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On the Calibration of Pressure Transducers for use in Shock-Tunnels

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ON THE CALIBRATION OF PRESSURE TRANSDUCERS FOR USE IN SHOCK-TUNNELS

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SUMMARY

The calibration of high-sensitivity, fast response pressure transducers is discussed, particular attention being given to those factors which can lead to significant calibration errors. It is shown that static and dynamic calibrations of piezoelectric transducers are consistent, contrary to the experience of some earlier investigators, so that where static calibration is possible, this is sufficient. In cases where static calibration is not possible, the "semi-dynamic" technique using a quick-acting valve is both more convenient and potentially more accurate than the shock-tube technique, especially when digital recording can be employed.

An electrostatic calibrator is described which can apply a pressure (attractive) either statically or dynamically, the rate of application of the load being, in principle, adjustable. Although the device has several disadvantages it would appear worthy of development for operation in the pressure range up to 10 torr, a range not easily achieved by other methods of dynamic calibration.

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1. Introduction

For some time a research programme at Queen Mary College has been directed towards the design and construction of pressure transducers for use in shock tubes with the eventual aim of making aerodynamic measurements on models. An essential part of the evaluation of these transducers is calibration. However carefully any measurements may be taken they can never be more meaningful than the calibration of the measuring system itself will allow. The problem then arises of the accuracy with which the calibrator has been calibrated and the process of calibration can obviously be carried on ad infinitum.

The most common calibration technique is to apply a 'known' pressure to the transducer and to measure its output. In connection with shock tubes the different techniques available are frequently classified in three groups, static, semi-dynamic and dynamic. These refer to the rise times of the applied pressure and are obviously very loose terms; rise times of a second or more come under the heading static, those between say 100 μs and 1 s under semi-dynamic and those less than 100 μs under dynamic.

In practice equipment for the measurement of static quantities is more accurate than that for the measurement of a similar dynamic quantity. A very useful feature of any calibrator therefore is for it to have a flat response from d.c. through the desired dynamic frequency range. The calibrator may then be tested under static conditions against a standard device before it is used dynamically. The electrostatic calibrator described later is such a device.

The other aspect of calibration is the measurement of the transducer output and this is obviously of equal importance to the measurement of the applied pressure. This is discussed in detail in Section 4.3.

Section 2 outlines some of the different techniques available for applying pressure to a transducer for calibration purposes. In Section 3 reported discrepancies between calibrations by different techniques are considered. The next section describes the evolution of the shock-tube calibration technique used at Queen Mary College and this is followed by a description of some preliminary work done with an electrostatic calibrator. In the final section some of the more promising techniques are reviewed and a technique is recommended which offers high accuracy with relative simplicity.

It should be pointed out that all the work at Queen Mary College in this field has been on piezoelectric transducers which are probably the commonest, but by no means the only, type in general use in shock tubes. Thus much of the paper is directed specifically to such transducers. It is felt, however, that the conclusions and fundamental ideas have considerable relevance to other types of transducer.

2. Some common calibration techniques

Although there are many variations on these basic themes, the most important of the better known techniques for calibrating pressure transducers are.

(a) the dead weight tester,
(b) shared volume technique,
(c) quick-acting valve technique,
(d) piston-phone calibrator,
(e) shock-tube technique,
(f) electrostatic calibration.

The dead weight tester consists basically of a cylinder with a very finely machined bore in which slide a number of cylindrical, accurately measured weights. The air in the cylinder is compressed until the weight comes to rest and the pressure at the bottom is then determined from the cross-sectional area of the cylinder and these weights. The transducer under test is connected to the bottom of the cylinder by a pipe and therefore has a known pressure applied to it. In practice a number of refinements are incorporated into the device to minimise in particular the effects of leakage and friction. Because it works on a principle based on the definition of pressure (force/area) the dead weight tester in its most accurate form is regarded as a 'primary standard'.

In the shared volume technique two accurately known volumes at different pressures, one containing the transducer, are connected by means of a valve which can conveniently be hand operated. When the valve is opened the pressures will equalise giving the required change of pressure. There are many variations of this technique although all involve testing the transducer against a more accurate standard device. Since the technique is a static one, calibration may be performed using any one of a number of highly accurate pressure gauges, depending on the order of accuracy required. One of its chief advantages is that the transducer to be calibrated may have a different range from the 'standard'.

The first of the semi-dynamic techniques is the quick-acting valve calibrator which is a modification of the previous technique. The transducer is mounted in a small evacuated cavity which is connected to a very much larger reservoir at the required calibrating pressure. The two chambers are isolated from one another by a quick-acting valve and when this valve is operated (usually by means of an electric solenoid) a pressure pulse is applied to the transducer, the form of this pulse depending very much on the geometry of the system. Aronson & Waser (1963) in one of the earliest designs obtained a rise time of order 200 μs, whilst similar designs by Pallant (1966) and Pennelegion et al (1966) provided rise times of order 1-5 ms depending on the magnitude of the applied pressure.

A commercial calibrator designed specifically for the calibration of microphones is known as the 'Piston phone' (Beranek, 1949). This consists of a closed cavity in one side of which the microphone or transducer is mounted. On the opposite side a small piston slides in a hole so that it alters the effective volume of the cavity by a small amount. It is driven in a reciprocating motion by an electric motor giving rise to approximately sinusoidal pressure variations. The device is designed primarily for generating pressures up to about 1 torr, although this could presumably be increased in a design specifically for calibrating pressure transducers as opposed to conventional microphones. However, it suffers to some extent from the fact that the device itself is not easy to calibrate, and corrections must be applied for the manner of compression of the gas (which is not strictly adiabatic) and these corrections vary with frequency. This technique again comes under the heading semi-dynamic.

The most common truly 'dynamic' technique uses the shock wave in the channel of a shock tube. Either the primary or the reflected shock wave may be used. This method is described in more detail in Section 4.

An electrostatic attraction technique is described in Section 5. It is based on the principle that if the transducer (which must have a metal diaphragm) forms one plate of an electrical capacitor and a voltage is applied between the plates, the diaphragm will experience an electrostatic attraction. Two particular advantages of the method are that it is calibrated by the measurement of two electrical quantities which may be determined to a high degree of accuracy, and that according to the form of the applied voltage the method may come under any of the dynamic, semi-dynamic and static headings. The main disadvantage is that as yet it is difficult to raise the maximum pressure much above 0.1 torr, although some suggestions for doing this are made.

3. Reported differences in calibration

At the start of this work there were several workers (see, for example, Pallant 1966) who had reported differences in the calibration of transducers obtained by different techniques. The general trend was for static and semi-dynamic calibrations to give fairly close agreement but for dynamic calibration to show relatively large discrepancies. In addition to differences in slope some experiments gave dynamic calibration curves which do not pass through the origin. While no output being obtained until a certain pressure was exceeded (Pennelegion, 1965) might be explained by a kind of mechanical backlash, the reverse situation of a non-zero output for no applied pressure is much harder to explain.

While such results are not what we would expect, it is important to consider first what effects in a transducer might cause such errors. The first is non-linearity. Some later calibrations of a Queen Mary College designed transducer (Goodchild & Bernstein, 1969) are shown in figure 1. The transducer exhibits a distinct change in calibration above a certain pressure. This change was attributed to internal backlash. The transducer was assembled using a pre-loading technique and this is the sort of effect which would be expected if the parts were not properly aligned. As mentioned earlier, such effects are most likely to give an intercept on the pressure axis, and it is very difficult (though not impossible) to imagine a situation which would give rise to an intercept on the output axis.

A second effect in transducers is hysteresis. When a transducer is subject to a cyclical change in pressure it almost always exhibits hysteresis although this may be small. When excited dynamically the transducer oscillates at its natural frequency with a peak amplitude roughly twice that of the static displacement. During this oscillation the transducer will be going continually round a hysteresis loop. What sort of errors might this cause? The maximum hysteresis error of transducers is usually of order several per cent of the maximum pressure output. In dynamic calibration we would therefore expect intercept errors due to hysteresis to be no more than several per cent of the full range covered by the calibration.

A further suggested cause was the difference between the adiabatic and isothermal responses of materials. Such differences, however, are so small that they would be extremely difficult to detect. One final point concerns explanations based on the fact that the oscillatory response is double the static response. Provided the system is allowed sufficient time to settle down, which may be readily checked by monitoring the transducer output on an oscilloscope, it should do so at the static value. Even when an oscilloscope is not used as the measuring instrument, it is perhaps wise to include one to give a visual check on what is happening.

4. Shock tube calibration technique

4.1 Initial technique

Since we were directly concerned with shock tubes it was natural that we should study its use as a calibration tool. Some of the work by Harris and Kaegi (1958) had indicated that the calibration of transducers was more repeatable when they were recessed from the flow and shielded by a cavity. It was therefore decided to calibrate a gauge which could be mounted either flush with the shock tube wall or recessed behind a number of different cavities. Because of its generally accepted reliability, a Kistler type 701A piezoelectric pressure transducer was chosen for the initial experiments. This has an additional advantage that since the sensing element is quartz rather than a ceramic, a sufficiently long electrical time constant may be obtained to allow quasi-static calibration.

The calibration experiments were performed in the channel of the Queen Mary College 76.2 mm square cross-section shock tube at a distance of about 10 m from the main diaphragm. The arrangement is sketched in figure 2. The transducer was mounted between two shock wave detector stations 254 mm apart. The primary shock wave was used for the calibration, its speed being measured by two piezoelectric detectors (Bernstein and Goodchild, 1967) used in conjunction with a decimicrosecond chronometer. The initial channel pressure was measured using a bank of three Wallace & Tiernan Bourdon tube gauges spanning 0-20, 0-100 and 0-800 torr. The transducer output was processed by a Kistler type 566 charge amplifier, filtered and photographed from a Tektronix oscilloscope.

The initial experiments were conducted using nitrogen as both driven and driver gas to give pressure rises in the range 50-800 torr. Two series of tests were conducted, one with, and one without, the orifice plate shown in figure 3. Some typical traces are shown in figure 4. Without the plate the waveform is very good. With the orifice plate the pressure rise time is of order 300-500 μs and there are relatively large fluctuations in the output which made the measurements less accurate*. A static calibration of the transducers was performed by evacuating the channel and then filling it to the required pressure and measuring the change in transducer output. Careful attention was paid to electronic 'drift' during the static calibration, and small corrections were applied where necessary.

The results are shown in figure 5 and, in deriving these, the only correction applied was for the gain of the filter unit. The makers' calibration is also shown, although this serves mainly as a reference point as it is done at a pressure of 250 atm (approx. 2 x 10^5 torr). The main points drawn from these results were

(i) The two dynamic calibrations differ by only about 1% but these are some 4% from the static calibration performed and nearly 10% from the makers' calibration,

(ii) the calibration lines do not pass through the origin. While that for the cavity mounted gauges causes little concern, those for the static and flush mounted dynamic tests have intercepts on the 'charge' axis of about 0.8 pC, corresponding to a pressure of 8 torr.

Following these conclusions a systematic investigation into the calibration of the individual items of equipment was conducted. This led to the identification of several possible sources of error, which are summarised in the table below.

The Wallace and Tiernan gauges for the measurement of channel pressure were calibrated against a Texas Instruments quartz Bourdon tube gauge having a resolution of 10^{-3} torr, and calibrations over a period of several days indicated that changes in calibration are less than the errors in 'reading' the gauge. This has been confirmed by re-calibration several months later. The other parameter necessary for the determination of the applied pressure is the shock strength, and this is discussed in more detail later in this section.

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* The second step rise in pressure seen in figure 4 corresponds to the arrival of the shock wave reflected from the closed end of the shock tube.

Source of Error	Maximum deviation from nominal value (%)	Final Error ± %
Shock strength (P_{21} - 1)	-	2
Channel Pressure	2	0.1*
Reading of oscilloscope traces	-	1
Filter gain (nominally unity)	- 4	1
Gain of charge amplifier due to switch capacitance and tolerance of feedback capacitor	- 4	0.1
Gain of charge amplifier due to effect of transducer and connecting cable capacitance	- 2	0.1
Gain (sensitivity) of oscilloscope	5	1
Drift of oscilloscope gain over 5 hours	2	

* of full-scale

The signal level on the oscilloscope trace was measured using a pair of calipers, and for a magnitude of three or four centimetres the estimated error is 1%. On several occasions a set of traces was re-measured after several days in an attempt to assess the 'human error' in trace reading. Differences were within ± .01 on a reading of order 4 in eight cases out of ten (on average) and were within ± .02 in virtually all other cases. This error is probably constant, i.e. independent of measured amplitude, and therefore amplitudes less than 2 cm are to be avoided if accuracy is to be maintained.

The gain of the filter was measured by recording the input and output waveforms using a square wave, and the error is therefore determined by the accuracy of the trace measurement. The oscilloscope gain was estimated using a Weston Standard Cell to provide the calibrating voltage, and this meant that calibration could not be performed over a complete range of sensitivities. It was found that the sensitivity of the oscilloscope and its pre-amplifier varied by several per cent over the course of a day.

