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The Measurement of High Frequency Alternating Pressures in Gas Turbines

By
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The Measurement of High Frequency Alternating Pressures in Gas Turbines

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Summary.—The measurement of alternating pressures in gas turbines could not be achieved by existing techniques. The pressures consisted of small-amplitude alternating pressures superimposed on pressures up to 100 lb per sq in. and at temperatures up to 250 deg C in compressors and up to 850 deg C in turbines. The frequencies of the predominant harmonic components varied from 100 to 17,000 c.p.s. and those for the smaller components up to 40,000 c.p.s.

Improvements were required in the recording techniques which are reported elsewhere but the changes in amplifiers are described. The development of a capacity pressure element to record the alternating pressures at a point in a casing is described. A small diameter diaphragm was used to facilitate installation and to obtain the pressure over as small an area as possible. The diaphragm was arranged near the gas stream and the effect of temperature changes was eliminated by applying a filtered balance air supply behind the diaphragm to permit calibration during the investigation. The balance air supply permits equalisation of pressure across the diaphragm so that higher sensitivities can be used.

The alternating pressures decrease sharply with distance from the source and if the alternating pressure is required at a point other than in the casing a special approach will be required.

1. *Introduction*.—The study of vibration in the gas turbine has consisted of a survey of the lower natural frequencies of the blades and a study of the geometry of the compressor and turbine to ascertain the exciting forces. This has proved to be adequate for blades of low aspect ratio when using low values of the mean gas bending stress. It was thought that a knowledge of the alternating pressures would check the validity of the above approach and give an estimate of the severity of the various forcing orders. Subsequent investigations have shown that the alternating pressures persist for a short distance from the source, and the predominant harmonic components of the alternating pressure at the casing of a compressor are dissimilar from the harmonic components of the strain obtained from a blade in the stage. This is due to the sharp decrease in the alternating pressure with distance from the source and the relatively small value of the damping of the blades in the fundamental and lower modes of vibration. However a knowledge of the alternating pressures is necessary to understand the excitation.

The available experimental techniques were limited in gain and frequency response and extensive development was required. The development of the pressure elements required to record these high-frequency oscillations of small amplitude and also for high-temperature applications is described together with additional electronic circuits. A reloading drum camera was found to be the best solution to the problem of recording a number of exposures in quick succession with high film speeds and minimum wastage of film. The development of these cameras is described in Ref. 1.

Results are given of the alternating pressures recorded, in the outlet casing of a centrifugal compressor, the casing of an axial-flow compressor and the shroud ring of a single-stage turbine.

* N.G.T.E. Memo. M.213, received 21st October, 1954.

1.1. *Alternating Pressures in Gas Turbines.*—The pressures in compressors comprise small amplitude alternating pressures superimposed on steady pressures up to 100 lb/sq in. and at temperatures up to 250 deg C; those in turbines comprise small amplitude alternating pressures superimposed on smaller steady pressures and at temperatures up to 850 deg C. This is different from previous requirements and a special element is necessary.

1.2. *Application of Existing Pressure Elements.*—The capacity pressure elements which were developed for investigating the pressures in reciprocating engines and which have been reviewed in Ref. 2 were fitted with 0·001-in. and 0·003-in. thick diaphragms, to obtain the required sensitivity and were used to measure the alternating pressures in compressors. Qualitative results were obtained, the more accurate results being obtained near the inlet of compressors. The effects of temperature on the diaphragm, the frequency response of the diaphragm assembly and the effects of the connecting passage introduced inaccuracies.

The best results were obtained from the element shown in Fig. 1. The errors due to temperature could have been eliminated by using the water-cooled element shown in Fig. 2, but the complex diaphragm assembly and connecting passages would reduce the frequency range.

The balanced disc calibrating unit shown in Fig. 3 and described in Ref. 3 has given accurate results for recurring cycles; a point is given each time the pressure equals the pressure behind the disc and the full cycle is obtained by a point-by-point plot. The operating conditions of a gas turbine are not sufficiently steady to suit this technique.

1.3. *Effect of Temperature on Element.*—The element shown in Fig. 1 was attached to a cylinder in which the temperature of the air could be changed at constant pressure. The change in capacity with change in temperature is plotted in Fig. 4. The change in capacity is dependent on the temperature and the time for which it is applied and quite arbitrary changes could be achieved. In addition there are changes in the sensitivity of the element.

Isolation of the element from the heat source is impracticable because of the design complications, but calibration during the observations would permit correct interpretation of the records.

2. *Balanced Diaphragm Pressure Element.*—To overcome the difficulties previously stated the element shown in Fig. 5 was developed which incorporates the following features:

(*a*) The diaphragm as near as possible to the point at which it is desired to record the pressure

(*b*) Diameter of diaphragm as small as possible to limit the area over which the pressure is recorded

(*c*) Stretched diaphragm to improve frequency response

(*d*) Supply of balance air behind diaphragm to provide means of calibration during the experiment and to permit equalisation of balance air and steady pressure of stream so that a light diaphragm can be used to increase the sensitivity of the element

(*e*) Attachment by two studs to facilitate attachment to compressor or turbine and to obtain plain nose to improve the stress distribution in the parts supporting the diaphragm.

Diaphragms 0·001 in. and 0·003 in. thick in shim steel and phosphor bronze have been used. The diameter of the nose of the element is $\frac{9}{16}$ in. Another element was developed to obtain a flush diaphragm, a smaller diameter nose and generally smaller dimensions as is shown in Fig. 6. The diaphragm withstood a steady pressure of 60 lb/sq in. and gave satisfactory readings when applied to an axial-flow compressor with small amplitude signals. It is not known if the element will be satisfactory for the more arduous applications.

2.1. *Sensitivity of Balanced Diaphragm Elements.*—The range of linear response with change in pressure is limited due to the small diameter diaphragms and small gaps used to achieve the required sensitivities. However, with careful manufacture and assembly an adequate range of linearity can be obtained, a typical calibration curve being shown in Fig. 7.

2.2. *Static Calibration.*—The element was fitted to a pressure cell for calibration. The air pressure was obtained from a small air compressor and the control system is as shown in Fig. 8 the dotted lines showing the additional valves required for static calibration. The air pressures to the cell and behind the diaphragm were controlled by reducing valves and fine needle bleed valves in the individual lines, a pressure gauge indicated the pressure in each line and the differential pressure across the diaphragm was given by a mercury manometer.

2.3. *Dynamic Calibration with Large Amplitude Alternating Signals.*—The pressure elements were subjected to alternating pressures in a resonant tube forced by a steady pressure interrupted by a rotating disc. The disc had 30 holes and was driven by a $\frac{1}{2}$ h.p. motor with B.T.H. thyatron speed control. A frequency range up to 1,200 c.p.s. could be covered with adequate amplitude. Two elements could be placed in the end of the resonant tube and calibrations of the alternating pressures were obtained by the Standard Sunbury balanced disc calibrating unit. The equipment used is shown in Fig. 9.

2.4. *Dynamic Calibrations Using Shock Tube.*—Excitation of the pressure element by sharp-fronted waves in a shock tube gave satisfactory readings. The element was fitted in the end of a 2·5-in. diameter tube 4 ft long separated from a 2-ft length of the same diameter tube by a 0·001-in. thick cellophane diaphragm. Air at a pressure of 1 lb/sq in. gauge was held in the shorter tube with a back pressure of 0·5 lb/sq in. gauge applied behind the element diaphragm with atmospheric pressure in the longer tube. The cellophane diaphragm was pierced by a rod extending from the end of the shorter tube. The reflected waves required approximately $\frac{1}{100}$th second to travel the double length of the tube and sufficient reflections occurred to permit manual synchronisation of the shutter of a drum camera recording the element signal when displayed on a cathode-ray oscillograph.

