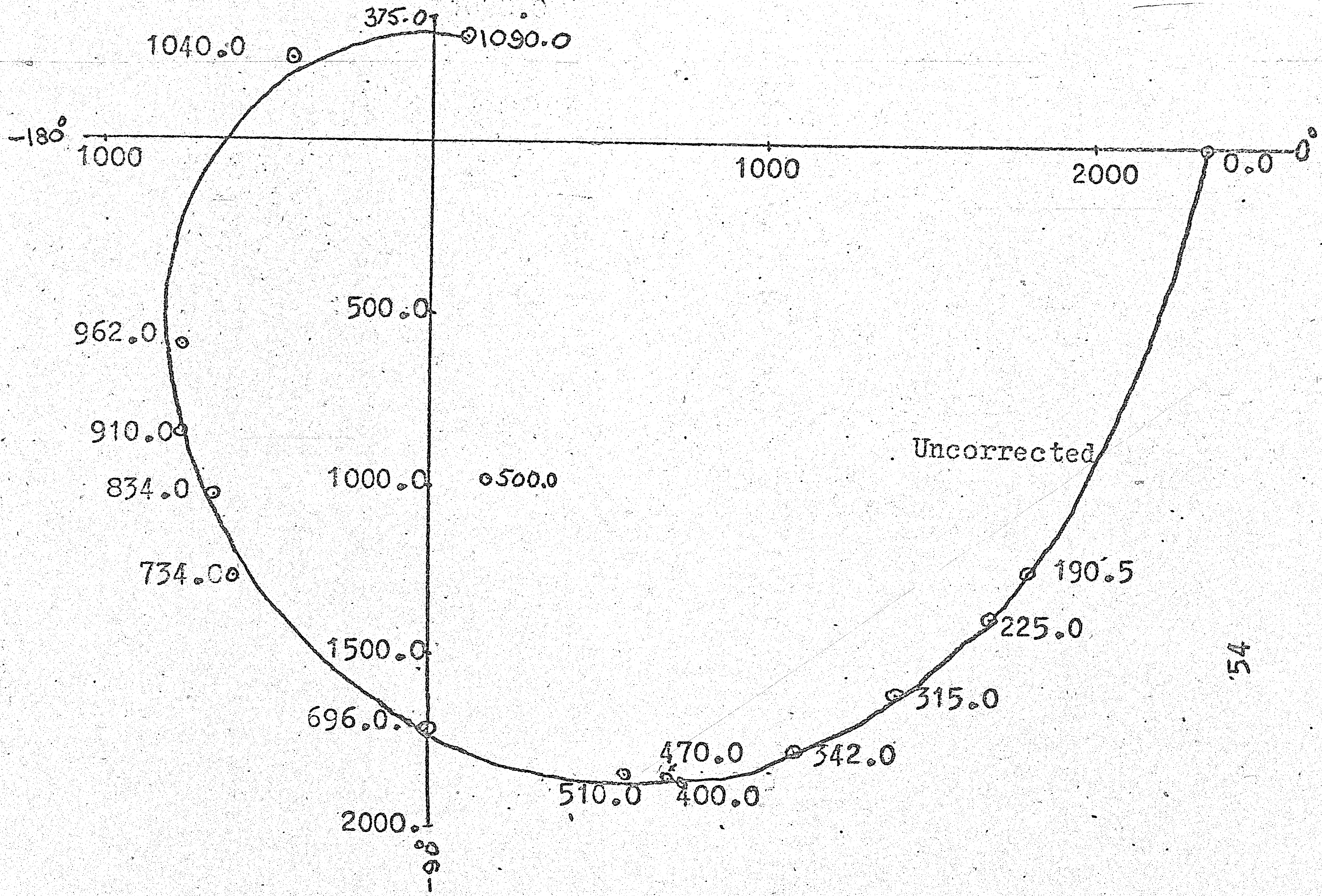


Fig.K Transfer Characteristics(Polar Plot)
Scale: 1"=500

APPENDIX

TABLE Input Impedance Data

	f Hz.	S.No	Magnitude P_i (Cm.)	A CM.	B CM.	C CM.	D CM.	LISAJOR
1.	131.5	1.	1.57(100μ st.)	--	--	--	--	
2.	420.0	2.	1.77(50 " ")	--	--	--	--	
3.	600.0	3.	2.10(50 " ")	3.6	0.6	4.0	0.765	
4.	758.0	4.	2.60(50 " ")	--	--	--	--	
5.	816.0	5.	0.95(20 " ")	1.37	0.5	4.2	1.6	
6.	1100.	6.	2.23(50 " ")	--	--	--	--	
7.	1135.	7.	2.04(50 " ")	3.6	1.855	2.4	1.31	
8.	1540.	8.	2.09(50 " ")	--	---	--	--	

Table Input Impedance Data(cont.)