One of the most interesting effects resulted from the alteration in charge amplifier gain caused by the cable plus transducer capacitance, and the switch capacitance. The charge sensitivity V_q is given by

$$V_q = \frac{m}{C_c + C_e + (m + 1)\ (C_F + C_F')} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where C_F' represents any stray feedback capacitance and m is the open-loop gain of the amplifier. In this particular instance $C_c + C_e \approx 40$ pF, and $C_F' \approx 0.5$ pF, so that at a nominal sensitivity of 100 mV/pC (C_F = 10pF) the resulting error may be as high as 6% or 7%, decreasing with nominal sensitivity. In a typical series of experiments the sensitivity will be increased as the applied pressure is reduced, and this effect will therefore lead to under-estimation of the charge output by an increasing proportion at lower charge outputs. As well as introducing scatter into the results this would also lead to the curve not passing through the origin, but having an intercept on the pressure axis. Whilst this is in agreement with the results of Pennelegion (1965), it does not explain the intercept on the charge axis given by this series of experiments.

A further series of experiments was then conducted with individual corrections applied for each of the effects mentioned in the previous table, and the results are shown in figure 6 for two ranges: 50 - 1300 torr and 10 - 100 torr. In both cases the linearity is good, and the higher pressure range shows excellent agreement with the makers' calibration. However, in the lower pressure range the calibration still gives a small intercept on the charge axis.

4.2 Measurement of applied pressure

The calibration of a pressure transducer necessitates two distinct measurements. We consider first the measurement of the applied pressure. In the next sub-section we shall discuss the measurement of the resulting transducer output.

With shock tube calibration techniques the applied pressure depends upon the initial channel pressure p_1, and the relationship between this pressure and the pressure rise seen by the transducer. In techniques based on the primary shock it is the pressure rise $(p_2 - p_1)$ across this shock that is required.

The accuracy of the measurement of initial channel pressure depends on the instrument used. In this case a series of Wallace and Tiernan Bourdon tube gauges were used, with a possible error of ± 0.1% of full scale. Thus for a pressure of 10% of full scale the possible error has risen to 1% of the reading and for high accuracy it is therefore undesirable to use these gauges below say 10% of full scale. However, more accurate transducers can be obtained and the accuracy of the measurement of initial channel pressure is to a great extent a matter of finance.

The second aspect of pressure rise determination is the pressure ratio across the primary shock. The pressure ratio across the primary shock is given by

$$\Delta p = (P_{21} - 1)p_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

The errors arising from the uncertainty in the factor $(P_{21} - 1)$ come from two sources. The factor itself is a function of shock Mach number W_{11}, and the state of the initial undisturbed gas ahead of the shock. When W_{11} is large, 'real gas effects' play a part in determining the pressure ratio P_{21}, so strong shocks should be avoided to reduce uncertainties arising from this cause. (Where possible calibrations should be carried out at constant shock Mach number, only the channel pressure p_1 being varied. This is not usually practicable over a very wide range, so W_{11} usually has to be varied.) So long as the temperature T_2 behind the shock does not become too large the gas may be regarded as perfect, with the ratio γ of specific heat-capacities remaining constant. The pressure difference across the shock wave is then given by

$$\frac{\Delta p}{p_1} = \frac{2\gamma}{\gamma + 1}\left\{W_{11}^2 - 1\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

A possible error δW_{11} in W_{11} leads to an uncertainty $\delta(\Delta p)$ given by

$$\frac{\delta(\Delta p)}{\Delta p} = \frac{2W_{11}^2}{W_{11}^2 - 1}\left\{\frac{\delta W_{11}}{W_{11}}\right\} \quad \ldots\ldots\ldots\ldots(4)$$

so that for strong shocks the possible error is twice the uncertainty in W_{11} while at $W_{11} \approx 1.4$ it is four times, the ratio increasing rapidly as $W_{11} \to 1$ (see figure 7). Since strong shocks may introduce thermal and caloric imperfections in the gas and because they are usually associated with low values of p_1, which may introduce thermal relaxation effects, they should be avoided for calibrating pressure transducers. Additionally many pressure transducers are thermally sensitive, and the high temperatures T_2 associated with strong shocks could introduce further uncertainties. An upper limit of about $W_{11} = 4$ in a gas such as nitrogen would appear suitable. The pressure ratio $P_{21} = 18.76$ at this shock Mach number allowing for full vibrational excitation of the gas (Bernstein 1963) compared with the value 18.5 given by assuming $\gamma = 7/5$. Thus errors due to uncertainties in the correction for the effects of vibrational relaxation would be negligible. One might even consider using shock Mach numbers as high as $W_{11} = 6$ at which vibrational excitation affects the pressure ratio by less than 3% maximum, but the temperature T_2 behind the shock is 2000 K in this case, compared with about 1100 K at $W_{11} = 4$.

A lower limit of $W_{11} = 1.4$ and a requirement that $\delta(\Delta p)/\Delta p < 2\%$ say, would require the shock Mach number to be known within 0.5%.

Measurement of W_{11} involves measuring the shock velocity w_1 and knowing the speed of sound a_1 in the undisturbed channel gas. The latter is dependent upon thermodynamic constants of the gas and the absolute temperature T_1. These are known or can be measured quite accurately so that a_1 is known to within say 0.1%.

Determining the shock velocity w_1 usually involves measuring the time taken for the shock to pass between two stations along the shock-tube channel. Uncertainties in the distance apart of the shock-detectors are typically 0.1%, and attenuation of the shock as it traverses the distance Δx between the measuring stations may lead to a further error, though since an average value is determined this latter error is small so long as Δx is not too large. Again there is a lower limit to practical values of Δx because times are rarely measured with chronometers having a resolution better than 0.1 μs. Such chronometers have inherent 'gating errors' leading to possible errors of '± 2 counts', that is ± 0.2 μs, so that Δx should be chosen such that times of order 100 μs are measured.

4.3 Measurement of transducer output

The output impedance of piezoelectric transducers is very high and even when the signal level is such as not to need amplification before recording, a "buffer stage" amplifier is necessary to match the output impedance of the transducer to the input impedance of the recording device (for an oscilloscope this is typically 1 $M\Omega$). In many applications amplification is required, and of course the amplifier must also be calibrated. For reasons which are outlined in the Appendix, charge amplifiers are preferable to voltage amplifiers in the present context, even though their advantages are minimised by the need for frequent calibration.

Individual calibration of the separate items of electronics is not ideal and the technique was adopted of injecting a calibration charge into the input of the amplifier at the end of each experiment. After some experiments made with a commercial 'charge calibrator' it was decided that a considerable improvement could be afforded by some relatively simple modifications. The final design is shown in figure 8.

The circuit generates a constant amplitude square wave which is fed to a potential divider in the form of a ten-turn helical potentiometer. The output from the potentiometer is taken to a monitor socket and also to a switching arrangement for connecting the output to the appropriate channel through the necessary series capacitor. Values of 10, 100 and 1000 pF were chosen initially to give charge outputs of 10, 100 and 1000 pC for an input of 1 volt.

The most important features of this calibrator are the following.

(i) Up to three separate channels may be calibrated. Each channel is equipped with its own set of calibration capacitors so that no additional cables are required when changing from the 'operate' to the 'calibrate' position.

(ii) In the 'operate' position the calibrator sides of the series capacitors are earthed so that the total parallel capacitance across the charge amplifier input is the same in both 'calibrate' and 'operate' positions.

(iii) The frequency of the output square wave can be adjusted.

(iv) The amplitude of the output square wave can be monitored using a digital voltmeter (DVM). In the d.c. monitor position the output transistor is switched hard 'on', the collector voltage then corresponds to the square wave peak.

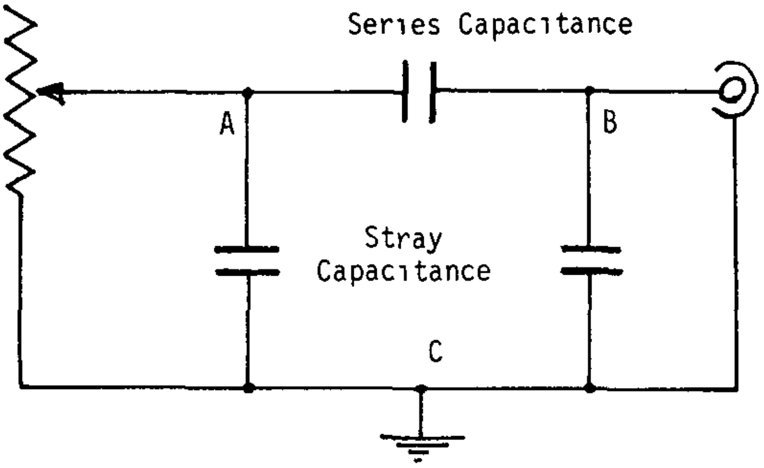
(v) For normal operation the output can be preset so that a ten-turn potentiometer reads directly in volts This is suitable for all but the highest accuracy requirements

The accuracy of the calibration obviously depends on the accuracy of both the generated voltage and the series capacitor. Two experiments were performed to assess the accuracy of each of these components

To check that the output measured by the DVM in the d.c. monitor monitored on a d.c.-coupled oscilloscope with a differential input having a sufficiently large common mode range. With the oscilloscope set at a high sensitivity and using a stabilized power supply as the second voltage to keep the trace on the screen, the mode switch was changed from the 'a.c. calibrate' to 'd.c. monitor'. The difference between the d.c. output and the square wave amplitude was found to be much less than 10 mV for an output of 10 volts corresponding to an error of $<<$ 0.1%.

The other point considered was the effect, if any, of stray capacitance on the effective value of the series capacitor. The equivalent circuit is sketched below. Since these capacitances are effectively in parallel with the amplifier input we would expect them to have some effect on the amplifier gain (depending of course on how the amplifier gain is affected by such capacitance) but not to alter the effective series capacitance. However, it was felt wise to verify the fact. Using a Wayne Kerr Impedance Bridge in a three terminal mode* between the points A, B and C, it was found that the in-circuit value agreed with the out-of-circuit value for the same capacitor measured on the same bridge. An additional check was provided by using a series capacitor of 10 pF (the same order as the stray capacitances) to feed an external 1000 pF capacitor, and measuring the appropriate signal levels.

In this particular calibrator the range capacitors are equipped with trimmers. Using the 'three terminal' method of measurement they are adjusted to give the desired value. The final error from this source should therefore be of the same order as that of the bridge, that is 0.1%.



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* In this mode the bridge measures only the series component of impedance between A and B and compensates for the effect of any impedance between A and C or B and C.

4.4 The technique adopted

The technique was basically that described in Section 4.1 with refinements.

The shock wave speed was measured as before and the pressure ratio across the wave calculated using Bernstein's (1963) tables. The temperature in the laboratory was measured at intervals of about half an hour and this was taken as the initial channel-gas temperature for calculating the Mach Number, it being assumed that the gas rapidly attained the temperature of the shock tube.,

The initial channel pressure was measured using the Wallace and Tiernan gauges.

The electronic system was calibrated using the technique described earlier. Immediately after each 'run' a calibration charge comparable with the expected signal level was injected and the ratio of the two signals on the oscilloscope record enabled the experimental signal to be measured. To improve the accuracy of tne calibrator slightly its output was monitored using a digital voltmeter.

Using this technique the following are the sources of error

(i) Errors in $(P_{21}-1)$ due to errors in W_{11} and in the calculation of $(P_{21}-1)$ from W_{11}, ... $< 2\%$

(ii) Errors in p_1, ... $< 0.5\%$

(iii) Errors in calibration charge, ... $\ll 0.5\%$

(iv) Errors in amplitude ratio of two oscilloscope traces .... $< 2\%$

Thus we see that even using the comparatively refined final technique the maximum errors may be as high as 5%. Some of these will be systematic and will give rise to errors in the overall calibration; others are random and will lead to experimental scatter.

Possible techniques for improving the accuracy still further are described in Section 6.

5. An electrostatic calibration technique

5.1. The electrostatic calibrator

One of the disadvantages of the shock tube dynamic calibration method described earlier is that it is not easily adapted for pressures lower than about 10 torr. Even with specially designed calibration shock tubes it is doubtful whether the method can be extended to pressures much below 1 torr. Transducers for use in the hypersonic test section of a shock tunnel, particularly those for the measurement of static pressure, are likely to be required to measure pressures much less than 10 torr and it is important that they should be calibrated in the range over which they are to be used.

In the field of acoustics where the extreme range of pressures encountered is of order 10^{-7} torr to 1 torr, the electrostatic calibration technique has often been used for microphones and commercial equipment is available for this purpose. Unfortunately this equipment does not apply pressures above about 0.01 torr. It was therefore decided to investigate the possibility of designing a calibrator capable of applying pressures as high as 10 torr and with as rapid a pressure rise time as possible to fill the gap in calibration facilities at low pressures.

