C.P. No. 198
(16,272)
A.R.C. Technical Report

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MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL
CURRENT PAPERS

Wide Range Amplifier for Turbulence Measurements with Adjustable Upper Frequency Limit

By

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LONDON: HER MAJESTY'S STATIONERY OFFICE

1955

Price 4s. 0d. net

C.P. No. 198

U.D.C. No. 533.6.082.73

Report No. Aero 2492

August, 1953.

ROYAL AIRCRAFT ESTABLISHMENT

Wide Range Amplifier for Turbulence Measurements With Adjustable Upper Frequency Limit

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SUMMARY

Requirements are discussed for an amplifier suitable for subsonic and supersonic turbulence work with hot wires. Such an amplifier needs to have a constant gain at low frequencies, and a gain rising in proportion to frequency at high frequencies, in order to compensate for the thermal lag of the hot wire. A fairly sharp cut-off is required at the high frequency end, and it is desirable that this cut-off frequency should be adjustable, so as to limit the band width of the amplifier to no more than is essential, thus preserving the maximum 'signal-to-noise' ratio. The amplifier should also be free of interference arising from external vibrations or from the power supply.

An amplifier is described which has a frequency range from 1.4 c/s to 50 Kc/s, dealing with a range of thermal time lag from 0.1 m.s. to 5 m.s. An iron dust-cored inductance is used to give the required compensation for thermal lag, the circuit being a modification of Dryden's circuit. The upper frequency cut-off is adjustable in six steps from 1.5 Kc/s to 50 Kc/s. The output can be applied to a thermocouple meter and to an oscilloscope, and the sensitivity is such that full output is obtained for 100 μV low frequency input, at a setting of 0.5 m.s. time lag. The output in this case is about 5 volts giving an overall gain of 50,000 for low frequencies. The upper frequency gain for negligible noise interference is about 1.6×10^6. The low limit of turbulence which can be measured varies from 0.1% with 1 m.s. time lag and 10 Kc/s upper frequency cut-off, to 5% with 5 m.s. thermal time lag and 50 Kc/s cut-off. These values can be decreased if necessary by the use of a transformer input.

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1 Introduction

The conventional method of measuring turbulence is to use small wires, which are electrically heated and exposed to the air-stream. Wind fluctuations produce corresponding fluctuations in rate of cooling, in temperature and in electrical resistance of the wire. With suitable circuits, these fluctuations appear as voltage changes across the wire. The ratio of the voltage produced, to the magnitude of the wind fluctuation, varies with frequency, because of the thermal lag of the hot wire. The amplifier serves the double purpose of amplifying the small voltages produced by the wire, and of compensating for the lag of the wire in such a way that the combination of hot wire and amplifier produces an output proportional to the wind fluctuations.

Amplifiers for subsonic turbulence measurements have been described by Dryden and Mock[1], Schuh[2], Kovásnay[3], Schubauer and Klebanoff[4], A.A. Townsend[5] and others; these amplifiers are all similar in function, with a provision for compensating for the thermal lag of the hot wire, and with a frequency range from 5 c/s to 5,000 c/s or 10,000 c/s.

The amplifier described in this report was originally planned for turbulence work at supersonic speeds, where it is expected that an extended frequency range will be required. It was however soon apparent, that with some modification, the same equipment could be used also at subsonic speeds, and in its final version it is suitable for measuring subsonic wind tunnel turbulence of low intensity.

The design of an amplifier for turbulence measurements presents various problems, among which the most important are those of preventing self oscillation, ensuring a low noise-level, and designing a suitable compensation stage.

Since the response of a hot wire decreases at high frequencies, that of the amplifier has to increase, so as to give a uniform overall characteristic. Such a frequency characteristic in an amplifier involves some danger of self oscillation, and special precautions must be taken in screening both whole stages and individual components. The power supply to the amplifier should have a low impedance, and in the present case, filters are also used between each stage and the power supply.

The noise-level of an amplifier results from disturbances in valves and resistances in the early stages, and this limits the smallest turbulence which can be measured. The noise-level is kept as low as possible by the careful selection of these components. The noise increases rapidly with increasing band-width however, and depends also on the frequency characteristic of the amplifier. Although very little is known about supersonic turbulence, it is expected that frequencies of up to 50,000 c/s may be produced. On the other hand, in a good subsonic wind tunnel it may be found that frequencies higher than 1,000 c/s are of little importance. Thus it is useful to be able to limit the upper frequency to no more than is essential for each particular application. Circuits were therefore designed to cut-off the upper frequency at six points ranging from 1.5 Kc/s to 50 Kc/s.

Several circuits have been proposed to compensate for the theoretical fall off in sensitivity of a hot wire at high frequencies due to thermal lag. These circuits can be divided into two main classes; those incorporating a resistance and an inductance in series and those having a resistance and a condenser in parallel. In the former type, the impedance of the element increases with increasing frequency, and so it can be used directly as an anode load. The impedance of a resistance and condenser in parallel, decreases with increasing frequency, and the element must be incorporated in a negative feedback circuit or in an impedance network, in order to give the correct frequency characteristic. The circuit used in this amplifier is a modified form of the inductance circuit, using an iron dust-cored coil. The high frequency cut-off is effected by a parallel condenser, giving a resonance near the required cut-off frequency. The resonance circuit is damped by a parallel resistance, and another inductance in the cathode circuit gives a further reduction above the resonance frequency, due to high negative feedback.

2 Specification for Amplifier

The specification for the amplifier is determined by the requirements for turbulence measurements on the one hand, and the possibilities of amplifier design on the other. As our knowledge of turbulence is rather limited, the specification is to some extent a matter of opinion. It is determined by the following considerations:

(1) Intensity and frequency range of turbulence to be measured.

(2) Time constant and frequency distortion of the hot wire used.

(3) Output required from the amplifier.

(4) Need to avoid any interference by airborne noise or vibration.

Three main types of turbulence can be distinguished:

(a) High level turbulence such as is found behind screens, in wakes and in boundary layers. These intensities range from about $\frac{1}{2}\%$ to 10%, (intensities are measured as root mean squares of velocity fluctuation as a percentage of mean speed) and the frequencies encountered lie between 2 c/s and 10,000 c/s approximately.