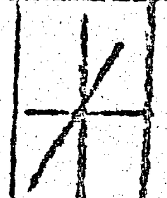
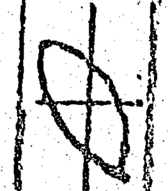
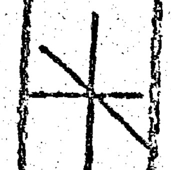
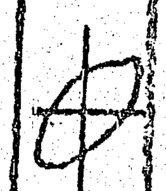
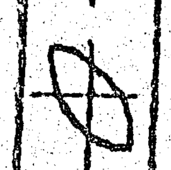
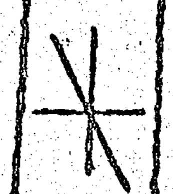
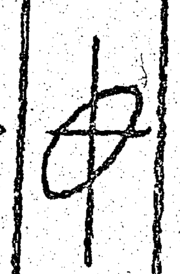
S.No.	LISAJOR	Magnitude P_o(Cm.)	A Cm.	B Cm.	C Cm.	D Cm.
1.		2.20(100u st.)	--	--	--	--
2.		2.40(50" ")	2.0	0.2	2.2	0.23
3.		2.82(50" ")	--	--	--	--
4.		1.40(20" ")	1.3	0.45	1.25	0.4
5.		1.25(20" ")	--	--	--	--
6.		3.00(50" ")	3.6	1.8	1.1	0.55
7.		2.70(50" ")	--	--	--	--
8.		22.80(50" ")	5.7	3.65	3.7	2.25

Table OUTPUT IMPEDANCE DATA

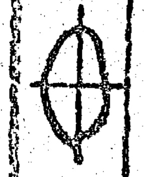
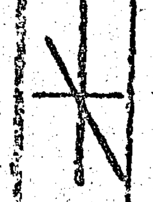
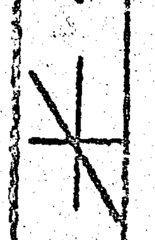
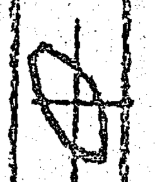
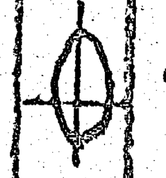
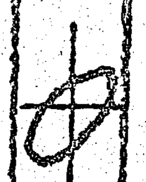
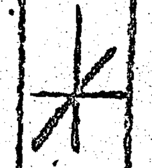
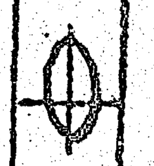
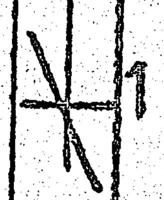
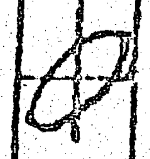
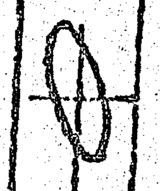
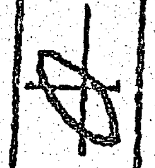
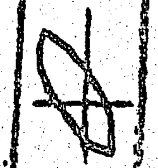
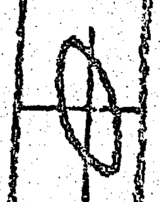
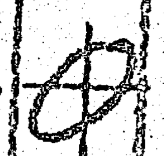
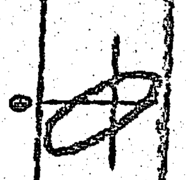
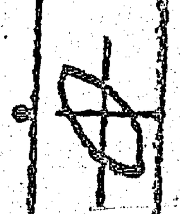
S.No.	LISAJOR	f Hz	Magnitude P_j (Cm.)	A Cm.	B Cm.	C Cm.	D Cm.
1.		208	0.49(200µ st.)	--	--	--	--
2.		423	0.65(200" ")	--	--	--	--
3.		580	1.105(200 ")	--	--	--	--
4.		589	1.90(200" ")	--	--	--	--
5.		690	1.735(200" ")	4.85	4.6	2.6	2.5
6.		714	1.97(200" ")	--	--	--	--
7.		755	1.825(200" ")	4.8	4.45	3.0	2.9
8.		847	1.66(200" ")	--	--	--	--
9.		958	1.08(200" ")	--	--	--	--
10.		1125	1.09(100" ")	--	--	--	--

TABLE Output Impedance Data(cont.)

S.No.	LISAJOR	Magnitude P_o(Cm.)	A Cm.	B Cm.	C Cm.	D Cm.
1.		1.0(200µ st.)	3.25	0.46	4.95	0.51
2.		1.4(200" ")	3.25	3.20	4.95	4.85
3.		2.4(200" ")	3.0	0.80	5.2	1.1
4.		3.2(200" ")	2.8	0.8	3.3	0.85
5.		3.4(200" ")	4.83	3.85	4.0	3.15
6.		3.8(200" ")	5.85	5.40	3.4	3.15
7.		3.1(200" ")	--	--	--	--
8.		3.0(200" ")	5.9	2.8	4.75	2.15
9.		1.9(200" ")	6.1	5.2	2.8	2.3
10.		2.0(100" ")	5.4	3.25	3.0	1.9

References

1. "Fluid Amplifier." Edited by J. M. Kirshner, McGraw-Hill Book Company.

2. "Journal of Basic Engineering." June 1970. Published quarterly by ASME. (pp. 303)

3. A. J. Chapman "Heat Transfer" New York, The MacMillan Company, 1968 (pp. 217)

4. Schlichting "Boundary layer Theory" Fourth edition, 1960 (pp 10)

5. Schlichting "Boundary layer Theory" Fourth edition 1960 (Chapter XVI)

VITA

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