The basic principle of the electrostatic technique is that if the transducer has a metal diaphragm and is placed close to a metal plate, then a potential difference applied between the plate and the diaphragm will cause them both to experience a force of attraction at their surfaces. Assuming that the two surfaces form part of an infinite, parallel-plate capacitor, the pressure p at the surface is given in terms of the potential difference V, and the plate separation h, by

$$\frac{p}{\text{torr}} = 3.32 \times 10^{-8} \left\{ \frac{V}{\text{volts}} \; \frac{\text{mm}}{h} \right\}^2 \qquad \text{.........} \quad (5)$$

Although it appears at first that the pressure developed may be increased at will simply by increasing V and decreasing h, serious limitations are imposed by the dielectric breakdown of the insulating medium. For the moment this will be assumed to be air although the possibility of using other gases will be considered later. For air the dielectric strength depends on the shape of the electrodes and their distance apart; for the distances and shapes likely to be used here a value of 3 kV/mm was used to allow a margin of safety. This gives a maximum pressure of about 0.3 torr which is an order of magnitude lower than that originally desired. Since some of the pressures to be measured in the shock tunnel at Queen Mary College are likely to be of this order, work on this technique was continued despite this apparent limitation.

There were two other reasons for continuing work on this method. Firstly, as mentioned earlier, considerable doubt was being expressed at that time about the linearity of transducers at lower pressures and about the agreement between static and dynamic calibration techniques. Since it may be either static or dynamic, the electrostatic technique provides a convenient method of investigating this question. Secondly, calibration of the device ideally requires only the measurement of a voltage, a capacitance and a linear dimension, each of which may be determined very accurately. The practical design of the calibrator is conveniently described in two parts, the first dealing with the calibrator itself and the second with the means of applying the exciting voltage.

The calibrator is shown diagrammatically in figure 9. It consists of a parallel plate capacitor with the two plates separated by a thin sheet of Melinex. Melinex was chosen because it has a high dielectric strength and is readily available in thin uniform sheets. In the upper of the two plates is a hole which is larger than the active area of the transducer diaphragm and the transducer is clamped centrally over the hole. Driving plates of a variety of sizes are available for different transducers.

One point of considerable importance in the calibrator arises from the way in which the applied pressure is calculated. The average pressure on the diaphragm may be shown to be given by

$$p = \frac{V^2 C^2}{2 \varepsilon_o \varepsilon_r A^2} \qquad \ldots\ldots\ldots\ldots \qquad (6)$$

where ε_r is the relative permittivity (1.0 for air) and C refers to the capacitance between the exposed part of the diaphragm (of area A) and the lower plate. Whilst A may be determined from the diameter of the hole in the driving plate, C may only be measured as the difference in the overall capacitance of the device with and without the transducer in place. In addition the areas with no air gap have a higher capacitance per area than those with an air gap due to the higher permittivity of the Melinex.

The combined effect is that for high accuracy in the value of C to be used in equation (6) the ratio of exposed diaphragm area to driving plate area should be as close to unity as possible. The calibrator described here is rather poor in this respect, a point which is elaborated later.

The means of applying the exciting voltage and the form it should take are of obvious importance. The two basic types of excitation are to apply a d.c. polarising voltage upon which is superimposed an alternating voltage or to apply a large alternating voltage to the calibrator without the polarising voltage. The alternating voltage component is usually either a sine wave or a square wave for convenience. In this application as high a pressure as possible was wanted and since this pressure depends on the difference between the squares of the maximum and minimum voltages it was decided to use a simple alternating voltage for excitation. It is also important that the applied voltage should be easily and accurately measurable and using a square wave this could be done using a conventional digital voltmeter. It was decided therefore to use a high voltage square wave of variable frequency. Eventually it was also hoped to vary the rise time of this square wave so that the transient performance of transducers could be studied. The method of excitation using a polarising voltage and a superimposed sine wave is discussed in detail in the instruction booklet for the 'Microphone Calibration Apparatus Type 4142' (Bruel & Kjaer).

The methods available for generating a square wave with an amplitude which might be as high as 1000 volts fall into two main classes. The first uses a high voltage oscillator or an oscillator-amplifier configuration and the second uses a high voltage d.c. supply and a switching circuit to generate the varying waveform. The problem encountered in the initial tests on a very high amplitude valve oscillator led to this approach being abandoned in favour of the second.

Switching circuits may again be subdivided into those employing a mechanical switch or relay and those employing an electronic switch such as a thyratron or a silicon controlled rectifier. A particularly simple solution was provided by using a reed switch and this was adopted. The circuit of the reed switching unit and that associated with the calibrator itself are shown in figures 10 & 11. Some of the main features of this particular unit are as follows.

(i) Using a suitable E.H.T. supply a square wave amplitude of over 2000 volts may be generated.

(ii) The output frequency can be varied from about 10 Hz to about 0.01 Hz.

(iii) Using the monitor circuit (once the potential divider ratio has been accurately measured) and operating the switch at the lowest frequency, the amplitude of the square wave may be accurately measured with the aid of a digital voltmeter.

The switching circuit was mounted on sponge rubber supports on the base of the calibrator itself and the calibrator formed the lid of the case for the electronic switching circuit.

5.2 Results from the Q.M.C. electrostatic calibrator

To assess the performance of the calibrator a series of experiments was conducted using a type K2 pressure transducer, designed and built at Queen Mary College (Goodchild & Bernstein, 1969), which had previously been calibrated and found to have a sensitivity of 20.8 pC/torr. The transducer output was measured using a high-gain charge amplifier and a four stage R-C filter and the voltage applied to the calibrator was measured using a digital voltmeter connected to the 'monitor' socket on the electrostatic calibrator.

Some typical traces are shown in figure 12. The fluctuations on the basic square wave signal were thought at first to be due to electronic noise in the amplifying system, but were eventually found to be a combination of acoustic noise and mechanical vibration signals. Although these fluctuations were relatively large it was found that if the amplitude of the square wave was measured close to the step changes, consistent readings were obtained, and this was felt to be more accurate than attempting to draw a 'mean line' through the noise signals.

Since the effective pressure on the transducer depends on the square of the applied voltage it was expected that plotting transducer output Q against applied voltage V_a, would lead to a curve of the form

$$Q = kV_a^2 \qquad \ldots\ldots\ldots\ldots \quad (7)$$

The results of the tests are presented in figure 13 as a graph of Q versus V_a. Whilst the curve approximates closely to a parabola there is a portion of it below the V_a-axis which suggests that either the pressure on the transducer is a repulsion rather than an attraction, or that the transducer sensitivity changes sign. Since the electrostatic force is proportional to V_a^2 the former can be discounted, and the latter would seem most unlikely. Since the curve is not symmetrical about the Q-axis there must be a dominant odd-power term in the series expansion for Q in terms of V_a, and this was found to be a linear term. When the exciting potential is applied to the calibrator there is a high intensity electric field in front of the transducer diaphragm and it is likely that the diaphragm will not provide complete shielding so that some field will exist inside the transducer. The sensing element is capacitive and will therefore give an apparent output proportional to the internal field which in turn will probably be proportional to the applied voltage. This is supported by the fact that under some conditions high frequency 'peaks' are present in the output, suggesting that the 'pick-up' component unlike the pressure component is not limited by the mechanical natural frequencies of the transducer.

Assuming that the transducer output consists of a pressure component proportional to V_a^2 and a pick-up component proportional to V_a, it may be shown that

$$(Q)_{PRESS} = (Q)_{TOT} \left\{ 1 - \frac{V_b}{V_a} \right\}^{-1} \qquad \ldots\ldots\ldots\ldots (8)$$

where V_b is the intercept on the V_a-axis.
If we then plot $(Q)_{PRESS}$ against V_a^2 we should obtain a straight line through the origin. To obtain the value of V_b a 'least'squares' parabola was fitted to the experimental points. Since the curve should pass through the origin a form without the constant term was chosen, i.e.

$$(Q)_{TOT} = aV_a^2 + bV_a \qquad \ldots\ldots\ldots\ldots (9)$$

The values of $(Q)_{PRESS}$ were calculated from equation (8) and the results are shown in figure 14. The points are plotted on different sides of the Q-axis for V_a positive and V_a negative although of course V_a^2 is always positive. Whilst the points for negative V_a approximate quite closely to a straight line through the origin, those for positive values of V_a less than about 100 volts show a considerable amount of scatter. Why this should be so is not clear, although it may be that any experimental errors or departures from the ideal linear V_a relationship for the pick-up component will be more important in the region of maximum curvature of the parabola. Also shown in figure 14 are the two straight lines obtained from the least squares analysis.

To calculate the transducer sensitivity from these results it is necessary to measure the transducer-lower plate capacitance. Because this is very small compared with the overall capacitance of the device it proved impossible to measure experimentally even the order of magnitude of this capacitance. Consequently a value was calculated from the dimensions of the device. When this value was used together with the constant obtained from the least squares analysis the sensitivity of the transducer was 18.4 pC/torr, which is to be compared with the previously measured value of 20.8 pC/torr. In view of the scatter in the experimental results, the difficulty in determining the capacitance (which is a critical factor) and the doubt which may surround some of the assumptions, the closeness of these two would at least seem to be encouraging.

5.3. Possible improvements to the electrostatic calibrator

During these experiments it was found that this electrostatic calibrator design had several serious drawbacks and these are now outlined with possible solutions. The calibrator operates at very low pressures and is therefore extremely sensitive to acoustic noise and vibration; extensive precautions must be taken to minimise these effects. To reduce external noise the calibrator could be mounted in a bell jar, and this would prove convenient were the calibrator to be used filled with compressed air or another gas, as is suggested in section 5.4. The calibrator could also be mounted on foam rubber pads or suspended by elastic strips to isolate it from mechanical vibration. In this connection the reed switch proved to be a troublesome source of vibration despite being isolated from the main base of the unit by foam rubber pads. It is suggested that future designs incorporate electronic rather than mechanical switching. Suitable circuits are available using silicon controlled rectifiers.

Another fault concerns the ratio of the capacitance of the device with and without the transducer. In this design the transducer-lower plate capacitance is only 5-10 pF compared with the total capacitance of about 200 pF. To overcome this the basic design of figure 15 is suggested. In this the 'driving plate' has been dispensed with, and a small guard ring is used to minimise edge effects. If the electrical connection between the transducer and the guard ring can be broken the capacitance between the transducer and the lower plate could be measured directly using a capacitance bridge operated in a three point connection mode (see section 4.3). During operation the two would, of course, be electrically connected.

Finally, it must be remembered that there is one inherent disadvantage in the electrostatic calibration technique. This is that the applied force is always one of attraction, whereas transducers are designed to operate under pressure. It can only be used where the diaphragm is connected to the anvil or element in such a way that its positive and negative force transmitting characteristics are identical, and this is by no means easy to achieve.

5.4. Increasing the working range of the electrostatic calibrator

The general equation for the maximum uniform electrostatic attraction between the plates of a parallel plate condenser is

$$p = \tfrac{1}{2}\varepsilon_0 \varepsilon_r (V/h)^2 = \tfrac{1}{2}\varepsilon_0 \varepsilon_r E_c{}^2 \quad \ldots\ldots \quad (10)$$

where E_c is the critical breakdown field or dielectric strength. For air since E_c is of order 3 kV/mm the maximum pressure which can be obtained without breakdown is about 0.3 torr, and it is therefore important to assess the possibility of improving this performance. The two obvious ways of doing this are to use a dielectric medium with a high value of ε_r, or E_c or both. It is desirable to use a gas for the dielectric so that the problem of acoustic loading of the transducer diaphragm is minimised, and for gases ε_r is close to unity (1.00 - 1.01) so that to achieve a substantial improvement in performance we must find a gas with a dielectric strength considerably higher than 3 kV/mm.

There are a large number of such gases (see, for example, American Institute of Physics Handbook, 1957) and using nitrogen as the reference gas examples of relative dielectric strength are Freon 2.4, sulphur dioxide 1.9, carbon disulphide 1.5. A second method available which avoids the use of these somewhat unpleasant gases is based on the fact that for air the dielectric strength depends on the pressure, and for pressures up to about 10 atmospheres is approximately proportional to the absolute pressure. Thus if the pressure within the calibrator can be increased to about 3.3 atmospheres, the dielectric strength would be 10kV/mm, and the maximum operating pressure would be of order 3 torr. This method of increasing the working range of the electrostatic calibrator therefore merits particular attention. Special care must be taken that this pressure is not allowed to appear across the diaphragm of highly sensitive transducers, as this could cause considerable damage.

6. Discussion

In Section 3 some reported discrepancies in calibration obtained by different techniques were discussed. It is felt by the authors (and this is probably a widely held view) that calibrations by different techniques should not give different results, except that hysteresis might cause errors which we would expect to be relatively small.* In the experiments described earlier no significant differences were encountered. It would seem very reasonable to suggest that large divergences between calibrations by different techniques give information on the accuracy of one or both techniques rather than on the performance of the transducer.

As stated at the beginning of Section 4.2, the problem of calibration separates into the measurement of the applied pressure and the measurement of the transducer output. Taking first the measurement of the applied pressure, three techniques have been considered. The first and second of these are the shock tube technique and the electrostatic technique. The third is the semi-dynamic (quick acting valve) technique of which the work by Pennelegion et al (1966) at the N.P.L. may be taken as an example.