(b) Wind tunnel turbulence, which may be as low as 0.01% for the best tunnels^{6}. In most cases, an upper frequency limit of 10,000 c/s seems to be sufficient. However, fluctuations of very low frequency have been observed, down to 1 c/s, and even lower frequencies may be of importance.

(c) Supersonic turbulence. Very little is known about this type of turbulence. Estimates of frequency range are normally made by assuming that a pattern of turbulence is swept along with the mean speed. If the pattern consists of eddies with a diameter of $\frac{1}{4}$", frequencies as high as 50,000 c/s may occur, if the mean speed is the sonic speed. The intensity of turbulence is likely to be higher than in subsonic wind tunnels.

The range of turbulence intensity can consequently be assumed to be 0.01% to 10%. In order to derive the corresponding input voltages, assumptions have to be made about hot wire sensitivity. For measuring turbulence of the order of 0.01% at ordinary wind tunnel speeds, (60-300 ft/sec), suitable wires have been found to be approximately 0.02" long and 0.0002" diameter. The voltage produced over such a wire for 0.01% wind fluctuation is about 10 µV, if no reduction of sensitivity due to thermal time lag occurs. It was known, however, from previous turbulence amplifier design, that it is difficult to measure inputs as low as this, even with a band-width limited to 10,000 c/s, because of noise interference. A transformer input has been used before to overcome this difficulty, and it was decided to use this method again. This meant that the amplifier itself could have a lower sensitivity, and 100 µV input to give full scale output, was the figure chosen. At the other extreme, with an input of say 10 mV, one stage is by-passed to avoid overloading and distortion.

The frequency range of the amplifier without compensation was fixed from about 1 c/s to 50,000 c/s with a drop in sensitivity of 30% at either end. To extend the frequency range of the amplifier below 1 c/s would involve considerable difficulties in design and operation of the amplifier. On the other hand, the significance of these low frequencies in turbulence work is not yet clear. They probably contribute appreciably to the total energy only in low turbulence wind tunnels. In supersonic wind tunnels, frequencies above 50,000 c/s may be important, but the hot wire response is unknown at frequencies as high as this. At medium frequencies it was sufficient to consider the heat capacity of the wire, the relevant flow and temperature fields being assumed to be the same as in the steady state. Thus equation (1) (see later) was obtained. However, for sufficiently high frequencies, the following effects will occur:

(a) A sort of thermal skin effect, whereby the temperature of the wire is not constant over the cross section of the wire.

(b) Dynamic effects in the flow field and the temperature field around the hot wire.

A rough estimate was made in Ref.7 of both effects, and according to this they occur above 30,000 c/s for a wire of about 0.0002" diameter. The upper frequency limit of the amplifier was therefore fixed at 50,000 c/s.

The change in sensitivity of a hot wire with frequency, due to its thermal lag, is given by:-

$$A = \frac{A_0}{\sqrt{1 + (2\pi)^2 f^2 \tau^2}} \qquad (1)$$

where A is the wire sensitivity at the frequency f, and A_0 at zero frequency; τ is the time constant, which depends on wire diameter, wind speed and temperature. This change in sensitivity is also accompanied by a phase shift, but since only r.m.s. values are of interest in almost all turbulence measurements, the phase angle is of little importance. For a platinum wire of 0.0002" diameter, and wind speeds of 60-300 ft/sec., the time constant is between 0.1 m.s. and 0.5 m.s. approximately. Wires smaller than 0.0001" diameter are seldom used. For supersonic turbulence, tungsten wires up to 0.0003" diameter are likely to be used. Since the time constant is approximately proportional to $(\text{diam})^{5/3}$, a range of time constant from 0.1 m.s. to 5 m.s. is considered to be sufficient.

The compensation stage, which is described more fully in Section 4, contains a suitable circuit such that its amplification is proportional to $\sqrt{1 + (2\pi)^2 f^2 \tau^2}$ within the desired frequency range; thus compensation is made for the thermal lag as given by equation (1).

The output of the amplifier serves two purposes; one is to give a visual display on a cathode ray tube, and the other is to feed a thermojunction for measurement of root mean squares of input voltages. A thermojunction is generally used in connection with turbulence measurements since the reading of this instrument is independent of waveform and frequency. The thermojunction used in this amplifier has a maximum current of 5 m.a. Assuming a working current of 1.5 m.a., the input needed to the current limiting circuit in which it is incorporated is 5 v. This voltage is also adequate for use as input to a cathode ray oscilloscope, and gives a total gain needed for the amplifier of 50,000.

An amplifier which works well in an electronic laboratory may be useless near a wind tunnel, because of the large amount of vibration and airborne noise present. This may cause vibrations of the inner systems of the valves and these in turn result in alternating voltages at the output terminals of the valves. The susceptibility of a valve to vibration is known as microphony, and the amplifier must be reasonably free from the effects of microphonic valves.

3 General Features of Amplifier

This section deals with general considerations for the design of the amplifier whose circuit diagram is given in Fig.1. For more detailed considerations as to the value of individual components, see Section 6.

The amplifier consists of 6 stages with an end stage feeding a thermo-junction, and a separate end stage for an oscilloscope. The design of the amplifier is largely determined by two considerations: ensuring that no valve overloads, and maintaining a favourable ratio of signal to electronic noise throughout the amplifier.

The position of the compensation stage has to be carefully considered. With the compensation circuit used in this amplifier, it is not possible to avoid having a gain of less than one for the compensation stage, for signals of low frequency. Therefore, in this stage, the level of signal in the plate circuit should be well above the noise level of the next valve, and, at the same time, the signal voltage on the grid of the compensation valve should not be so high as to exceed the linear range of operation. These requirements are met by making the compensation stage the third stage in the amplifier.