The diaphragm assembly was highly damped and difficulty was experienced in exciting the diaphragm in its natural modes of vibration. The reflected waves were recorded in each case but only in a few cases could the natural frequencies be obtained from the records. From a number of attempts the following frequencies were obtained:

Thickness of diaphragm (in.) ..	0·001	0·0027	0·0031
Frequency (c.p.s.)	7,750 11,700	8,000 15,700	8,450 16,500

Two frequencies were obtained, one of the order of that calculated for a built-in diaphragm without the loading sleeve, and the other higher than that calculated for a built-in diaphragm of diameter equal to that of the loading sleeve. The frequency increases were greater for the thinner diaphragms. Both modes of vibration were difficult to excite and when excited the damping was relatively high. The load on the diaphragm was restricted due to the thin diaphragms and was set as high as possible.

The high sensitivities necessitated thin diaphragms resulting in the natural frequencies occurring in the required frequency range. The relatively high damping of the diaphragm assembly permitted an adequate compromise to be made. If an accurate frequency response in a particular range is required the appropriate diaphragms and load on the diaphragm can be chosen.

2.5. *Application of Element.*—The control system for the element when applied to a compressor or turbine is shown in full in Fig. 8. The static pressure on the face of the diaphragm was obtained by drilling a $\frac{1}{16}$-in. diameter hole through the centre of one of the securing studs with appropriate end connections.

With careful operation of compressor or turbine and equipment the pressure on the face of the diaphragm can be followed satisfactorily, but with rapid changes in condition cross-connection valves may be required in the lines to the manometer and in the balance air and static pressure lines to protect the manometer and diaphragm during the changes in condition.

2.6. *Application to Measurement of Pressures at High Temperature.*—By being able to carry out calibrations of the element during an investigation it was possible to make pressure measurements at high temperature, and the element was applied to the shroud ring of a single-stage turbine. A heat dissipator brazed together from copper gauze was pressed on to the nose of the element and fitted in a cooling shroud. An air supply was provided to feed tangentially into the shroud and the whole assembly was attached to the turbine with a heat insulating washer. The cooling arrangements are shown in Fig. 10.

The element and shroud is shown in Fig. 11 fitted in a rig when subjected to a gas flame. The efflux of cooling air can be seen extending across the flame. The cooling air has an effect on the alternating pressures in the stream but this effect could not be detected in cold tests or in the experiments on the engine for varying quantities of cooling air.

A dummy element nose was fitted in the turbine and the quantity of cooling air adjusted to give diaphragm temperatures less than 100 deg. C for all operating conditions.

3. *Electronic Equipment.*—The capacity change of the pressure element frequency-modulates a carrier signal of approximately 2 megacycles per second which is amplified and fed to a discriminator, and two stages of push-pull amplification, which are d.c. coupled. This equipment was manufactured by Messrs. Southern Instruments, Ltd.

A five-channel oscillograph unit was constructed using VCRX.214 cathode-ray tubes with 1·5 kV applied to the anode and 3·2 kV applied to the post-accelerator to obtain adequate writing speed. A circuit diagram is shown in Fig. 12.

The use of cathode-ray tubes with high writing speeds requires high deflection voltages and the introduction of calibration during an investigation required deflection of any part of the signal to any part of the screen; thus increasing the desirable linear range of the amplifier output. An additional driver amplifier stage was required. The circuit diagram is shown in Fig. 13. A push-pull stage was used with E.L.38 (C.V.450) valves. The gain was approximately 10 with maximum output swing of 800 volts. The output was maintained constant with increase in frequency up to 35,000 c.p.s. by negative feed-back. A low effective output impedance was also obtained facilitating connection to the oscillographs.

4. *Alternating Pressures in Gas Turbines.*—The vibration of compressor and turbine blades is excited by alternating pressures in the gas stream set up by interruptions in the stream by spiders, inlet or nozzle guide vanes, stator and rotor blades and from non-uniform pressure distribution. In subsequent stages the flow in individual blade passages is dissimilar which may cause further alternating pressures. The amplitude of the alternating pressures reduce with distance from the source. If the numbers of rotor and stator blades differ and the numbers in adjacent stages differ the alternating pressure component rarely persists in the adjacent stages. If these numbers of blades are the same the harmonics are in phase for each stage and the alternating pressure components may persist for two or three stages up or downstream.

The decrease in alternating pressure with distance from the source also occurs in a particular stage in a radial direction. A reading of the alternating pressure at mean diameter includes alternating pressures set up by the blade movements but these are not detected in the alternating pressure recorded in the casing for the same stage.

In Figs. 14, 15 and 16 the alternating pressures in the casing are plotted for a centrifugal compressor, an axial-flow compressor and a single-stage turbine. The predominant harmonic component is the 1st-order component of the impulse from a rotor blade or an impeller vane. In some cases at low speeds the harmonic components corresponding to 1st and 2nd rotor orders are similar to above amplitudes. The amplitudes of the predominant harmonic components for the centrifugal compressor and for the single-stage turbine have the maximum amplitude of approximately ± 2 lb/sq in. and that for the casing of the axial-flow compressor approximately 25 per cent of above value. Harmonic components up to the 7th order of rotor blade or impeller vane impulses have been observed up to frequencies of 40,000 c.p.s.

4.1. *General Comments on Design of Pressure Elements.*—The preceding section gives an indication of the range of alternating pressures occurring in gas turbines. The design of a pressure element is extremely difficult and a compromise has to be made between sensitivity, frequency response and position of measurement, to accommodate the small amplitude pressures, the relatively high frequencies, and the sharp decay in amplitude of alternating pressure with distance from source of excitation.

Measurements of alternating pressures in the casings of compressors and turbines have been made in a survey of the forces exciting high frequency vibrations in gas turbines. This requires the minimum modification to the units and the pressure elements described were used. The compromise made between sensitivity, frequency response and size of element has been reviewed, and to obtain the alternating pressures at other points in the stage further difficulties are introduced. One instance of recording the alternating pressures in the aerofoil section of a compressor stator blade at 0·7 blade height is given in Ref. 4.

5. *Conclusions.*—Capacity-type pressure elements have been developed to record the alternating pressures in the casings of gas turbines. Thin stretched diaphragms are used to obtain adequate sensitivity. The lower natural frequencies of the diaphragm assembly occur in the required frequency range but the damping introduced permits an adequate compromise to be made. Connecting passages have been almost eliminated by having the diaphragm near the gas stream. A filtered balance air supply behind the diaphragm has been incorporated to permit calibration during the investigation and part equalisation of pressures across the diaphragm so that higher sensitivities can be used. Cooling arrangements have been developed for application of element to investigate the pressures in turbine casings.

The alternating pressures decrease sharply with distance from the source and special arrangements will be required to record the pressures at points other than at the limits of the gas stream.