In the semi-dynamic technique the pressure difference between the measuring surface of the transducer and the main pressure chamber is measured. Except for a very small effect caused by the change in volume (for which a small correction may be applied) this is the pressure applied to the transducer. It may therefore be measured to a high degree of accuracy depending on the quality of pressure 'gauge' available for this measurement. In the case of the shock tube we have to measure the initial channel pressure. The accuracy here can be the same as that for the semi-dynamic case. There is possibly a slight advantage that in the former we are measuring an absolute pressure whereas in the semi-dynamic case we are measuring a differential pressure.

For the shock tube technique we have also to measure the velocity of the shock wave. As outlined in Section 4.2 the errors involved in this may be of order 1 - 2%. Using a high accuracy pressure gauge measurement of static pressure can, with care, be made to better than 0 1%, so in the case of the shock tube technique the major source of error would then be in the measurement of shock-wave velocity. It is therefore apparent that for high accuracy calibrations the semi-dynamic technique is preferable to the shock tube technique.

The electrostatic technique did at first appear to be very attractive. It does, however, have two main disadvantages. Firstly the pressure applied is attractive rather than repulsive. For this technique to be of

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* Even in a so-called static calibration it is not easy to eliminate uncertainty caused by hysteresis unless we can be sure that there is no 'overshoot' in the pressure applied to the transducer measuring surface.

real use we must be sure that the calibration of the transducer is the same for both positive and negative pressures. This would involve a further calibration by an alternative technique over the same pressure range. The second disadvantage is that piezoelectric transducers can be sensitive to electrostatic fields. This problem is not insuperable and does not apply to all types of transducer. While a transducer (for the application to which this paper is mainly directed) should be reasonably immune to electro-static field, it would be unreasonable to suggest that the degree of immunity should be increased (by modifying the design) solely because of the calibration technique to be used.

One of the major problems at low pressures (below say 10 torr) is the lack of availability of any really accurate transducer. An electrostatic force balance transducer has recently been developed at the R.A.E. to fill the gap*. In this case such a transducer combined with a semi-dynamic calibrator would seem an ideal technique for the calibration of shock tube type transducers at lower pressures.

The second aspect of calibration is the measurement of transducer output. For many purposes the method outlined in Section 4.3 is adequate. This is particularly true since the transducer output is frequently recorded on an oscilloscope in shock tube experiments and this limits the accuracy of the measurements to be made. To increase the accuracy of the transducer output measurement the oscilloscope could be replaced by an analogue-to-digital converter (ADC). It is not proposed to discuss digital techniques in detail here, since these have been discussed by many authors elsewhere. However since the work described here was carried out, high speed digital recording techniques have become available. The recording of transient data from shock-tubes and shock-tunnels in digital form has a number of distinct advantages over oscilloscope recording, though as pointed out earlier a visual check on the waveform is a very useful adjunct to any transient measurement. These advantages carry over to the calibration process.

The specification of any recording system is governed largely by operational rather than calibration requirements, and since we have noted the desirability of calibrating the measuring system as a whole, we shall discuss the advantages of digital recording in general terms only.

To fix ideas we consider a system such as that outlined in figure 16.

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* W.R. Macdonald, private communication.

In the "record" mode the data lines are sampled, digitized and stored. On "playback" the readings may be converted from digital to analogue form before being fed to an appropriate line. In each case the record/playback rate may be varied over a wide range, and the number of channels scanned may be altered.

The advantages of such a system over conventional oscilloscope recording systems are many.

(i) The potential accuracy of a digital system is higher than that of the conventional oscilloscope technique, where photographic recordings and trace measurements can lead to combined errors which it would be difficult to keep within 2% - 3%.

(ii) Since the data are easily played back, they may be recorded without filtering. Any filtering may be used on playback, and the filter characteristics can be altered to examine the data in detail.

(iii) Filters combining a high rejection ratio and variable characteristic frequency are difficult to design. Using digital recording techniques, playback through a fixed frequency filter can be at a variable rate.

(iv) In cases where a computer analysis of the data is required, digital recording techniques have obvious advantages.

(v) In studying the dynamic response of a transducer, the data may be played back at varying frequency in a search for harmonics. Alternatively, repetitive replay would enable the transient response to be examined using a spectrum analyser. Spectrum analysers operating at the high frequencies of interest in the present application would be expensive, but since "frequency translation" is relatively easy using digital techniques, they would not be necessary.

(vi) At the highest recording rate the digital system offers higher time resolution than the conventional oscilloscope. For example a large amplitude transient occupying say 1 (or 2)/2048 units of the sweep would not be visible on an oscilloscope trace, but would readily show in a digital record with the appropriate sampling rate. Using a second oscilloscope at a higher sweep rate would achieve the same end, but this assumes that the timing of the transient is known beforehand.

(vii) The system would allow the use of digital filtering techniques.

Thus using the general arrangement described in Section 4.3, but replacing the oscilloscope by an analogue-to-digital converter and digital storage it should be possible using a semi-dynamic calibrator to keep calibration errors well within say, 0.5%.

With such high accuracies achievable it is probably necessary to examine the possibility that hysteresis could introduce significant uncertainties into the measurements. Most transducers suffer from hysteresis effects to some extent though these may be negligible in some cases. As a general rule the hysteresis is proportional to the maximum input applied during a cyclic variation. Since the stress levels are oscillatory for a dynamically excited system, the transducer is essentially going round a hysteresis loop. This will lead to uncertainties of a *magnitude depending on the hysteresis characteristics of the transducer.*

Where a transducer can be statically calibrated, a very slow calibration may be carried out in addition to a dynamic (or "semi-dynamic") calibration so that the extent of this uncertainty may be determined for a transducer used for dynamic measurements.

However where the transducer has a poor d.c. response a slow calibration cannot be performed to measure the hysteresis. Thus there may well be an inherent uncertainty in all shock-tube measurements employing such transducers.

Appendix

A note on charge and voltage amplifiers

The two main types of amplifier available for use with piezoelectric transducers are charge and voltage amplifiers. For calibration purposes one is more concerned, in general, with the accuracy and stability of the amplifier gain, rather than with the frequency response or the noise performance, though these are of some importance. As is well known the chief characteristic of charge amplifiers is the relative insensitivity of the gain to cable and other stray input capacitance.

The voltage gain of the two configurations are

$$\frac{mC_o}{C_o + C_e} \qquad \text{for the voltage amplifier} \; \ldots\ldots\ldots \; (1)$$

and $$\frac{mC_o}{C_o + C_e + (m+1)C_F} \qquad \text{for the charge amplifier} \; \ldots\ldots\ldots \; (2)$$

where C_o is the capacitance of the transducer, C_e is the total capacitance (cable plus stray) across the input, C_F is the feedback capacitance and m is the open-loop (mid-band) gain. Thus for a change in stray capacitance C_e' across the input, the proportional changes in gain are

$$\frac{C_e'}{C_o + C_e} \qquad \text{for the voltage amplifier} \; \ldots\ldots\ldots \; (3)$$

and $$\frac{C_e'}{C_o + C_e + (m+1)C_F} \qquad \text{for the charge amplifier} \; \ldots\ldots\ldots \; (4)$$

Since a charge amplifier is designed with $(m + 1)C_F >> (C_o + C_e)$, the gain of such an amplifier depends far less on the stray capacitance. Now we have noted that for high accuracy calibration it is necessary, whichever amplifier is used, to calibrate the "whole chain" with an "in-circuit" calibrator. Thus the advantages of the charge amplifier configuration are minimised.

However the stray capacitance within the charge calibrator, which arises from both the wiring and the "grounding" switch, may easily amount to 1 - 2 pF. At low signal levels using a quartz transducer, a short cable would need to be used to minimise the effects of C_e and so maintain gain in the voltage amplifier configuration. Thus the effects of stray capacitance may be significant, see equation (3). As an example a transducer having a capacitance of 10 pF used with say 600 mm of miniature coaxial cable having a capacitance of about 40 pF would suffer a 2% change in gain for a 1 pF change in stray capacitance.

Since stray capacitance is difficult to control and so may not remain constant, for high accuracy work its effects must be minimised. The charge amplifier therefore offers significant advantages over the voltage amplifier in this respect, even though frequent in-circuit calibration minimises its other advantages.

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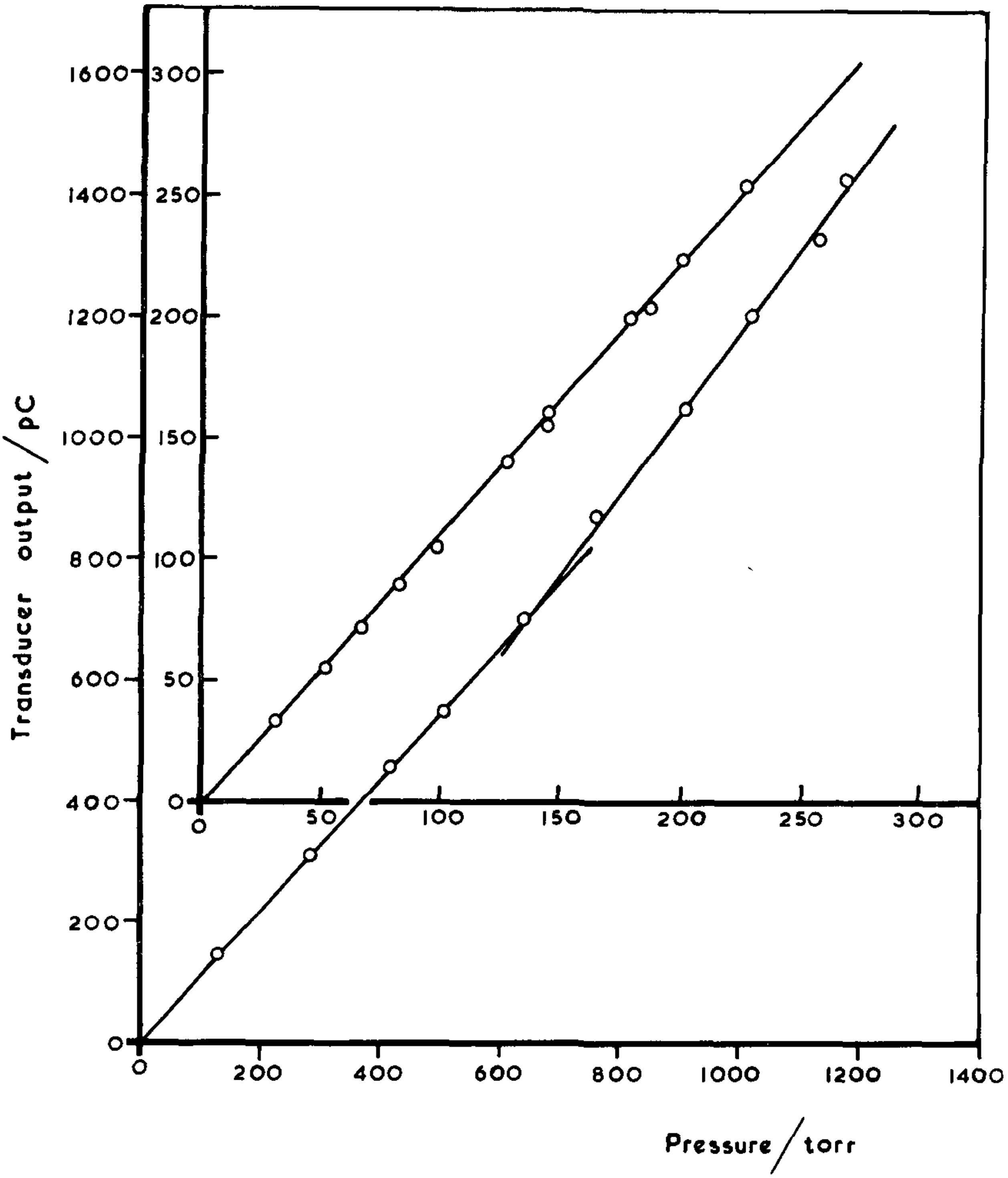