A reduction in sensitivity of an amplifier can be effected by a potentiometer ('volume control') in the grid circuit of one of the stages. Similar considerations apply to the position of this potentiometer. If it were placed at the input of the amplifier, it would reduce all input signals to the level of the smallest to be measured and consequently the signal-to-noise level would be unnecessarily unfavourable for the higher values of input. On the other hand, if placed at the grid of the end stage, it would endanger the previous stages with overloading. Both ill effects are avoided by placing the potentiometer at the grid of the third stage. However, its range of operation must be limited to a reduction in gain by a factor of about 20; in order to reduce the sensitivity still further, the first stage can be by-passed.

In order to achieve the necessary response at low frequencies, there are no by-pass condensers to the cathode resistances. This results in a drop in amplification for each stage. If all stages were of the push-pull type, this drop in amplification could be avoided without ill effect on the low frequency characteristic of the amplifier, but the noise-level of the amplifier would then be increased by a factor of approximately $\sqrt{2}$.* This is one reason why in this amplifier only the last two stages are of the push-pull type.

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* With two independent sources of electricity of random character, the resulting voltage (or current) is the root of the sum of the squares of each voltage (or current).

Each stage is connected to the power supply through an electric filter which consists of a resistance and a condenser (R-C filter). This is one of factors which helps to prevent self oscillation in the amplifier. Another factor is careful screening of individual stages against each other. The whole amplifier is operated by one stabilised H.T. power supply, and accumulators supply the valve heating current.

Microphony of the first valve is avoided by carefully selecting a miniature valve, and housing it in a steel box which is suspended on rubber bands. The valve is completely sealed in the box to avoid air-borne noise reaching it.

4 Compensation Stage

Among various alternatives, Dryden's circuit[8] (see Fig.4(a)) with a dust-core coil as inductance, was found to be suitable for compensating the thermal lag of a hot wire for a frequency range up to 50,000 c/s. It consists of an inductance L and a resistance R in series in the plate circuit of a valve; its frequency characteristic is determined by a time constant $\tau = L/R$. If the valve is a pentode, the plate current is independent of the anode load, and the output voltage of this stage is proportional to the anode impedance i.e. $R\sqrt{1 + (2\pi)^2 f^2 \tau^2}$. If $\tau = L/R$ is equal to the time constant of the hot wire, the thermal lag (see equation (1)) is accurately compensated. Toroidal dust-core coils combine a sufficiently high inductance with low losses. They are small in size, and commercially available. In Fig.2 a circuit is shown which provides, in addition to the compensation, a provision for adjusting the upper frequency limit at will. The resistance R and inductance L form the compensating element at low frequencies. As the frequency rises, the condenser C gives a parallel resonance with the inductance L, the maximum impedance being determined by the parallel resistance R_p. At the same time, the impedance in the cathode circuit increases due to L_B, thus giving a high negative feedback and the gain of the stage falls steeply above the resonance frequency. By a suitable choice of R_p, C, L_B and the mutual conductance of the valve, g_m, the gain of the stage follows the ideal gain very closely, up to the resonant frequency. In practice, the resistance R in Fig.2 can be neglected in comparison with the impedance of the coil L, for all but the lowest frequencies. In order to facilitate analysis, this resistance has been omitted in the following discussion. Thus the ideal gain in this case is proportional to $\sqrt{(2\pi)^2 f^2 L^2}$ i.e. to $2\pi fL$. The impedance in the plate circuit is now a parallel resonance circuit, consisting of an inductance L, a condenser C, and a resistance R_p. The impedance of this circuit is (with $\omega = 2\pi f$ and $j = \sqrt{-1}$):

$$Z = \frac{1}{\frac{1}{R_p} + \frac{1}{j\omega L} + j\omega C} \qquad (2)$$

The plate current is

$$I_p = \frac{g_m E_g}{1 + R_B g_m + j\omega L_B g_m} \qquad (3)$$

where E_g is the grid voltage. The amplification of the stage is given by:

$$\frac{E_p}{E_g} = \frac{ZI_p}{E_g} \qquad (4)$$

Before combining equations (2), (3) and (4), the following dimensionless quantities are introduced:

$$\eta = \frac{\omega}{\omega_o}$$

$$\delta = \frac{\omega_o L}{R_p}$$

$$\varepsilon = \frac{L_B\ \omega_o}{\frac{1}{g_m} + R_B}$$

and

$$\gamma = \frac{\omega_o L}{\frac{1}{g_m} + R_B}$$

with

$$\omega_o = \frac{1}{\sqrt{LC}} \cdot$$

Then the complex quantity E_p/E_g can be expressed by η, δ, ε and γ; its modulus is:

$$\left|\frac{E_p}{E_g}\right| = \frac{\gamma\eta}{\sqrt{\{(1 - \eta^2)^2 + \delta^2\ \eta^2\}\ \{1 + \eta^2\ \varepsilon^2\}}} \qquad (5)$$

and its argument

$$\varphi = \frac{\pi}{2} - \tan^{-1} \frac{\delta\eta}{1 - \eta^2} - \tan^{-1} \varepsilon\eta.$$

An examination of (5) shows that for low frequencies

$$\left|\frac{E_p}{E_g}\right| = \gamma\eta = \frac{\omega L}{\frac{1}{g_m} + R_B} \cdot$$

This is the ideal gain, since $\frac{1}{g_m} + R_B$ is constant. For high frequencies $\left|\frac{E_p}{E_g}\right|$ becomes proportional to $\frac{1}{\eta^2}$ and the circuit behaves as a simple low pass filter. The quantities ε and δ can be suitably chosen to give the best frequency characteristic, which is one that follows closely the ideal compensation as far as somewhere near $\eta = 1$, and then falls rapidly. Two possible cases suggested themselves:

(1) Terms in η^2 in the denominator of equation (5) to vanish*, and $\left|\frac{E_p}{E_g}\right|$ to be equal to the ideal compensation at $\eta = 1$.

(2) Terms in η^2 and in η^4 in the denominator of equation (5) to vanish.

In case (1), the result is $\varepsilon = 1.27$, $\delta = 0.616$, and in case (2) $\varepsilon = \delta = 1$. Both curves are shown in Fig.3. Obviously a curve with values of ε and δ between these two sets of values would be better. Thus $\varepsilon = 1.135$ and $\delta = 0.808$ were chosen for the amplifier.