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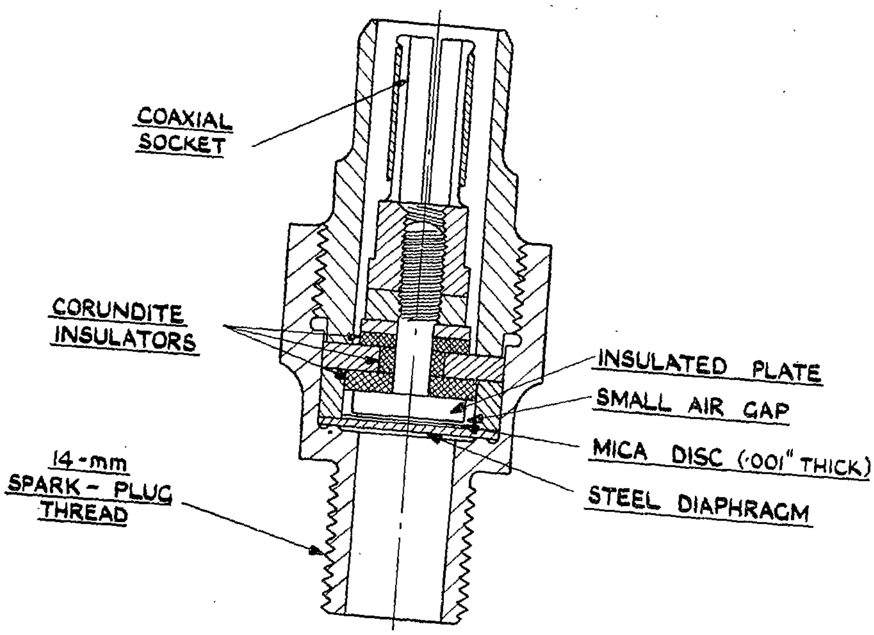


FIG. 1. Typical capacitance-type pressure element.

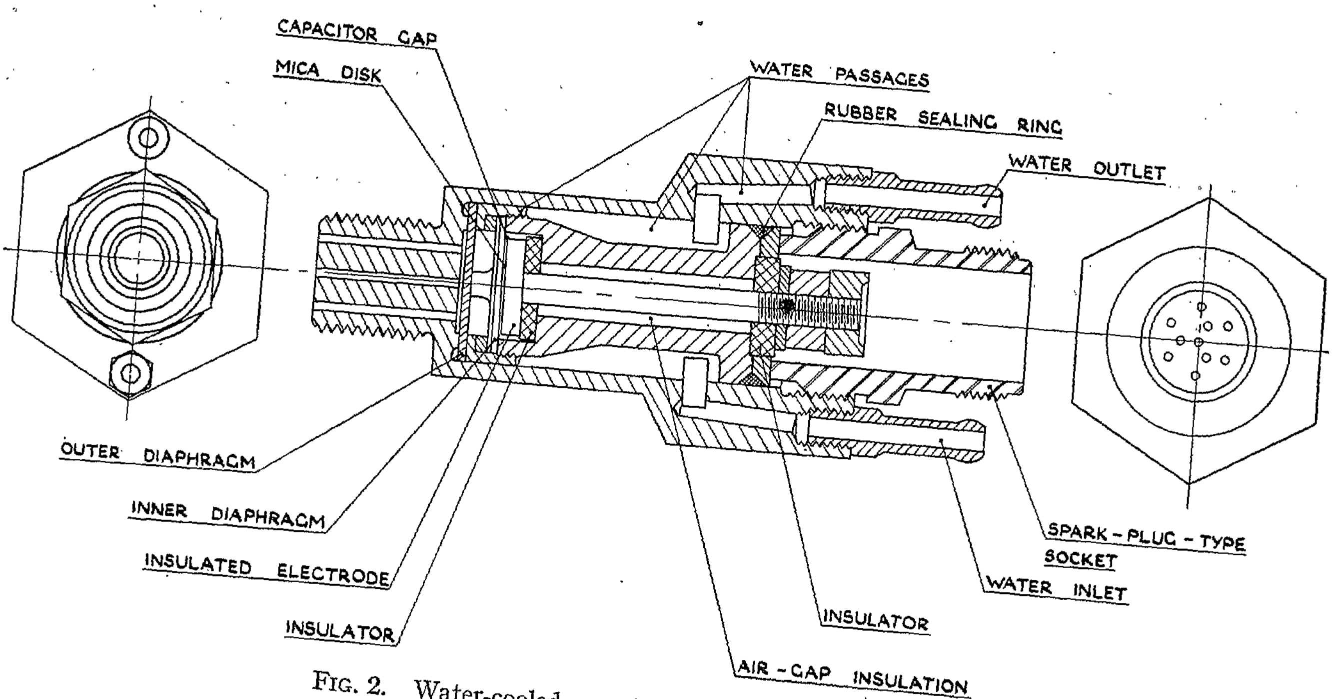


FIG. 2. Water-cooled capacitance-type engine indicator.

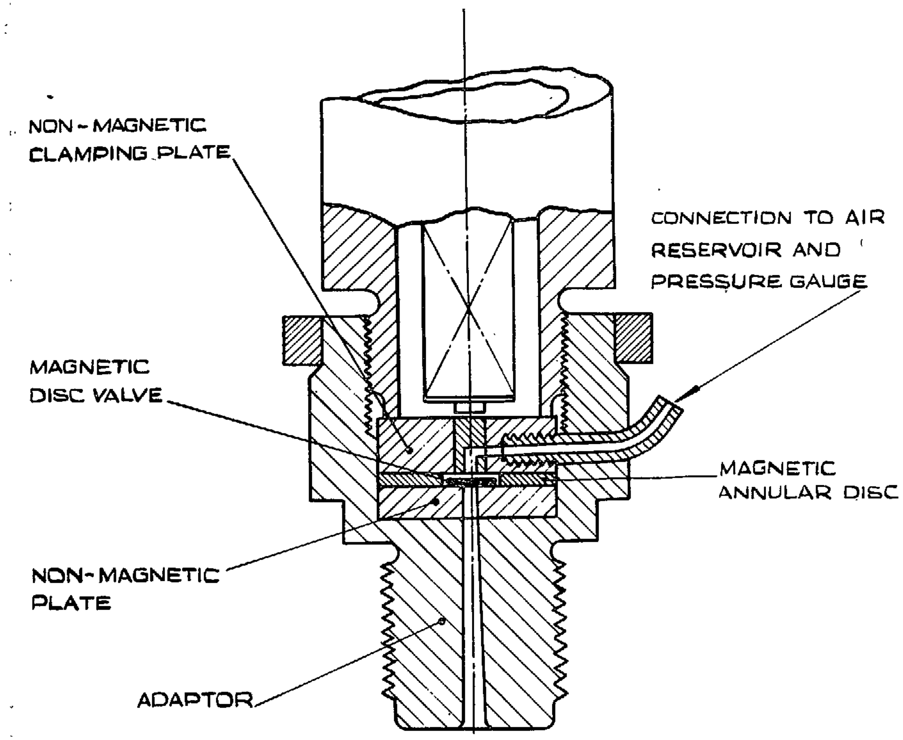


FIG. 3. Balanced disc valve pressure calibrating unit.