Figure 1 Calibration of type I_1 transducer

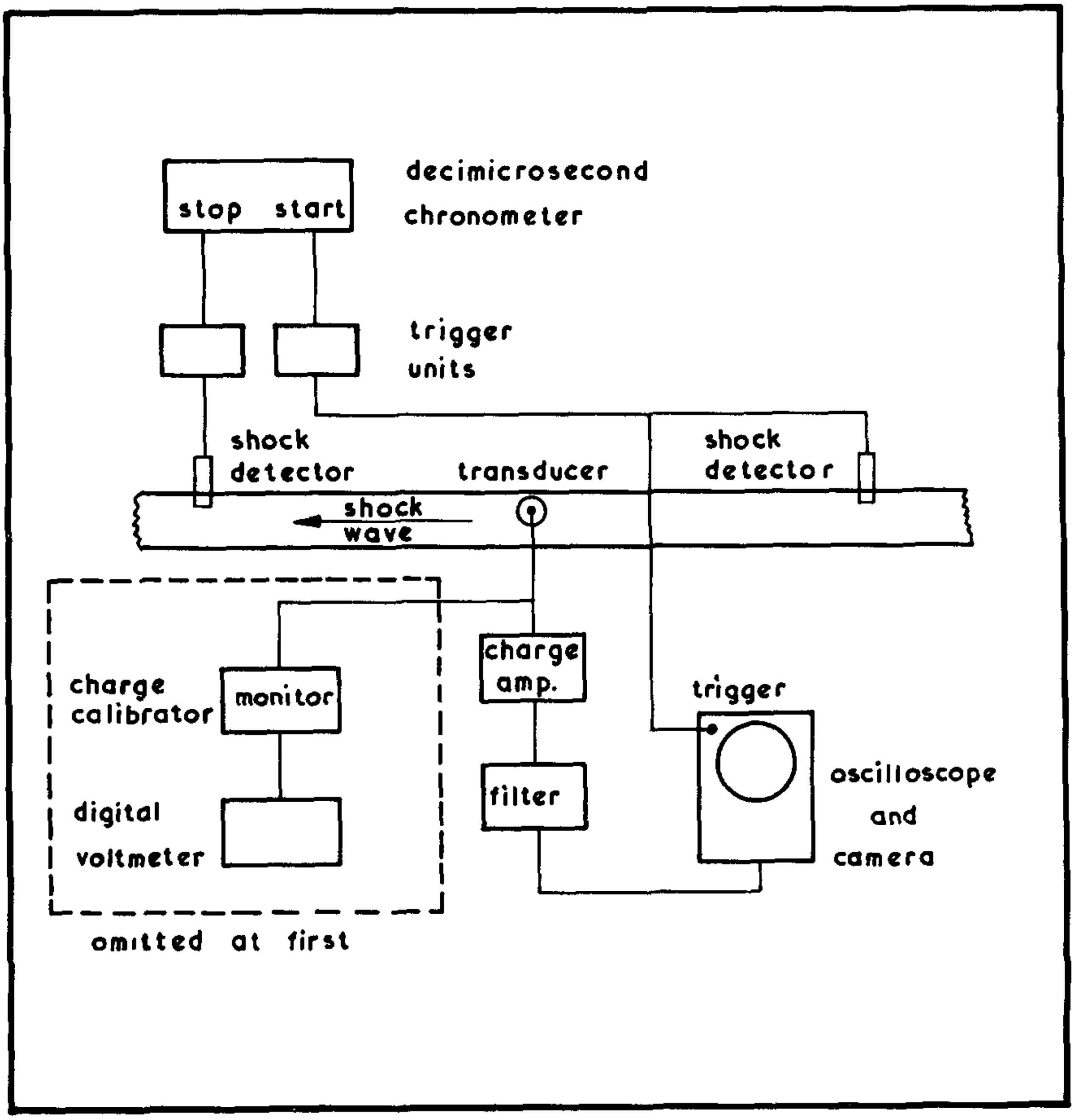


Figure 2 Transducer calibrating arrangement

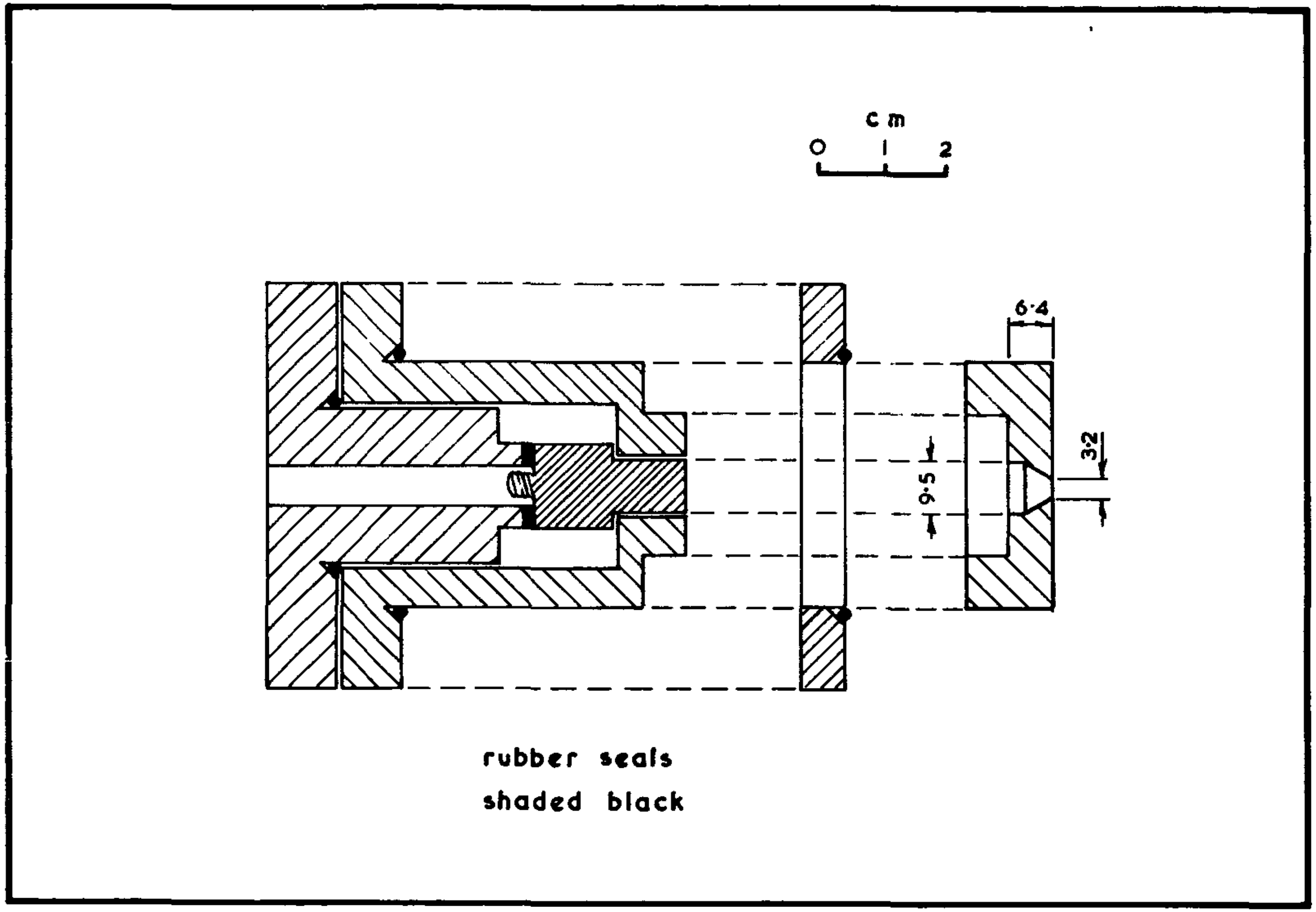
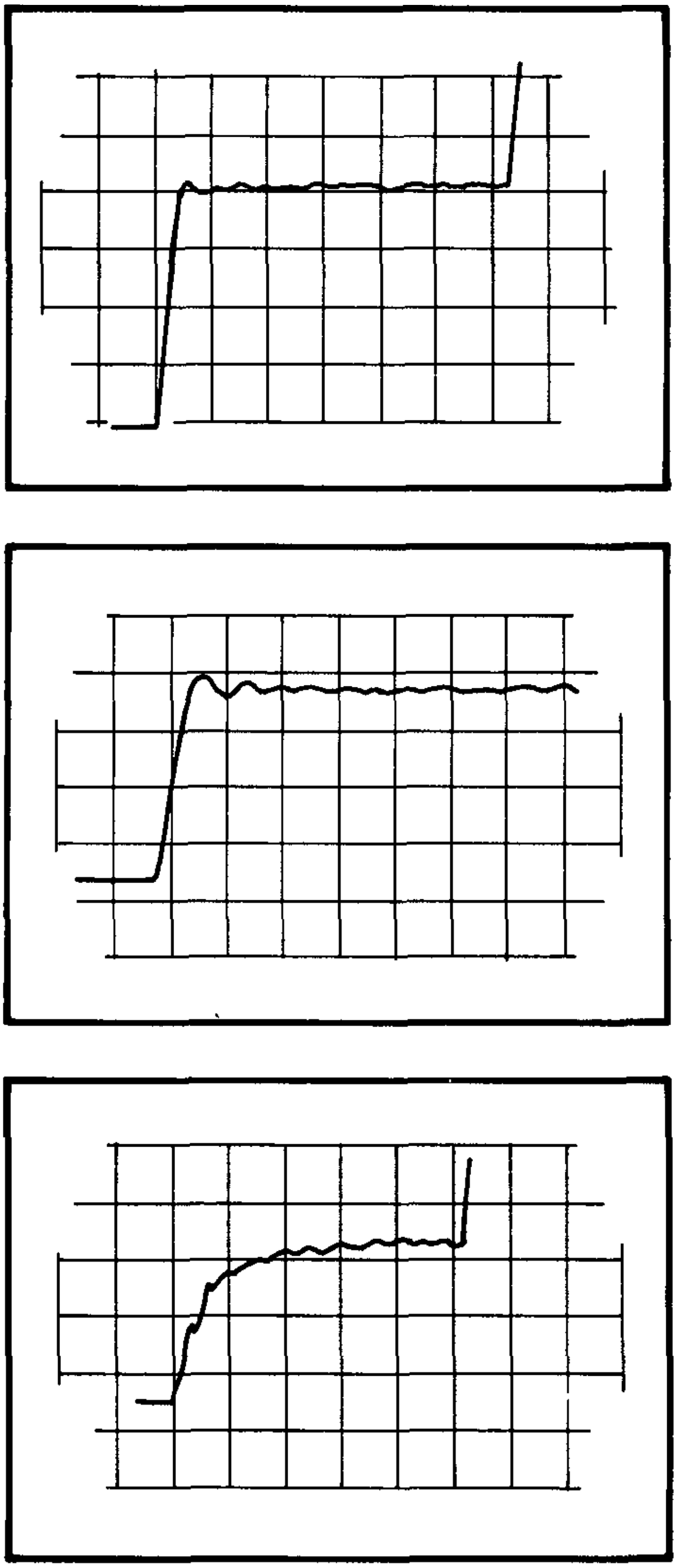


Figure 3 **Kistler gauge mounting and dimensions of cavity tested**



$p_1 = 500$ torr
$W_{11} = 1{\cdot}68$
$\Delta p = 1060$ torr
vert. sen. = 27·1 pC/div.
sweep = 200 μs/div.

$p_1 = 160$ torr
$W_{11} = 1{\cdot}69$
$\Delta p = 348$ torr
vert. sens. = 10·3 pC/div.
sweep = 100 μs / div.

$p_1 = 35$ torr
$W_{11} = 2{\cdot}14$
$\Delta p = 146$ torr
vert. sens. = 5·2 pC/div
sweep = 200 μs/div.
with cavity

Figure 4 Typical calibration traces

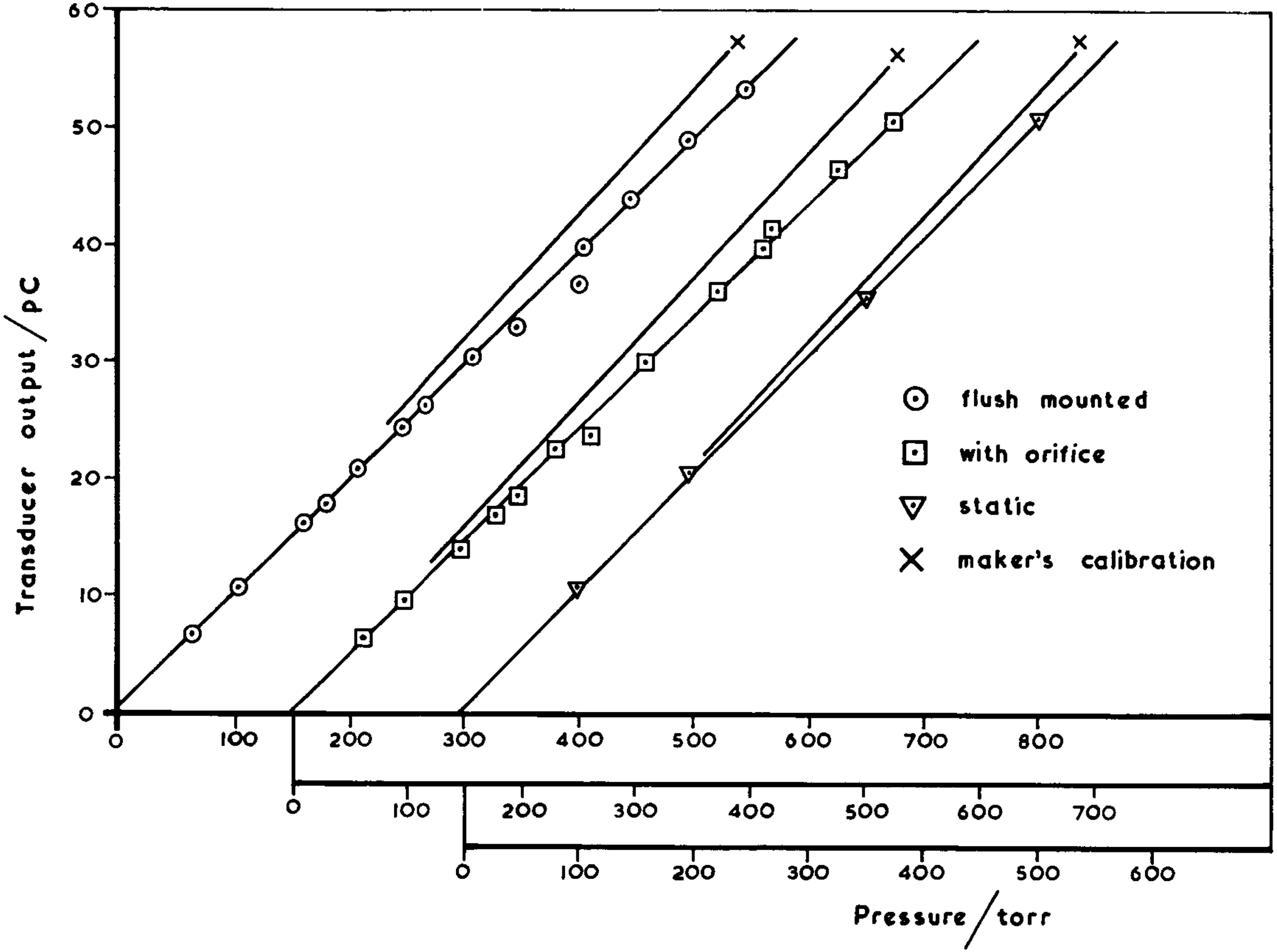


Figure 5 Initial calibration of a Kistler 701A gauge (SN 18450)