By using conventional filters, the same or better results could be obtained, but this would involve an additional stage, and more circuit elements; it is doubtful whether this extra refinement is worthwhile.

As a series of frequency ranges are wanted, some filter elements have to be made variable, and C, R_p and L_B are changed in steps.

5 Disturbance Level

5.1 Sources of Disturbance in the Amplifier

As the highest sensitivity of this amplifier is determined by the disturbance level, it is worthwhile to investigate its various sources. Disturbances arise mainly in valves and resistances. In valves, there are two main sources: electronic noise and microphony. The former can again be sub-divided into shot and flicker effect. The shot effect is due to the atomic structure of electricity, and has a uniform frequency distribution. The flicker effect is due to irregularities in the emission of electrons; it is of large intensity at low frequencies, falls with increasing frequency, and is usually small above 5,000 c/s. Microphony is due to the vibrations of the electrodes in valves which are excited by airborne noise and vibrations. The noise in resistances is due to the thermal movement of the electrons in the resistance. It has a uniform frequency distribution. In carbon resistances there is an additional disturbance due to the finite size of carbon granules; this appears when direct current passes through the resistance.

A further source of disturbances is the power supply. The influence of these disturbances can however be reduced by suitable filters. An estimate of the magnitudes involved is useful. It is evident from the diagram of Fig. 1, that the amplifier is most sensitive to disturbances

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* Multiplying the brackets under the root in the denominator of equation (5) yields $1 + \eta^2\ [\varepsilon^2 + \delta^2 - 2] + \eta^4\ [\varepsilon^2\ (\delta^2 - 2) + 1] + \eta^6\ \varepsilon^2$. Terms in η^2 vanish in this expression if $\varepsilon^2 + \delta^2 - 2 = 0$ and in η^4 if $\varepsilon^2\ (\delta^2 - 2) + 1 = 0$.

of this kind through the high tension lead which supplies the first stage. Roughly $\frac{3}{4}$ of the high tension voltage of 280 v lies on the grid of the second stage, if no filter for the power supply is used. The input level to this stage is about 2 m.v. If disturbances of 5% of this value are allowed, the high tension of the power supply should be constant to within $\frac{1}{2} \times 10^{-6}$ of its value, for disturbances which lie in the transmitted frequency band of the amplifier. This is rather a stringent condition for the power supply, which does not seem to be fulfilled by standard equipment: whence the need for a suitable filter between each stage and the power supply.

5.2 Apparent Noise Level of a Turbulence Amplifier

In order to find the smallest voltage which can be measured by an amplifier, it is customary to give the disturbances as equivalent voltages at the input of the amplifier, regardless of where they actually occur in the amplifier. This can be illustrated by the method of substitute circuits or diagrams. It is usual to substitute an amplifier with its disturbances by an ideal amplifier without internal disturbances, but with an equivalent source at the input of the amplifier. It will however be found in this case that another definition of an equivalent voltage is more useful. This problem will now be investigated in more detail.

The voltage across the hot wire, e, which is produced by the wind fluctuations, is determined by the sensitivity of the wire, the intensity of wind fluctuation U' and the frequency spectrum of the fluctuations. The sensitivity of the wire is defined by

$$e = A\,U' \tag{6}$$

Because of the thermal lag of the wire, A depends on the frequency f as given by equation (1) i.e.

$$A = \frac{A_o}{\sqrt{1 + (2\pi)^2 f^2 \tau^2}}$$

The frequency spectrum of wind fluctuations is characterised by a function F(f) defined by:

$$d(U'^2) = U'^2\,F(f)\,df \tag{7}$$

where $d(U'^2)$ is the turbulent energy between the frequencies f and f + df. With the help of (6), (7) and (1), the following equation can be written

$$d(e^2) = \frac{A_o^2\,d(U'^2)}{1 + (2\pi)^2 f^2 \tau^2} = \frac{A_o^2\,U'^2\,F(f)\,df}{1 + (2\pi)^2 f^2 \tau^2} \tag{8}$$

Finally, the voltage across the wire is obtained by integrating equation (8), whence

$$e^2 = A_o^2\,U'^2 \int_0^\infty \frac{F(f)\,df}{1 + (2\pi)^2 f^2 \tau^2} \tag{9}$$

This voltage is to be compared with the electronic noise level at the input of the amplifier in order to find the smallest turbulence level which can be measured. However, a comparison of this kind is of little use, since it depends also on the spectrum of turbulence instead of only on the properties of the measuring equipment. It will be shown that it is better to compare signal voltage and noise level at the output of the amplifier.

The ratio of output voltage to input voltage of the compensated amplifier is

$$C = C_o \sqrt{1 + (2\pi)^2 f^2 \tau^2},$$

where C_o is the corresponding ratio at $f = 0$. The output voltage E, due to wind fluctuations is given by

$$E^2 = U'^2 A_o^2 C_o^2 \tag{10}$$

and the output voltage due to the internal noise by

$$E_n^2 = C_o^2 \int_{f_1}^{f_2} K(f) \left[1 + (2\pi)^2 f^2 \tau^2\right] df \tag{11}$$

where $K(f)$ is the function characterising the frequency spectrum of the equivalent noise voltage at the input of the amplifier, and f_1, f_2 are the frequency limits of the amplifier. The factor C_o in both equations is not relevant to the problem, and therefore both sides of equations (10) and (11) are divided by C_o^2. For the purposes of this report, we define the expression E_n/C_o as the apparent noise level of a turbulence amplifier, since it gives a direct indication of the lowest intensity of turbulence which can be measured, when compared with the expression E/C_o*.

The actual measurement of the apparent noise level is made in the following way: no input is applied to the amplifier, and the output due to the internal disturbances is measured, while the compensation is set to a certain value of time constant 'τ'. Then the compensation is "switched off" and a signal is fed into the amplifier to give the same output. The amplitude of this signal is the quantity E_n/C_o, that is the equivalent noise level. "Switching off" the compensation means removing the inductance in Dryden's circuit (see Fig.4). In this amplifier it entails switching out the inductance in the anode circuit, and the one in the cathode circuit, thus giving a flat response at the low frequency value of the gain.