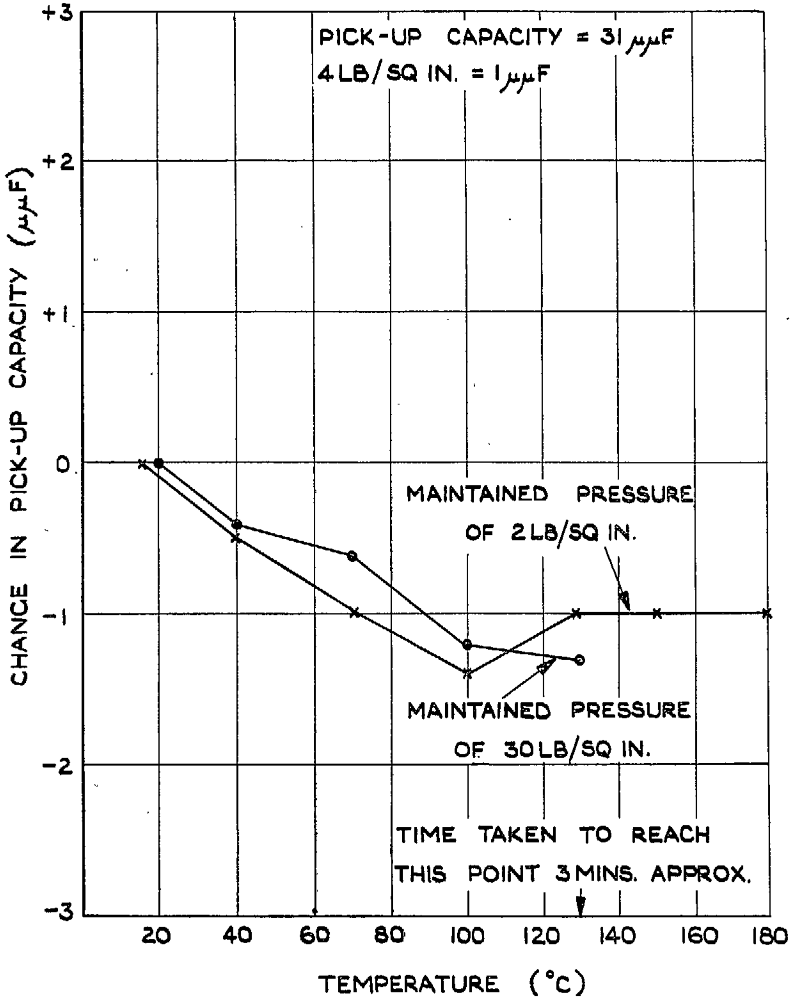


FIG. 4. Effect of temperature change on pressure pick-up.

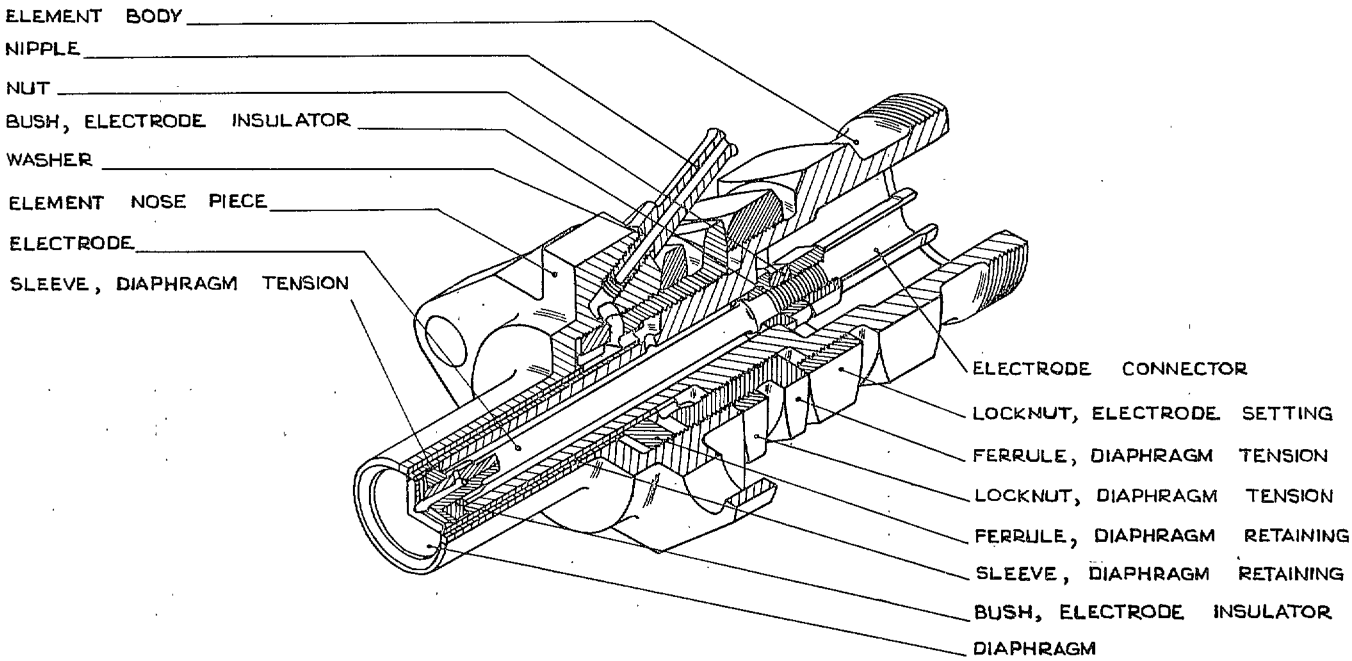


FIG. 5. Balanced diaphragm pressure element.

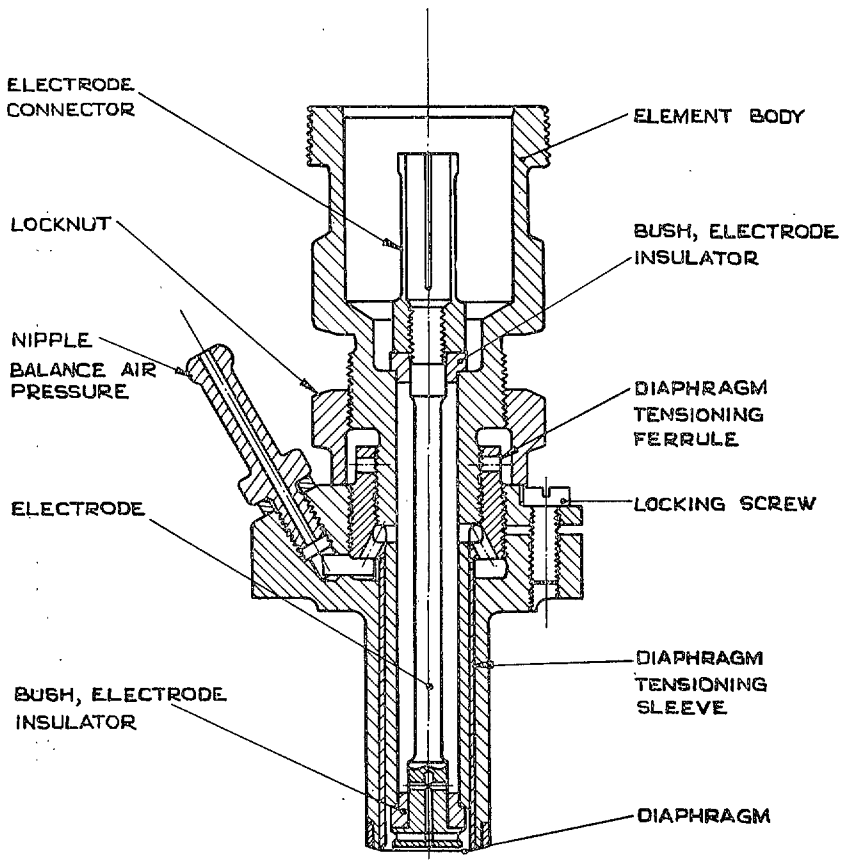


FIG. 6. Balanced diaphragm pressure element with flush diaphragm.