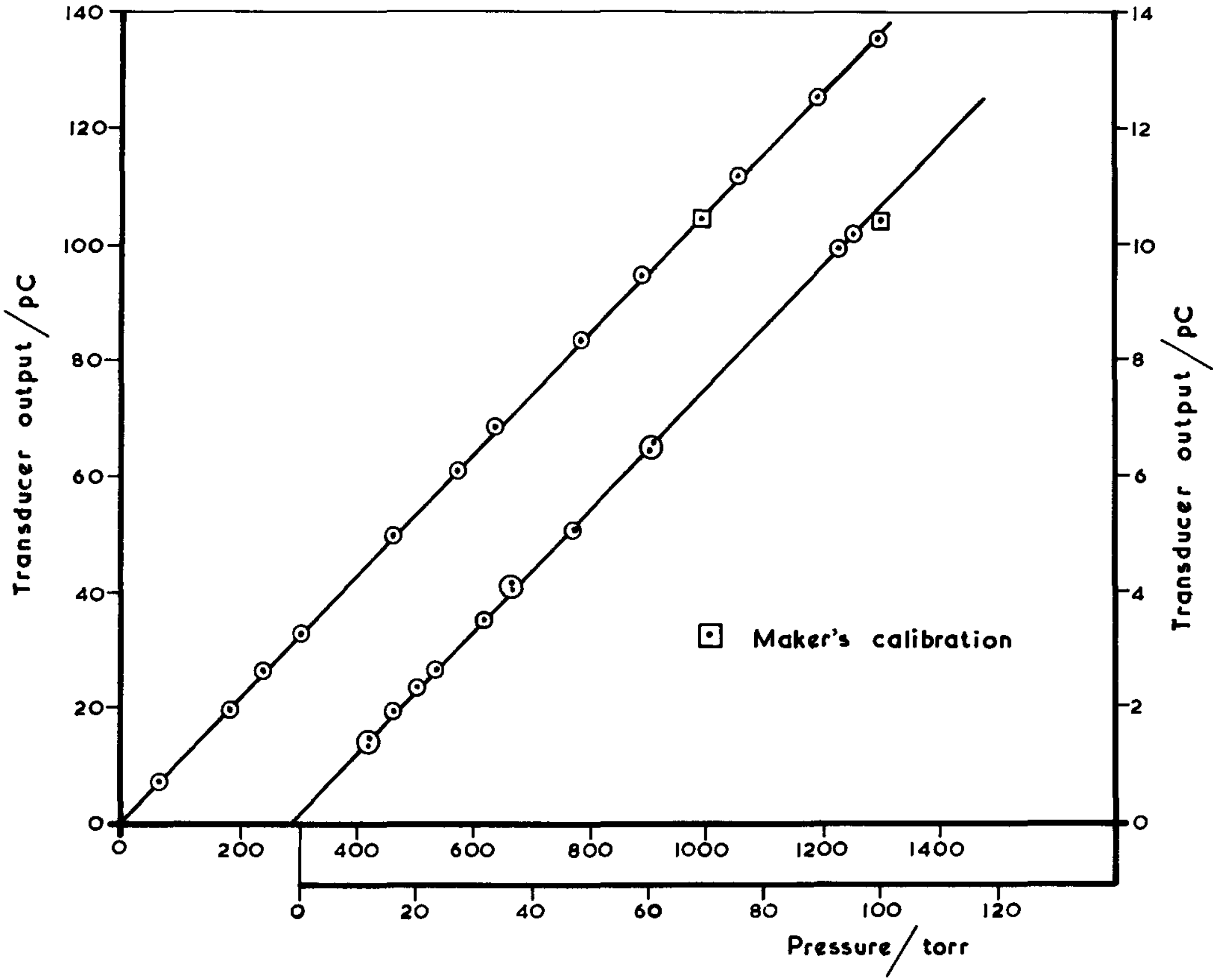


Figure 6 **Final calibration of a Kistler 701A gauge (SN 18451)**

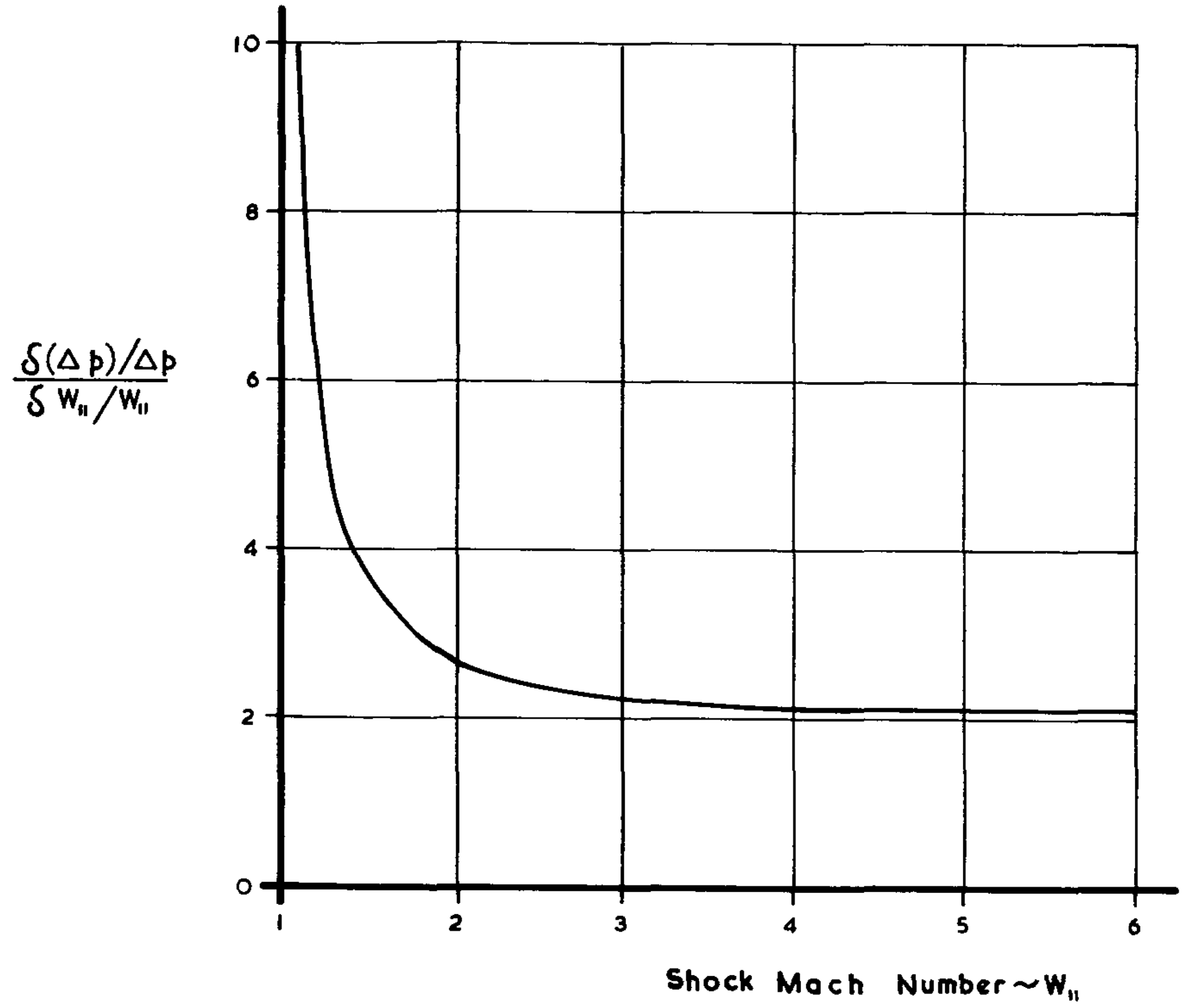
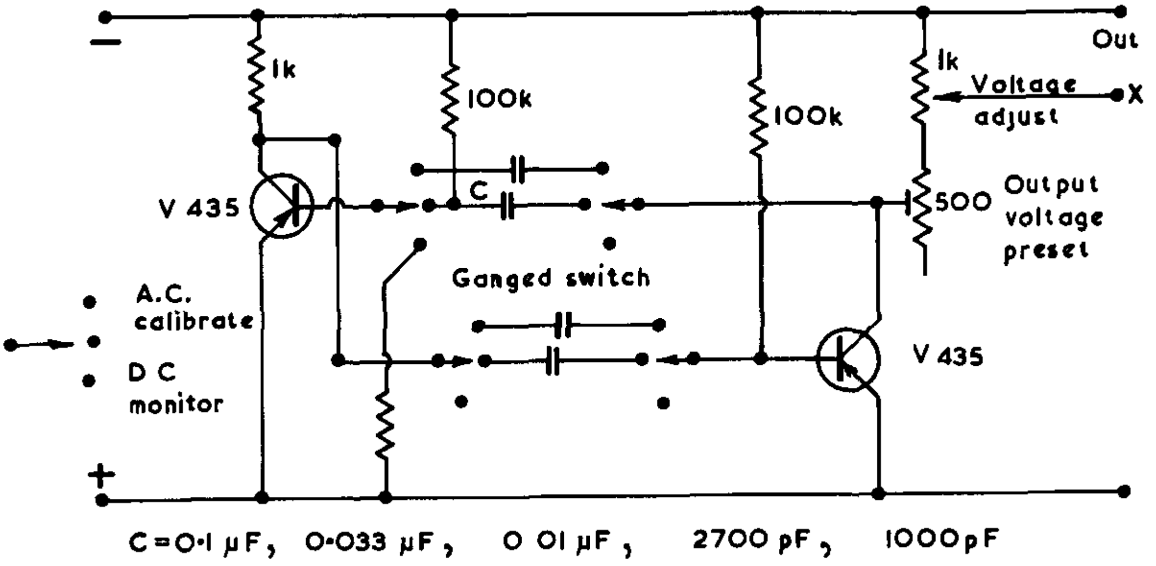
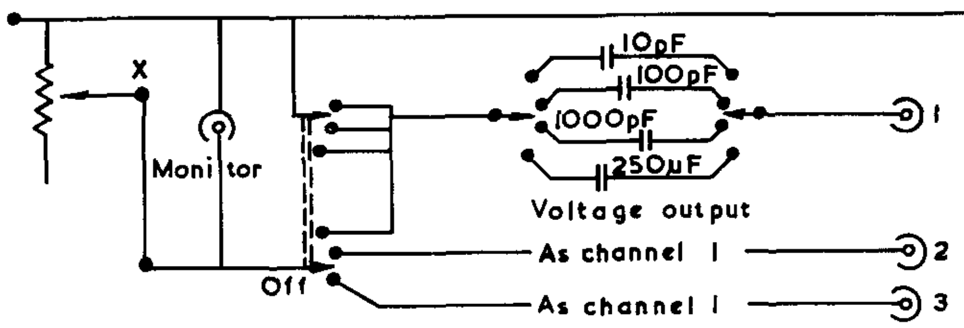


Figure 7, **Uncertainty in calibration pressure in a shock tube as a function of shock strength**



Square wave generator



Modified output circuit

Output ranges:

1. Voltage: 0 - 10 V
2. Charge: 0 - 100 pC
3. Charge: 100 - 1000 pC
4. Charge: 1000 - 10000 pC

Frequency ranges:

1. D.C./calibrate; 2. 120 Hz
3. 350 Hz ; 4. 1.1 kHz
5. 5.1 kHz ; 6. 15 kHz

Series capacitance measured to within 0.1%.
Output signal: rise-time < 2 µs on all ranges,
fall-time varies from 4µs on range 6 to 150µs on range 2
Output impedance < 1.2 kΩ for all voltage settings.