5.3 Filter Design for Power Supply

The function of the power supply filter is twofold.

(a) To reduce disturbances from the power supply.

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* $E/C_o = U' A_o$ from equation (10), and A_o will be known for individual wires by calibration, thus giving U'. In practice, E/C_o needs to be at least three times E_n/C_o in order that the noise shall have a negligible effect on the measurement of the turbulence.

(b) To avoid interference between different amplifier stages through the common power supply.

Design considerations have only been based on the first of the filter functions, the second being automatically fulfilled by the filters used here.

Two types of filter have been used; one consists of resistances and condensers only (simple R-C filters); the second uses neon tube voltage regulators in place of some condensers.

In Fig.5 a simple two stage low pass filter is shown. If the internal resistance of the source providing the input voltage is small, and the filter works on a load whose resistance is large, compared with the resistances of the filter, then the ratio of output voltage to input voltage is

$$\frac{1}{\sqrt{1 + 7\rho^2 + \rho^4}} \qquad (12)$$

where $\rho = 2\pi fRC$. In Fig.6, this filter is inserted between the power supply and the first stage. R_{p_1} is the plate resistance of the first stage in which the valve used is a triode. With an internal resistance R_i for the valve, the filter works on a load $R_{p_1} + R_i$ which in practice is bigger than the resistances of the filter. Thus expression (12) will be valid at least approximately. The rest of the amplifier incorporates a number of high pass filters, each of which consists of a coupling condenser and a grid leakage resistance; the corresponding substitute diagram is shown in Fig.7, where each square symbolises an amplifier stage. The ratio of output voltage to input voltage is

$$B\left(\frac{\sigma}{\sqrt{1+\sigma^2}}\right)^m \qquad (13)$$

if B is the total amplification of all stages after the first one, at frequencies for which $\frac{1}{2\pi fC_K} << R_g$, m the number of stages, and $\sigma = 2\pi fC_K R_g$. By multiplying expressions (12) and (13), the ratio of amplifier output to input due to disturbances is

$$P = \frac{B}{\sqrt{1 + 7\rho^2 + \rho^4}}\left(\frac{\sigma}{\sqrt{1+\sigma^2}}\right)^m \qquad (14)$$

Disturbances of low frequencies are suppressed by the amplifier proper (σ small) and those of high frequencies by the power supply filter (ρ large). By a suitable choice of σ/ρ, the medium frequencies can also be suppressed. In Fig.8, P/B is shown as a function of frequency, for $m = 4$ and for three values of σ/ρ. If the frequency spectrum of the power supply disturbances is known, the necessary filters supplying the first and other stages can be designed so that the disturbances are kept at the desired low level.

The by-pass condenser of the filter, which is directly in the plate circuit of a valve may have an influence on the frequency characteristic of the amplifier. To illustrate this, consider Fig.12, where an amplifier stage with a power supply filter is shown. For sufficiently low frequencies, the impedance of C_1 will be comparable with R_p and hence the amplification of this stage will rise with decreasing frequency. Whether this influences appreciably the frequency characteristic of the whole amplifier, depends on the value of the time constant $R_p\ C_1$. As the low frequency cut off of the amplifier is usually due to the action of coupling, coupling condenser C_K and grid leakage resistance R_g in each stage, there will be practically no influence on the frequency characteristic, if $R_p\ C_1$ is large compared with $R_g\ C_K$. For this amplifier, the value of C_1, as required by considerations of power supply filtering, was usually big enough to make $R_p\ C_1 \gg R_g\ C_K$. However, in some of the later stages, C_1 was purposely made much smaller, in order to improve the frequency characteristic of the amplifier. This will be dealt with in Section 6.7.

With suitable values for R and for the power supply voltage, some of the condensers C in Fig.6 can be replaced by neon tube voltage regulators, whose dynamic resistance varies according to type from 40-300 Ω. Dynamic resistance means their resistance to alternating voltages, and it is equal to dV/di if dV is a change in voltage, and di the corresponding change in current. The main advantage of using neon tubes in filters is that their impedance is practically constant even at very low frequencies, when otherwise very bulky condensers would have to be used. On the other hand, there is a danger that neon tubes may not be sufficiently constant in operation, thus introducing new disturbances. Filters with neon tubes were found to be satisfactory, although the tubes had to be selected; the amplifier with neon tubes has not been in operation long enough to decide how soon the tubes deteriorate and need replacing.

6 Design of Amplifier

6.1 General

In Sections 2 and 3 the specification and general features of the amplifier have been dealt with. As the circuits used are either orthodox or have been described previously, the considerations given here refer mainly to the actual values of components used. The suffix numbers given to the components refer to those used in Fig.1.

6.2 Low Frequency Considerations

The low frequency limit decided upon for the amplifier, determines the values of the grid circuit time constants $R_1\ C_1$, $R_7\ C_4$, $R_{14}\ C_8$ etc. A value for this time constant has been obtained by assuming

(a) 5 stages.

(b) At the frequency f_o, an overall decrease of sensitivity to $1/\sqrt{2}$ times the value at medium frequencies.

(c) Equal decrease in sensitivity in each stage.

Then[9]

$$\tau = \frac{1}{2\pi f_0 \sqrt{2^{1/5} - 1}}$$

(The assumption of five stages is made because the last stage has a high negative feedback and consequently its decrease in sensitivity at low frequencies is much smaller than for an ordinary stage with the same grid circuit time constant).

For $f_0 = 3$ c/s which was first chosen in view of the intended use for supersonic work, the time constant obtained is

$$\tau = 0.125 \text{ sec.}$$

In most cases, the values of R and C chosen to give this time constant were $R = 500{,}000\Omega$ and $C = 0.25\ \mu F$. The main exception was the compensation stage. Here the fall off is determined by the resistor R_{19} and the condenser C_{11}. R_{19} needs to be small compared with the internal resistance of the valve, and large compared with the compensation elements, which are parallel to it. At the same time, it must be small enough to give a reasonable anode voltage on valve V_3, and the best compromise was found to be $62{,}000\Omega$; C_{11} was consequently $2\ \mu F$.