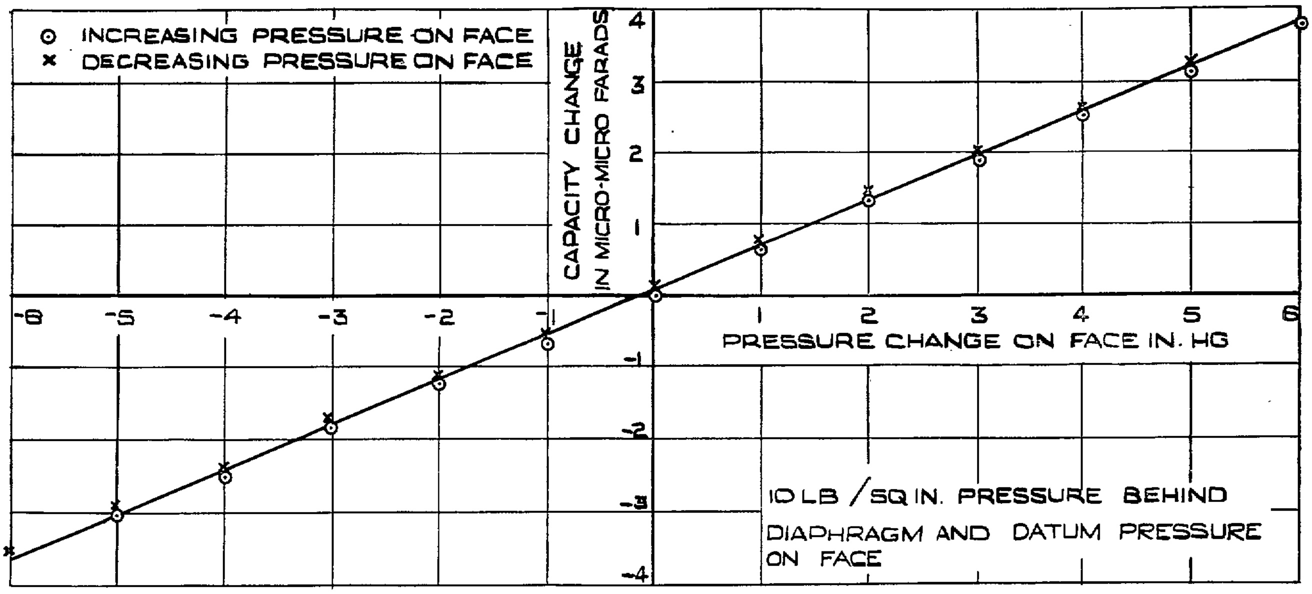


FIG. 7. Typical calibration curves.

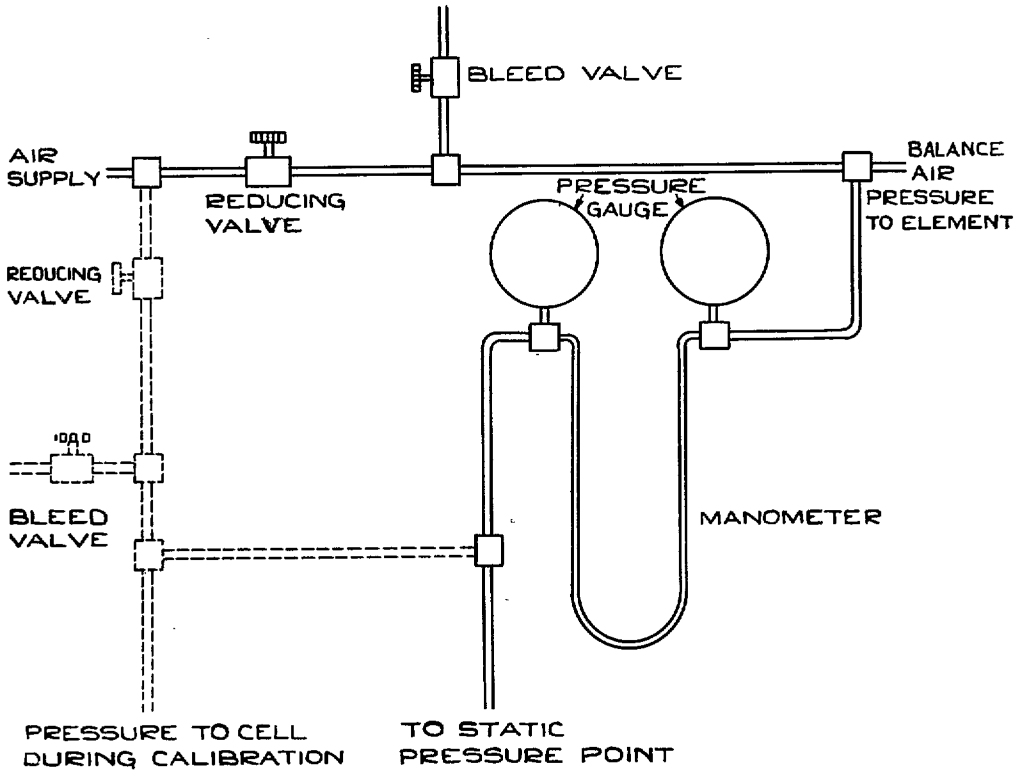


FIG. 8. Diagram of pressure control system.

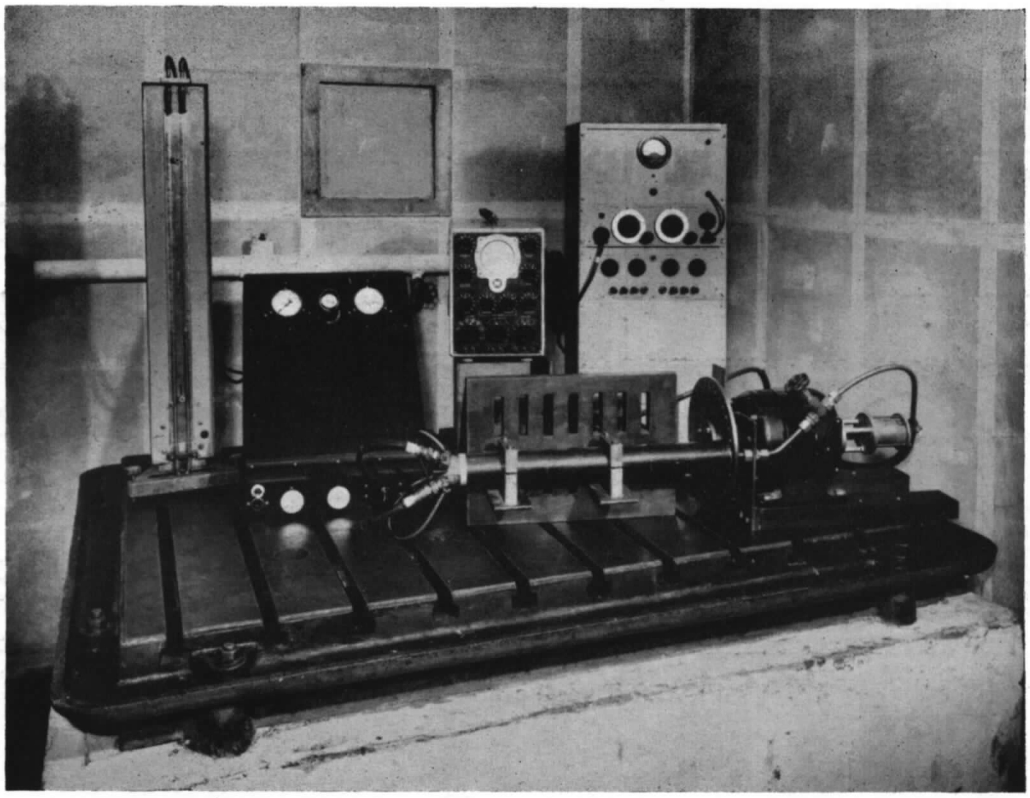


FIG. 9. Calibration of element with alternating pressures.