Voltage error: < ± 0.3 % long term (weeks)
< ± 0.05% short term (hours)
< ± 0.01% monitored PLUS error due to DVM

Figure 8 Charge calibrator circuit

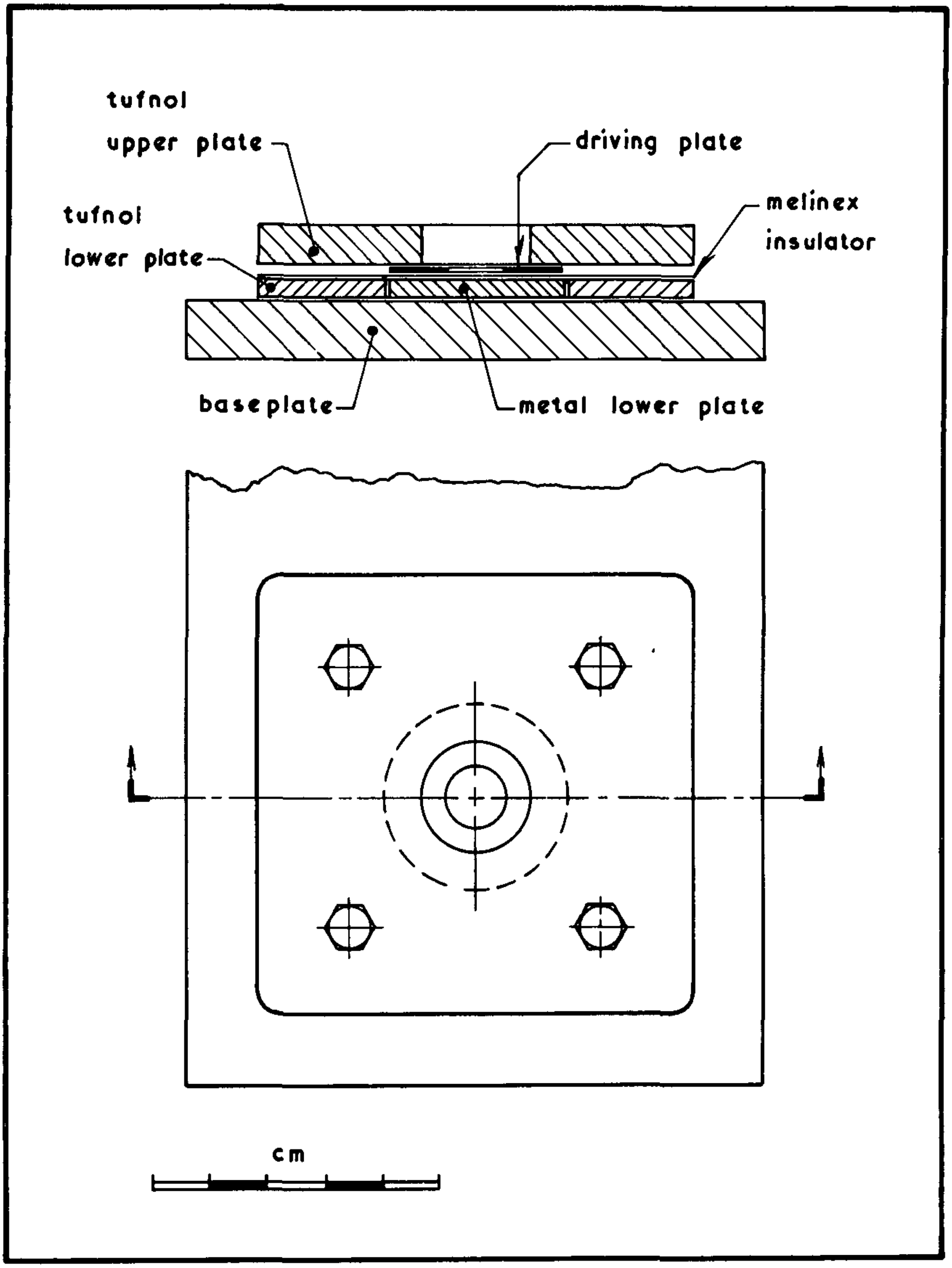


Figure 9 The electrostatic calibrator

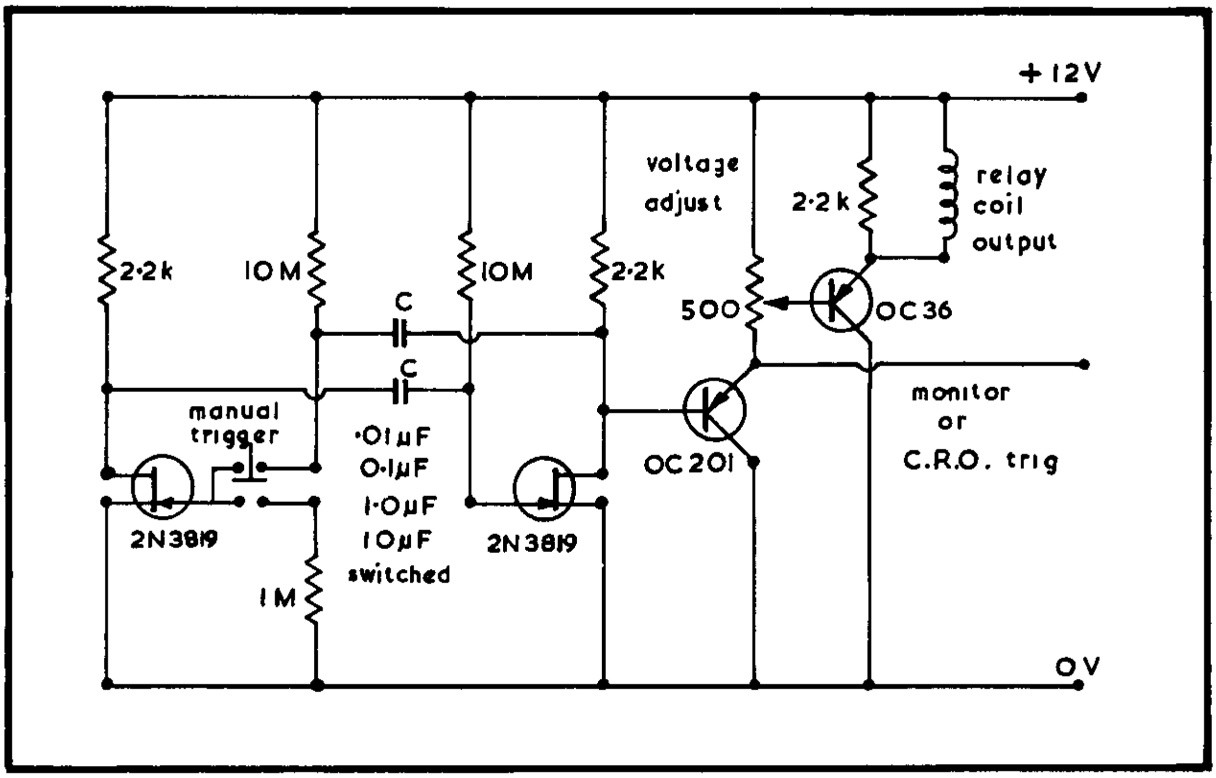


Figure 10 **Reed switch exciter circuit**

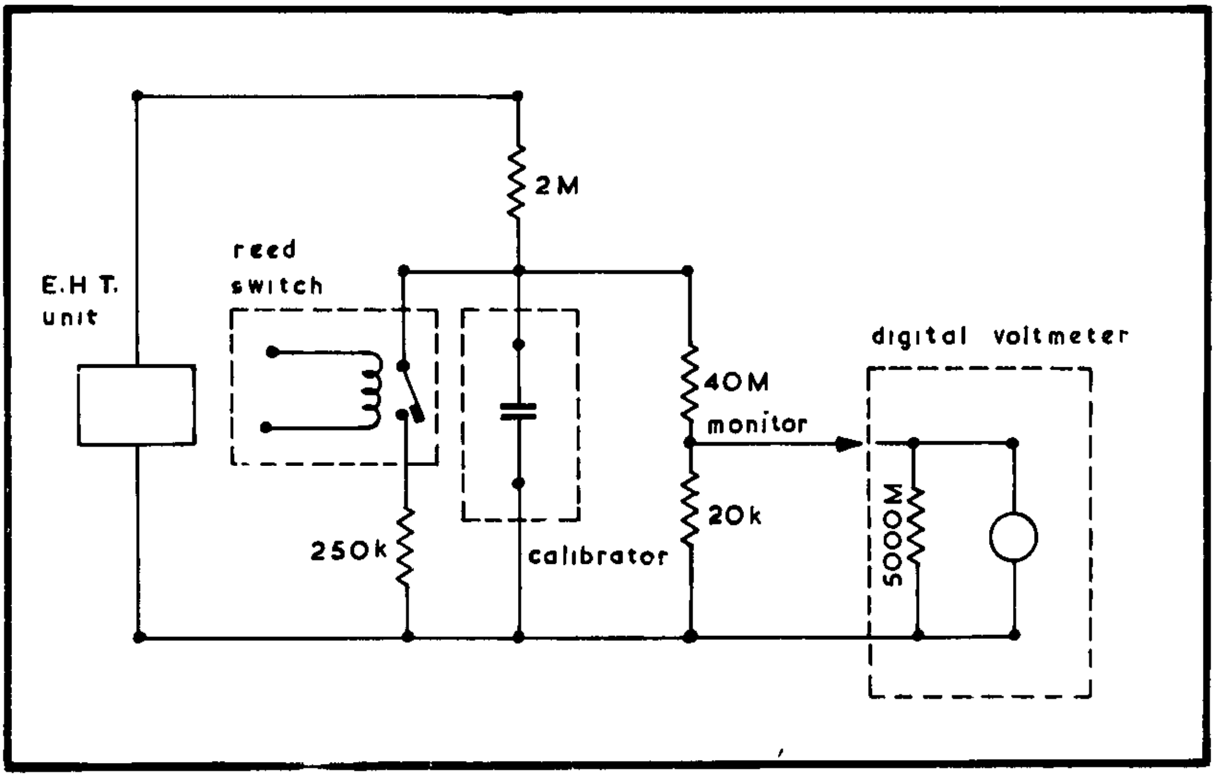
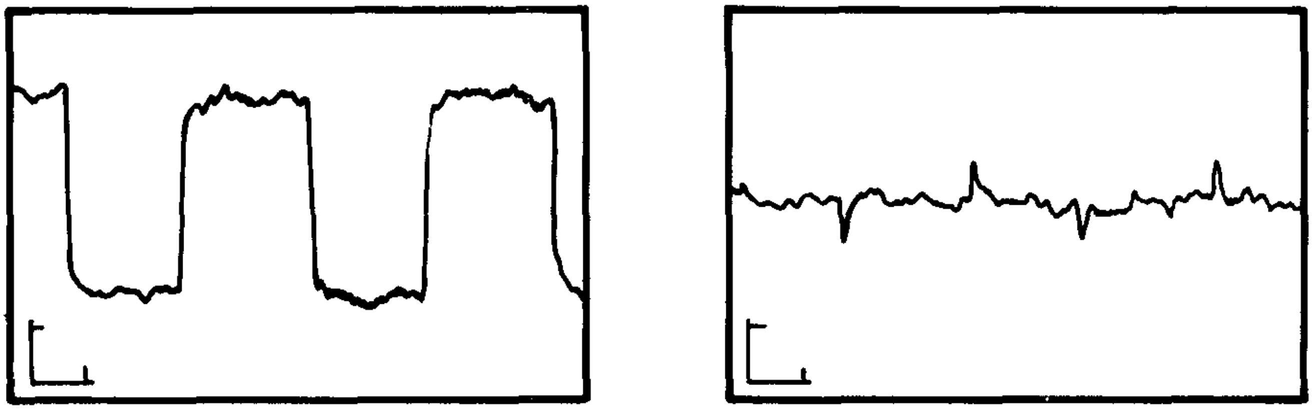
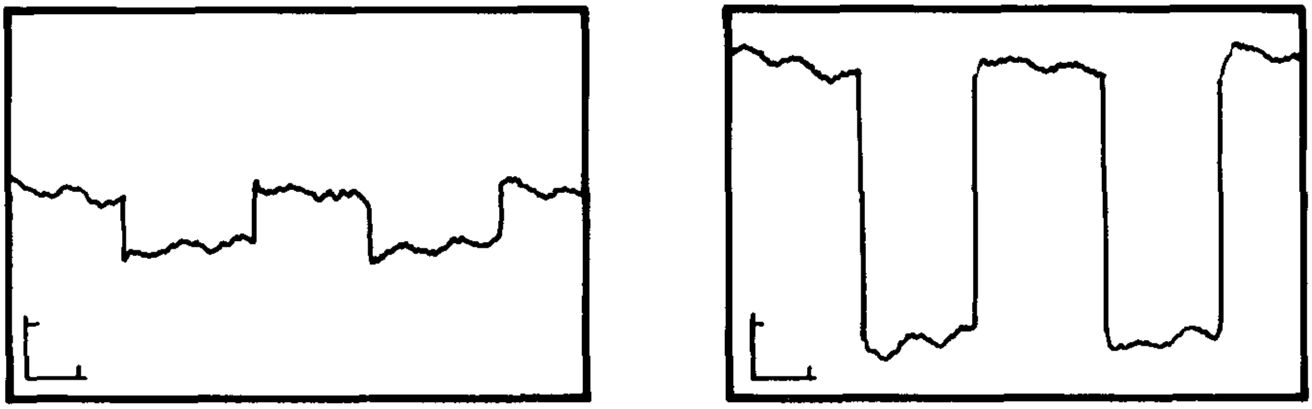


Figure 11 **Calibrator drive circuit**



$V_a = +188$ volts

$V_a = +117$ volts



$V_a = +67$ volts

$V_a = -94$ volts

Figure 12 Typical traces using electrostatic calibrator

vertical sensitivity = 0·15 pC/div.

sweep speed = 20 ms/div.