When the frequency limit was lowered to 1.4 c/s, the time constants of all the grid circuits were doubled to a value of 0.25 sec except in the case of R_{19} and C_{11}; here it was found to be impracticable to increase either component, since, in the case of the resistance, this would change the operating conditions of valve V_3 unfavourably, and in the case of the condenser it would involve too large a stray capacity. The extra decrease in sensitivity in this stage was compensated for in other stages by suitable circuits which will be described later (Section 6.7). In a similar way, the decrease in sensitivity in the first stage was arranged to be negligible down to 1.4 c/s; thus for measuring high levels of turbulence, the first stage can be by-passed without affecting the frequency characteristic of the amplifier. Allowance was also made for the low frequency fall off due to impedance in the screen circuits of the pentodes and the condensers C_5, C_9, C_{16} and C_{24} were increased from $4\ \mu F$ to $8\ \mu F$.

6.3 High Frequency Considerations

The values of the anode load resistances in the amplifier are determined by the high frequency cut off required, since the stray capacity across these resistances causes the fall off. Under the same assumptions as in Section 6.2, the time constant for the upper frequency limit f_1 is[10]

$$\tau = \frac{\sqrt{2^{1/5} - 1}}{2\pi f_1},$$

with $\tau = R_s C_s$, where $R_s = \dfrac{R_p R_i}{R_p + R_i}$, which is the combination of plate resistance R_p and internal resistance of the valve, R_i, in parallel; C_s is the stray capacity. For $f_1 = 60{,}000$ c/s and $C_s = 50\ \mu\mu F$ we obtain $R_s = 20{,}000\Omega$. In stages with pentodes, this is equal to the plate resistance. For the first stage, where a triode is used, the plate resistance may be higher. ($R_4 = 30{,}000\Omega$).

Another factor which influences the high frequency fall off is the value of the potentiometer in the grid circuit of the compensation stage (R_{14}). With this in any other position than full gain, the stray capacities across the two halves of the potentiometer cause the attenuation to vary with frequency. The effect is reduced if the resistance of the potentiometer is decreased, but this in turn necessitates an increase in the value of the condenser C_8, so that the time constant may be kept the same. A potentiometer of 250,000Ω was found to alter the frequency characteristic only to a rather small extent on changing the attenuation (see Fig.10); at the same time, 1 μF for the condenser C_8 does not involve too bulky a condenser. In order to reduce the high frequency fall off, the leads from anode to following grid were kept as short as possible, and the cut off value without compensation was found to be 70,000 c/s.

6.4 Filtering of Power Supply

The amount of filtering needed to cut out 50 c/s ripple and low frequency jumps from the power supply, was decided empirically. The power supply used is stabilised and has an internal impedance of about 2Ω. It incorporates two neon tube voltage regulators and these were carefully selected, as some of them seemed to strike in an unstable fashion and give rise to violent periodic jumps. Even with the best neon tubes, a certain amount of disturbance reaches the output of the amplifier. This was concentrated in the low frequencies, as for these frequencies, the power supply filter was the least effective. The by-pass condensers C_2 and C_3 were first of all chosen as 8 μF, but this was found to be insufficient to remove the low frequency jumping. They were increased to 16 μF each, and the resistances R_5 and R_6 increased from 15,000Ω to 33,000Ω. These values were satisfactory, although the jumping was still noticeable. Neon tube voltage regulators were tried in place of C_3 and C_7 and using these, the resistances R_5 and R_6 could be reduced to 15,000Ω without ill effect, as long as the neon tubes were carrying just less than their full load current, and faulty tubes were eliminated. The components in the filters were altered slightly, afterwards, to give the correct low frequency cut off, (see Section 6.7) but the filtering was still adequate.

The present arrangement of the compensation stage, with the anode coil and associated components isolated from the H.T. supply by condenser C_{11}, instead of being directly in the anode circuit of the valve, has two main advantages. Firstly, it provides excellent filtering of ripple and jumps from the power supply. The power supply filter discussed in Section 5.3 could not be used in an arrangement with the coil directly in the anode circuit, since the by-pass condenser (C_1 in Fig.12) would seriously effect the low frequency performance of that stage. Secondly, the losses of the anode coil are much less when it is carrying no direct current, and so the response is much nearer the ideal case.

Filters in the later stages do not need to be as efficient as those in the earlier ones, and the only difficulty experienced was in the first push-pull stage. It occurred with the so-called "phase converter stage" where the single input stages change over to the push-pull type. Originally, the circuit of Fig.10 was used. Here, the plate resistance is sub-divided and a fraction m of the output is fed back to the grid of the other valve in the pair. However, by following the grid circuit of valve II, it can be seen that any ripple of the power supply appears to a full extent on the grid of that valve, whereas the signal is reduced by a factor m, so that the ratio of ripple to input becomes rather unfavourable. (m being 80-100). In Fig.11 this difficulty is avoided by using a potentiometer, consisting of R_s and $R_{s/m}$, in parallel with the plate resistance R_p, by which both signal voltage and ripple are reduced by the same amount.

6.5 Compensation Stage

The component values in the compensation stage were modified from the original theoretical values for three reasons:

(1) because of the effect of R_{19} on high frequency performance.

(2) in order to compensate for some of the decrease in sensitivity of the amplifier at high frequencies.

(3) because of the effect of the compensation resistance R_{20} on the low frequency ranges.

The impedance of the anode coil L_2 and the parallel condenser and resistance, rises to about 20,000Ω at 50,000 c/s on the highest frequency range. Compared with this impedance, the resistance R_{19} (62,000Ω) cannot be neglected as has been done in the theory outlined in Section 4. In order to compensate for the influence of R_{19}, the resistance R_{21} was increased for each range by an appropriate amount. The resistance R_{21} which is used in the 50 Kc/s range was increased still further to compensate for the fall off in sensitivity of the rest of the amplifier at high frequencies. The losses of the coil L_2 may have had some effect on the high frequency characteristics, but from the data given by the manufacturers this would only be of the order of 1%.