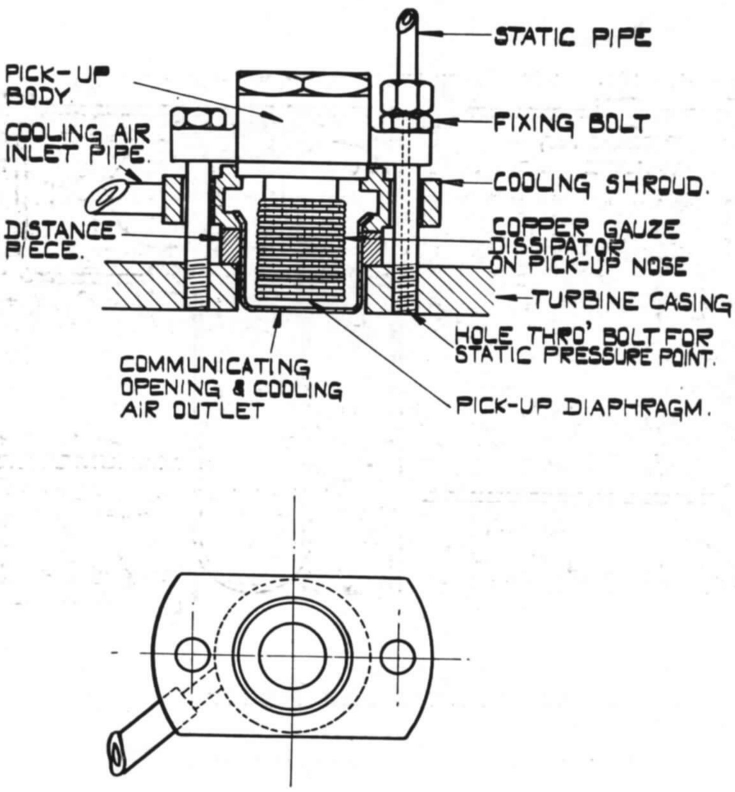
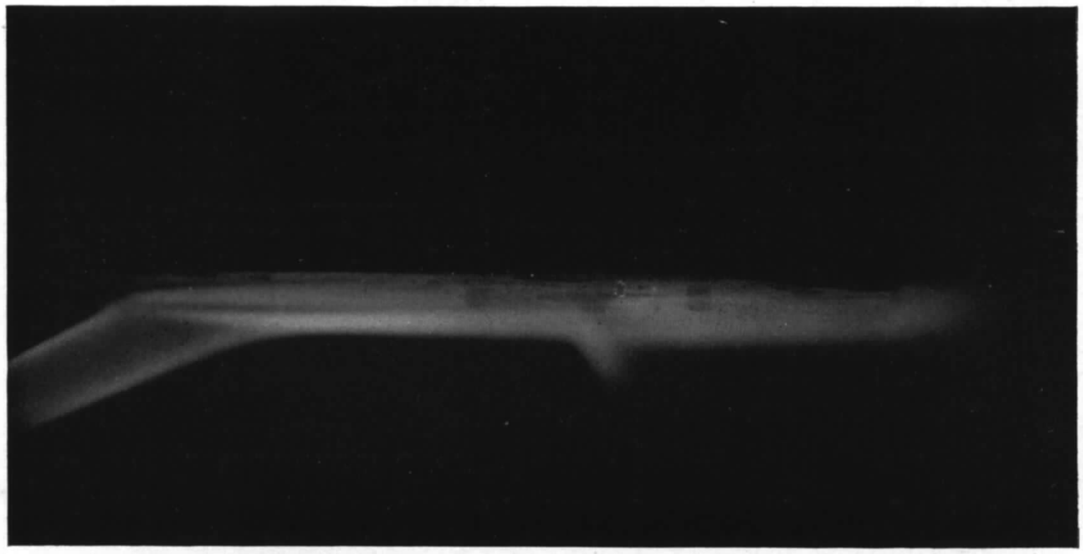


FIG. 10. Air cooling for pressure element.



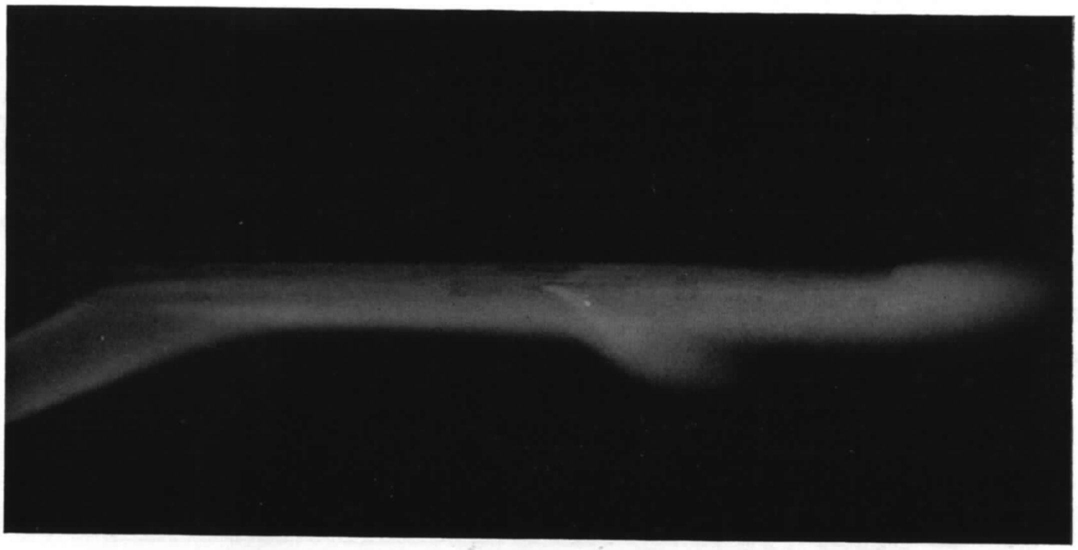


FIG. 11. Air-cooled element in rig heated with gas flame.