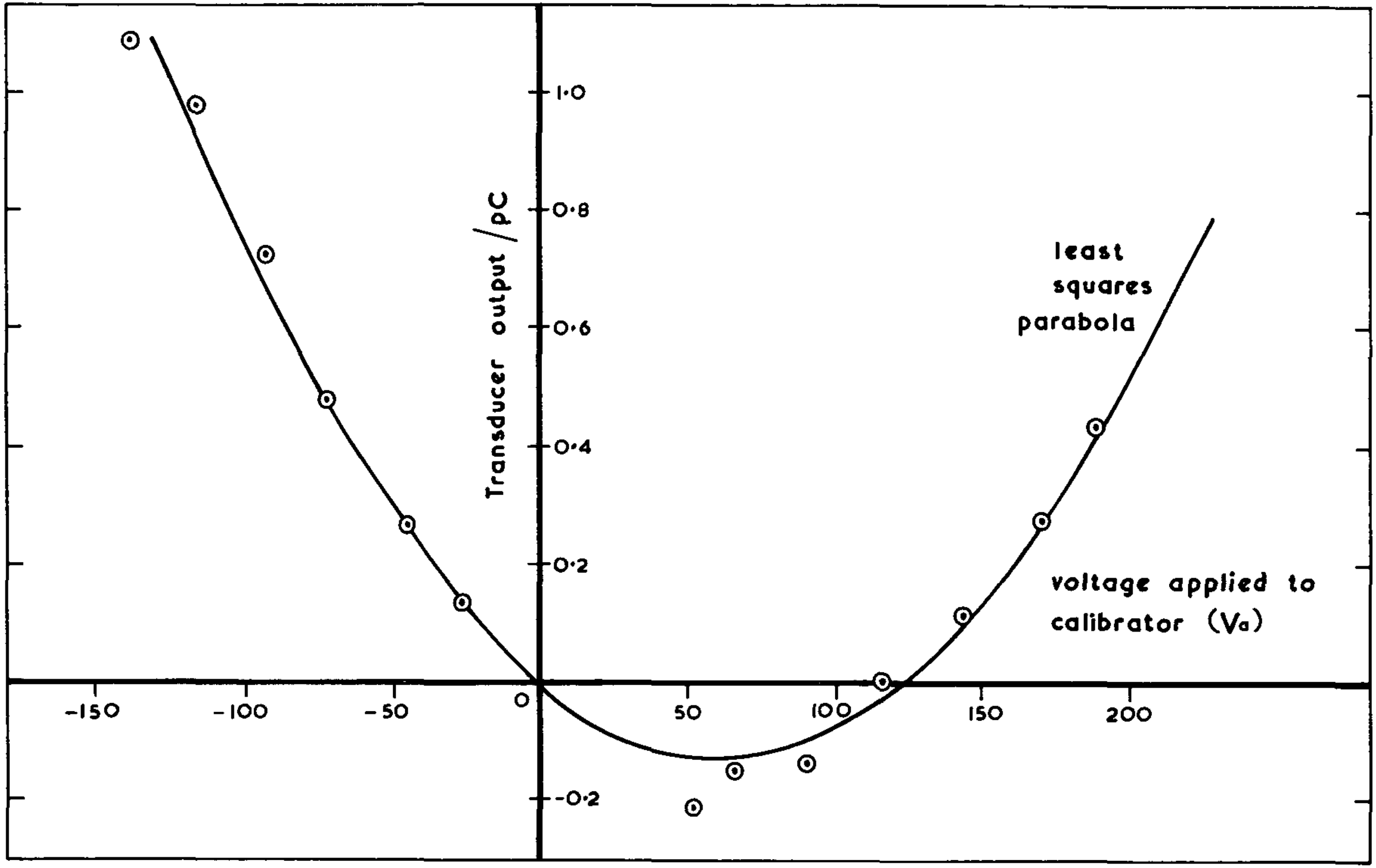


Figure 13 **Electrostatic calibrator, Q versus V_a**

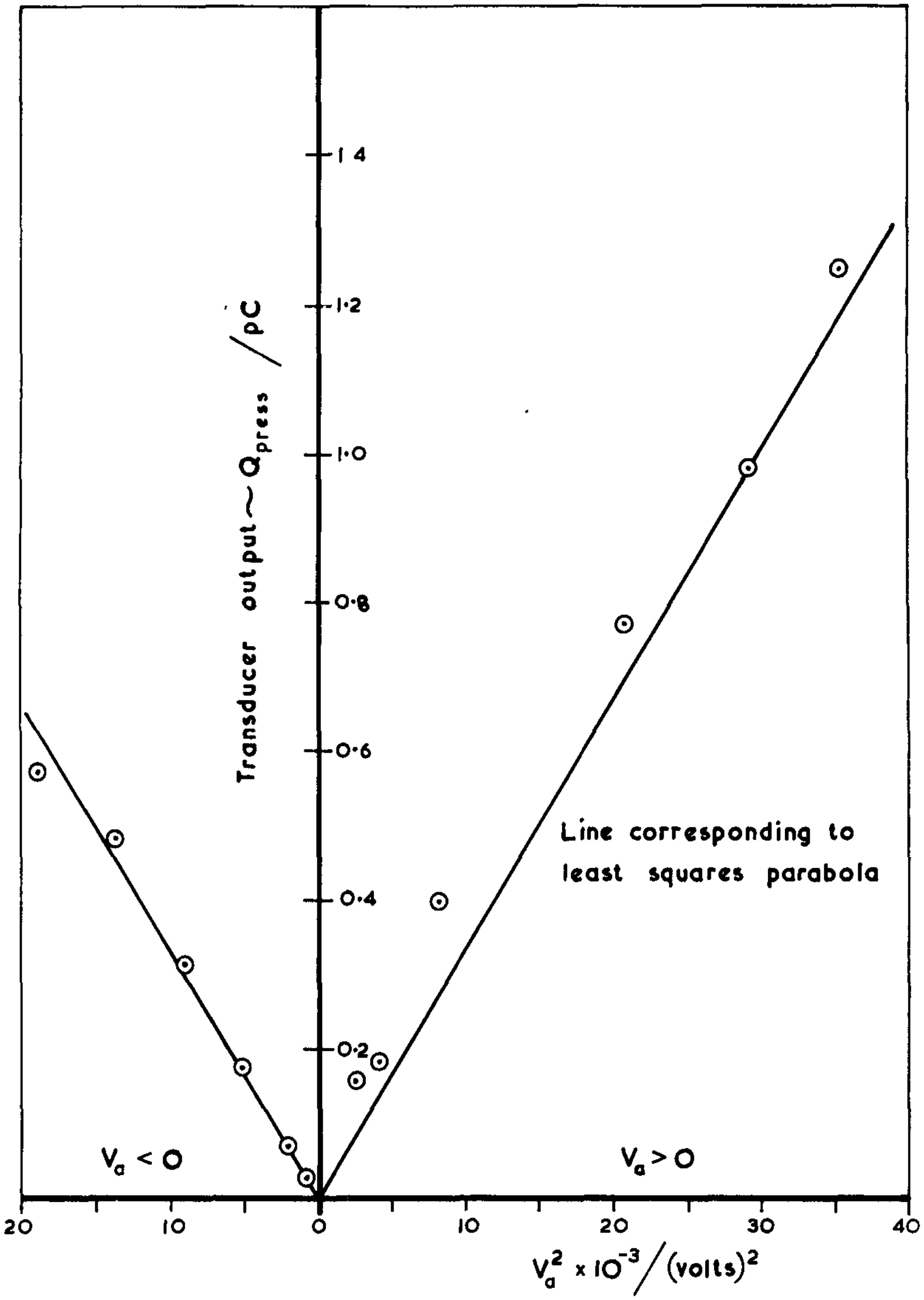


Figure 14 **Electrostatic calibrator, $Q_{press.}$ versus V_a**

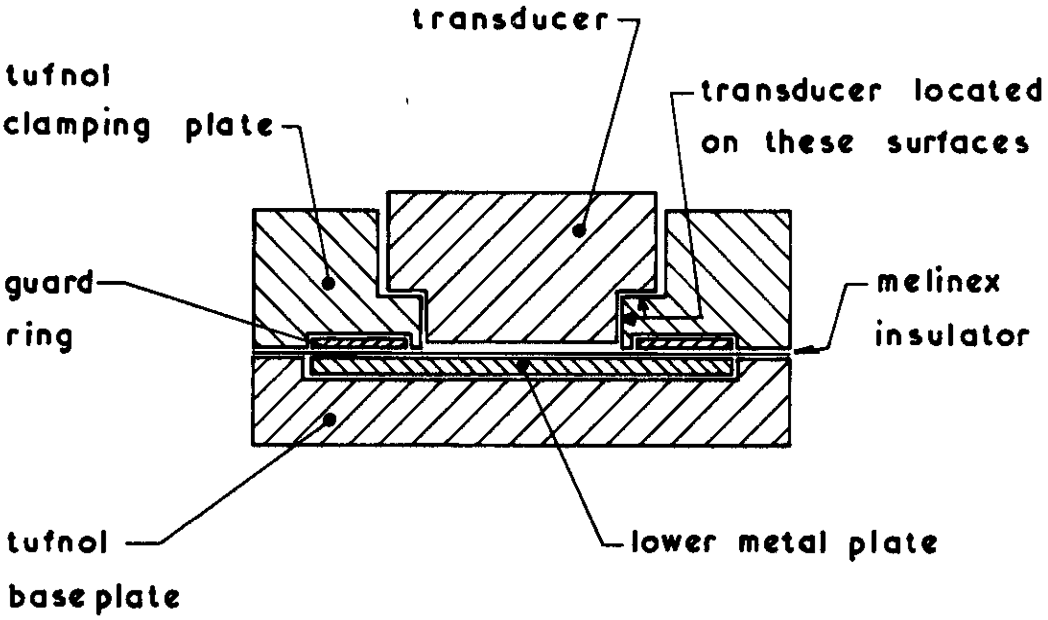
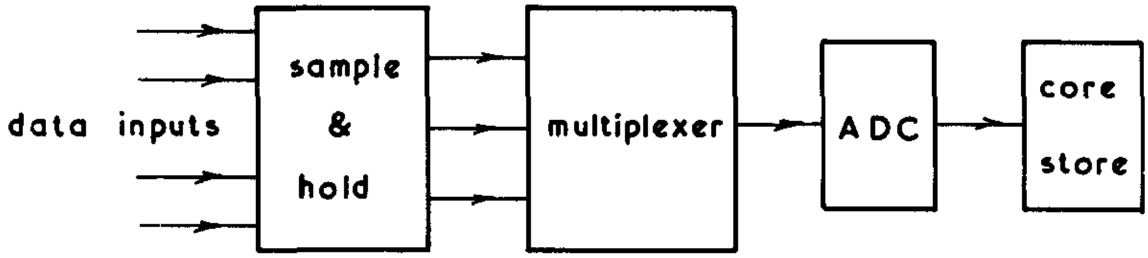
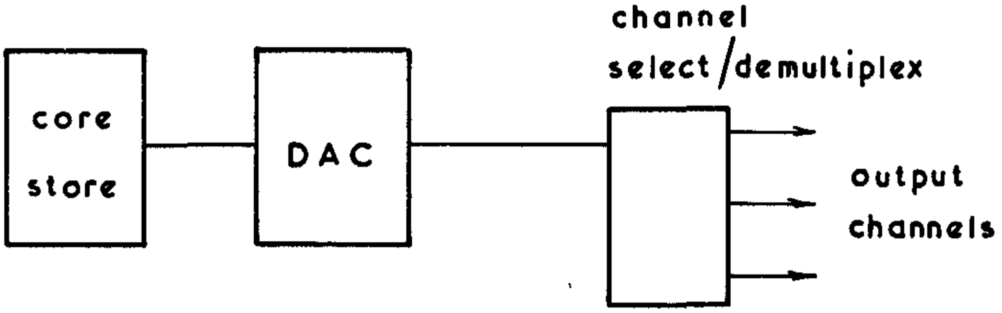


Figure 15 Suggested new electrostatic calibrator



(a) Record



(b) Playback

Figure 16 **Block diagram for digital recording system**

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