In the treatment of the frequency characteristic of the compensation stage, the compensation resistance R (see Fig.2) has been neglected. In doing so, it was assumed that the cut off frequency was high enough for R to be small compared with the impedance of the coil, over a considerable range below that frequency. However, with the low frequency ranges this is not the case, and the actual frequency characteristic differed from the one given by equation (5). The deviation consisted mainly of an additional increase in amplifier sensitivity at frequencies about 60% of the cut off frequency. In order to keep this increase within reasonable limits, the resistance R_{21} was reduced for the 1.5 Kc/s, 3.1 Kc/s and 6.25 Kc/s ranges. No adjustment was necessary in the higher frequency ranges. The effect of the compensation resistance, R, is the more marked the higher its value, or, since $\tau = L/R$, the lower the value of time constant τ. (See Figs.17, 18 and 19).

6.6 Output Stage

The output stage is the same as previously used by James and Mitchell[11]. It automatically protects the thermojunction by limiting the current through it. The maximum current depends on the circuit elements, but a convenient way of adjusting it within certain limits is to change the resistance R_{47}. The thermojunction used here has a maximum current of 5 m.a. and gives an output voltage of 10 m.V. D.C. for an input of 2.5 m.a.

6.7 Adjustment of Low Frequency Characteristic

It is not always possible, and in some cases not even desirable, to spread the "falling off" in the frequency characteristic of an amplifier, evenly over all the stages. As has already been mentioned (Section 6.2), an extra decrease at low frequencies can not be avoided in the compensation stage of this amplifier. Also, in order to measure high levels of turbulence, the first stage has to be by-passed; if this is not to result in a change in the overall frequency characteristic, the first stage must retain full sensitivity at lower frequencies than the rest of the amplifier.

A circuit has already been mentioned in Section 5.3 which can be used to improve the low frequency characteristic of the amplifier. The essentials of this circuit are shown in Fig.13; a constant current is applied to the input of the circuit, and the voltage at the output shows an increase at low frequencies when the impedance of C_1 is comparable with the resistance R_1. The resistance R_2 is sufficiently high for it to come into play only at still lower frequencies. If this circuit forms the plate circuit of a pentode, the current I is practically constant. R_2 is necessary in order to provide the D.C. power supply to the valve. With a view to later applications, it is more practical to base the analysis on the combination of this circuit with a R-C circuit (Fig.14) as exists for instance in the grid of an amplifier stage. In order to simplifying analysis, R is assumed to be very large compared with R_1. If V_o is the voltage at the output and I_1 the current applied to the input, the result of the analysis is

$$\frac{V_o}{I_1 R_1} = \frac{\rho}{\sqrt{1+\rho^2}} \left(\frac{\sqrt{(1+\delta)^2 + (\gamma\rho)^2}}{\sqrt{\delta^2 + (\gamma\rho)^2}} \right) \qquad (15)$$

where $\rho = 2\pi fRC$, $\delta = R_1/R_2$ and $\gamma = \frac{R_1 C_1}{RC}$.

Equation (15) is plotted for $\delta = 1$ and $\delta = 2$ in Figs.15 and 16 respectively for various values of γ. As the low frequency circuit and the R-C circuit do not influence each other, they may in reality be in different parts of the amplifier. As mentioned before, the power supply filter for each stage already contains the compensation circuit of Fig.13, if the value of the by-pass condenser which is directly in the plate circuit is suitably chosen. By doing so, the efficiency of the circuit as a power supply filter may be impaired, but it is always possible to effect the compensation at a later stage, where less need exists for power supply filtering. When neon tube voltage regulators were used in the power supply filter of the first stage, the efficiency of the first half of the filter, i.e. R_6 plus neon tubes, was such that the remaining part of the filter i.e. R_5 and C_2 could be chosen so that the fall off in this stage did not occur until well below the amplifier cut off frequency.

The compensation for the extra decrease in amplification in the third stage was effected by suitably choosing C_6 in the second stage and C_{14} in the fourth stage.

Apart from these permanent adjustments there is a need for temporary alterations to the frequency characteristics in two cases.

(1) If a transformer is used before the first stage.

(2) If the time constant of the amplifier is experimentally set by the method of square waves.

For the measurement of the lowest levels of turbulence, it is necessary to use a transformer between hot wire and amplifier input. The frequency range of a particular transformer used, extended from 2.3 c/s to about 10,000 c/s. It was considered desirable to improve the frequency characteristic of the transformer plus amplifier at low frequencies.

The usual method of determining the time constant of a hot wire, is by superimposing on the constant heating current of the hot wire, a small alternating current with a square wave form. Due to the thermal lag of the hot wire, this wave form is distorted, but it is brought back to its original form by a correct setting of the time constant in the amplifier compensation stage. In order to avoid any additional distortions by the amplifier itself, rather stringent conditions hold for the phase shift[11]. If a square wave is fed into the amplifier with the normal condenser C_{14} in the fourth stage, it is reproduced with a slight tilt in the horizontal part of the wave form. Although allowance could be made for this, it is more convenient to eliminate it in the amplifier by temporarily altering the circuit.

For both purposes, i.e. improvement of the low frequency characteristic of the amplifier with transformer input, and reduction of phase shift with a square wave input, the low frequency compensation circuit in the fourth stage has been used; the condenser C_{14} is replaced by $C_{13} = 3\ \mu F$ for transformer input and by $C_{15} = 1\ \mu F$ for square wave compensation setting.

6.8 Further Details of Amplifier

The amplifier is housed in two separate shielded boxes; the first one contains the first three stages, and the second one the remaining stages. Individual stages are shielded from each other by compartments within the boxes, and the anode and cathode coils are in separate mu-metal cans. This shielding was sufficient to prevent self oscillation under all operating conditions but there was an interference between elements of the compensation stage which was noticed by deviations from the calculated frequency characteristic. This was remedied by placing the compensation valve itself in a compartment, so that the grid was shielded from cathode and anode.