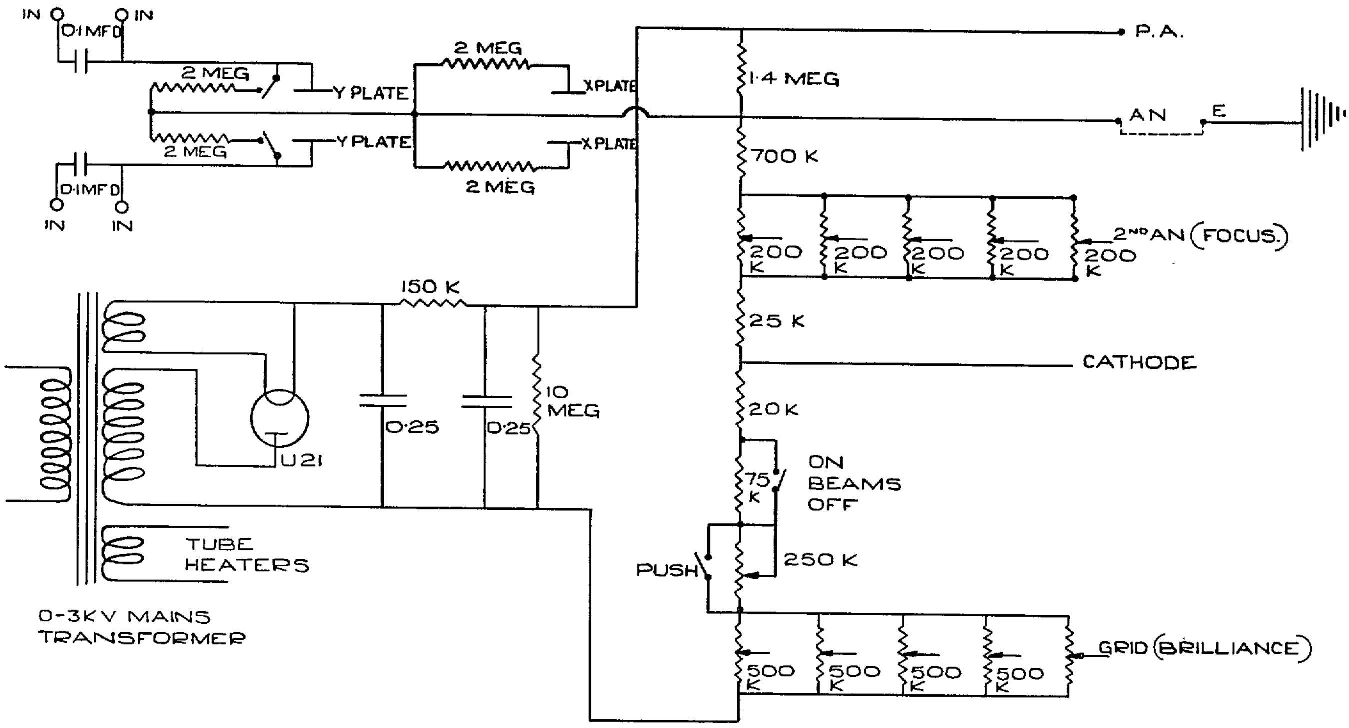


FIG. 12. Circuit diagram for 5-channel oscillograph unit.

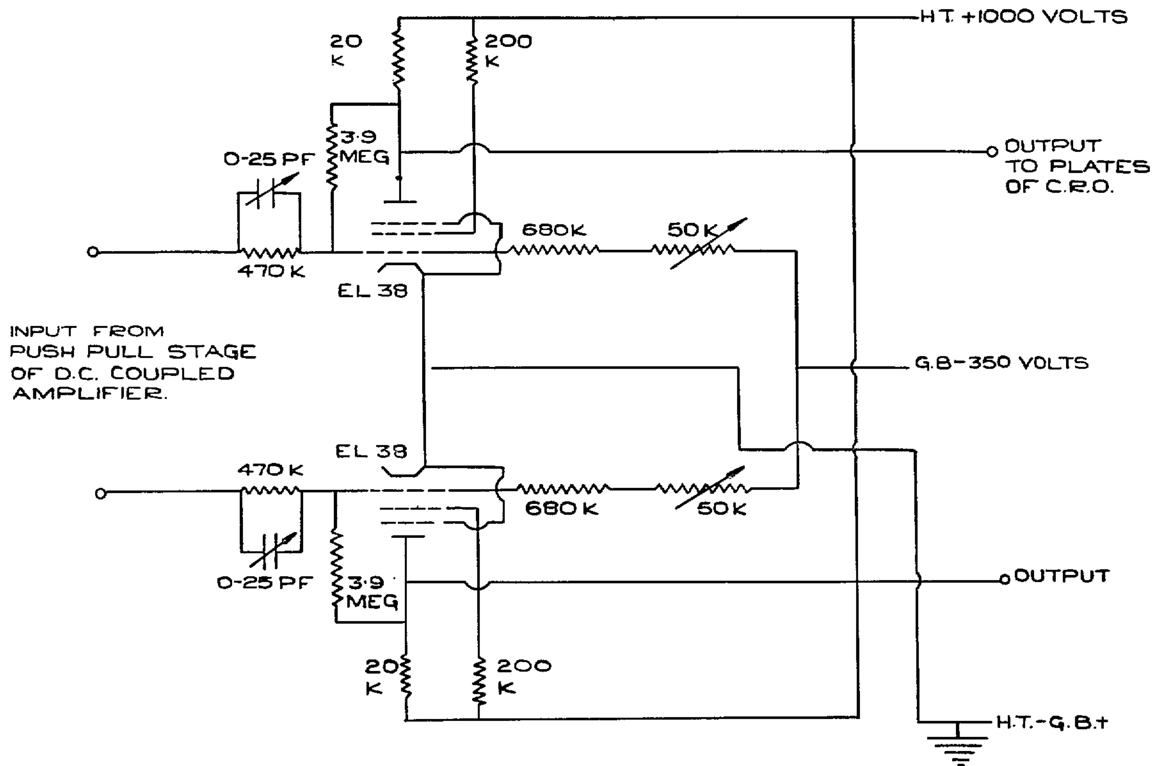


FIG. 13. Circuit diagram for d.c. driver amplifier.

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'E' DENOTES ORDERS OF VIBRATION RELATED TO COMPRESSOR SPEEDS

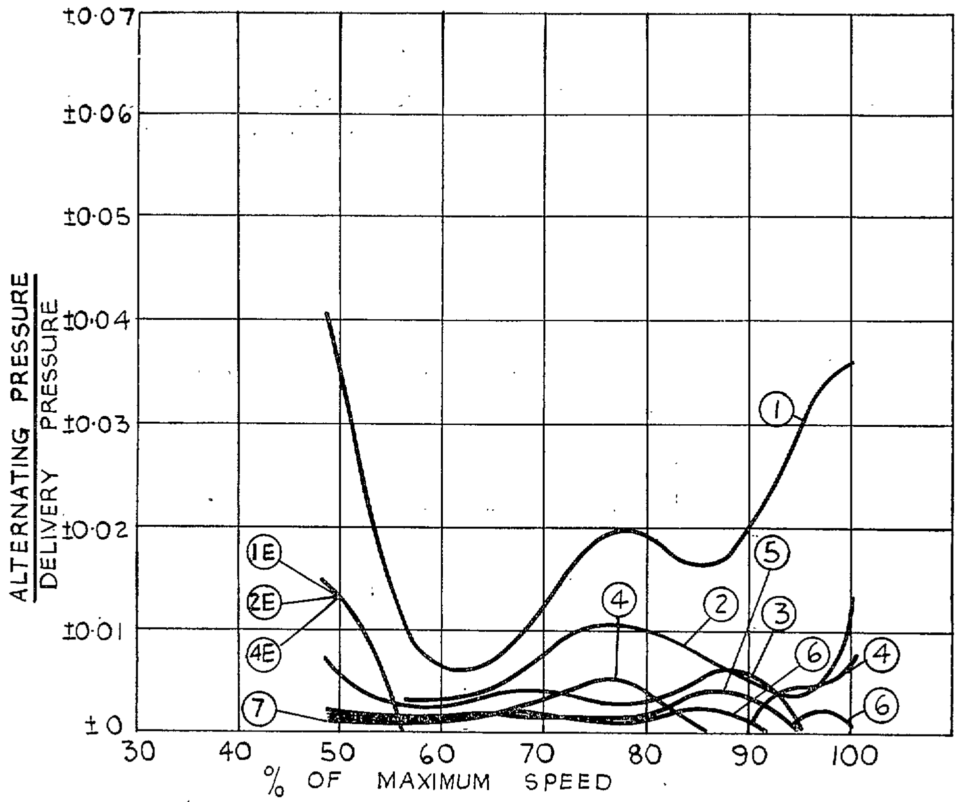

FIG. 14. Harmonic components of alternating pressure at outlet of centrifugal compressor.

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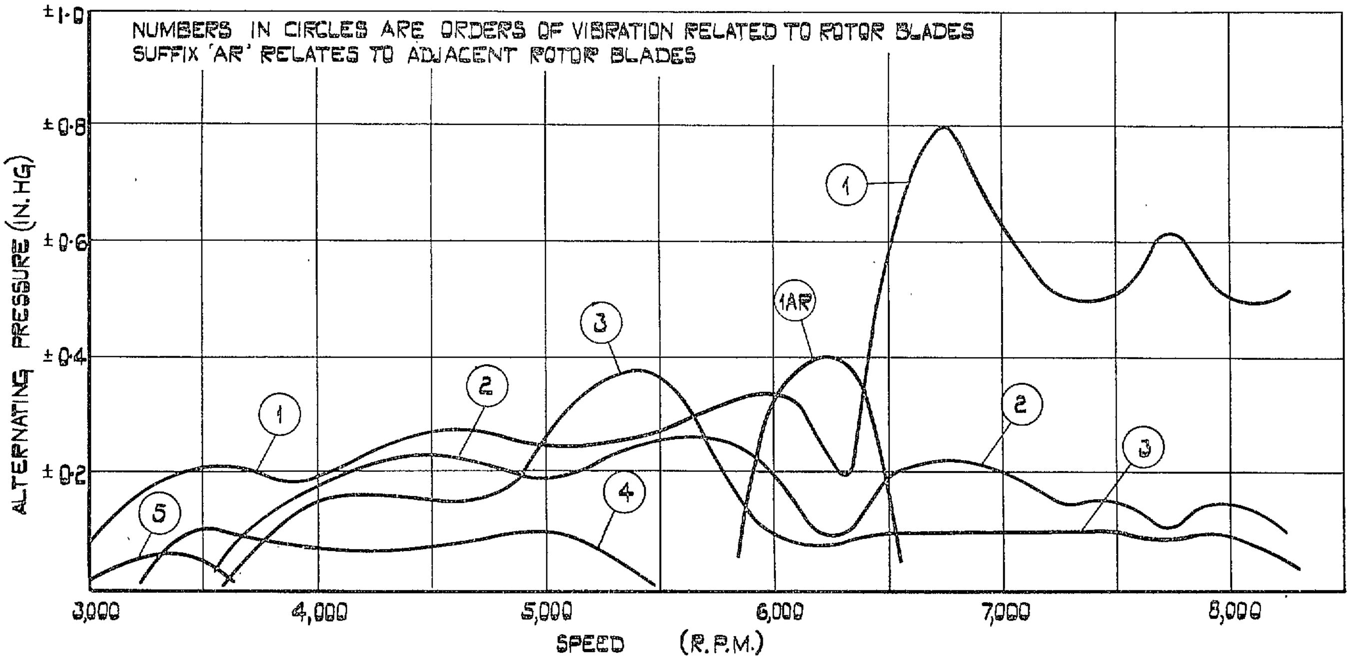

FIG. 15. Harmonic components of alternating pressure in an axial-flow compressor.

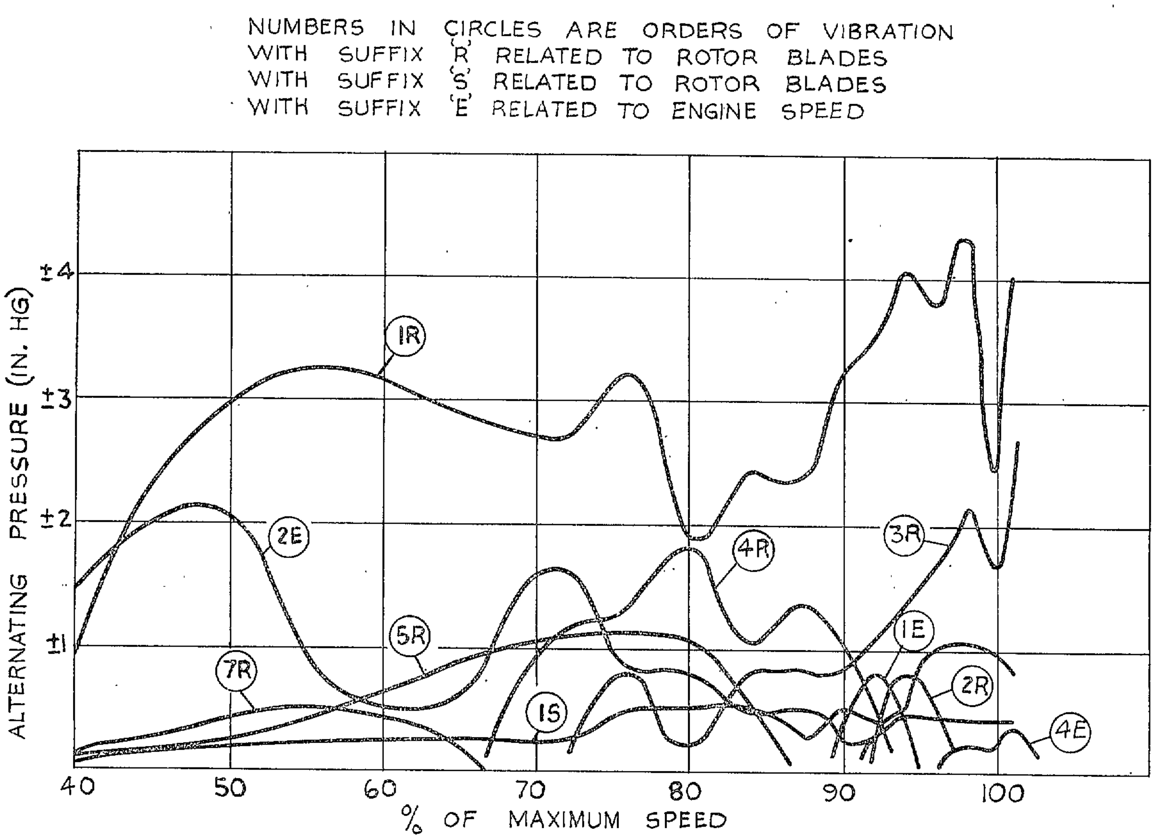

FIG. 16. Harmonic components of alternating pressure in a single-stage turbine.

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