Interference due to microphony in the valve in the first stage, was effectively removed by using a miniature triode and housing it in a sealed steel casing suspended by rubber bands. A pentode of normal size in the second stage had too much microphony even when using selected valves. A miniature pentode suspended on rubber bands proved satisfactory, but if a new amplifier is built, it is recommended to house this valve also in a steel box. The third and fourth stages are not so important, but even here, selected normal sized pentodes were used. It is probably advisable to use miniature pentodes here too, because their microphony is generally less than that of ordinary sized valves.

In order to avoid noise being produced by resistances, the 'grid stopper' resistances (R_2, R_8, R_{15} etc) were kept as low as possible (about 600Ω). As plate resistance of the first valve, a wire-wound resistor was chosen, in order to avoid the noise from a granular resistance when a direct current flows through it.

7 Discussion of Characteristics of Amplifier

Four curves are given for the low frequency characteristics of the amplifier without compensation (Fig.20). One is for the amplifier as originally built with a drop of 30% at 2.6 c/s. The second shows an improvement in the lower frequency limit from 2.6 c/s to 1.4 c/s and the third shows the overall gain of 1 amplifier plus a transformer with 25:1 amplification. In this case, the compensating condenser C_{13} is switched into the fourth stage. The amount of over compensation is thought to be tolerable. A curve is also given of amplifier plus transformer without low frequency compensation, i.e. with condenser C_{14} in circuit.

The curves of high frequency gain without compensation were taken for the whole amplifier ("high gain" in Fig.9) and for the amplifier with first stage by-passed ("low gain" in Fig.9). In each case, the frequency characteristic was taken for three settings of the potentiometer, R_{14}; full gain, middle of the potentiometer, and a setting somewhere near the bottom of the potentiometer. The first stage causes an extra fall off, and the effect of potentiometer setting is also quite noticeable. As the operation of the amplifier is restricted by a filter whose highest frequency is 50,000 c/s, both effects are considered to be tolerable.

Figs. 17, 18 and 19 show the gain of the amplifier with compensation, compared with the ideal gain, A, for a particular setting, τ, of the time constant, where

$$A = A_0\sqrt{1 + (2\pi)^2 f^2 \tau^2},$$

A_0 is the gain at zero frequency, and f is the frequency. The agreement is within a few percent, up to the cut off frequency, except in the case of the low value of time constant (Fig.19). This effect has been explained in Section 6.5 and was considered to be tolerable.

The apparent noise level of the amplifier (see Section 5.2) is shown in Fig.21. This quantity varies appreciably with the band width of the amplifier and with the time constant setting. Thus, for the low time constant of 0.2 m.s. and on the ranges lower than 6 Kc/s, the noise level is less than 10 μV. With a time constant of 5 m.s. and on the 50 Kc/s range, however, the noise level rises to 1600 μV. The input voltage needs to be at least three times the noise level so that the increase in r.m.s. output due to noise shall not exceed 5%. Thus the limits of input voltage set by the noise level appear to be 10-20 μV and 4.8 m.v. for the two extreme settings of time constant and frequency band mentioned before. Disturbances from the power supply do not allow input voltages of less than 100 μV to be measured. With the transformer input, the maximum sensitivity is 4 μV.

Fig.22 shows that above a certain value, the current through the thermojunction in the output stage ceases to be proportional to the amplifier input. This is due to the swing into the non-linear characteristics of the valves, where harmonics of the input frequencies arise. The linear range of the output is sufficient for practical purposes; some non-linear range is unavoidable if the circuits are to protect the thermojunction from overloading. In Fig.22 a plot of the galvanometer reading used in conjunction with the thermojunction is also given. About two thirds of the galvanometer scale is within the linear range of the amplifier.

The question now arises as to whether the specifications for the amplifier, as given in Section 2, have been fulfilled by the present amplifier. It appears from this section, that this is so, as far as frequency range and filter performance are concerned. It should also be mentioned that self oscillation and microphony of valves were both avoided. However, for supersonic turbulence work, where a large frequency range may be involved, the sensitivity of the present amplifier may not be sufficient, due to the high noise level. The noise level of the first valve, where the majority of the noise originates, can be expressed as an equivalent input resistance at the grid of the first valve. This resistance is about 3000Ω for the valve used, whereas the lowest values are about 300Ω[12]. This means, expressed in input voltages, a reduction to about 1/3 of the present value (the equivalent resistance is proportional to the square of the equivalent input voltages). Several other valves were used in turn in the first stage, and a table of their apparent noise levels is given in Fig.23. They were used under the same conditions as the miniature triode (C.V.139), the valve permanently connected in the first stage, and it can be seen that there was little to be gained by using any of the other valves. The lower values of equivalent resistance can be obtained by using a triode with a high transconductance, which in turn requires a high plate current. As the power supply filter requires a substantial voltage drop over the resistances which it contains, an increase in plate current can only be obtained either by a much higher voltage power supply (it need only be for the first stage) or by a reduction of the resistances in the filter. The latter would entail some restriction of the low frequency range. As one would expect the low frequency range not to be so important for supersonic turbulence, this seems to be a suitable way out. If the need arises, the best solution along these lines would be to build an extra first stage, perhaps with its own power supply. Alternatively, a transformer, designed to cover the required frequency range, would give a lower apparent noise level.

LIST OF SYMBOLS

f		frequency
A		wire sensitivity at frequency f
A_o		wire sensitivity at zero frequency
τ		time constant
L		inductance
R		resistance
R_p		cf. Section 4
R_B, I_B		cf. Fig.2
g_m		mutual conductance (cf. Section 4)
j		$\sqrt{-1}$
E_g		grid voltage
E_p		plate voltage
ω	=	$2\pi f$
ω_o	=	$1/\sqrt{LC}$
η		ω/ω_o
δ		$\omega_o L/R_p$
ε		$I_B\ \omega_o\Big/\left(\frac{1}{g_m} + R_B\right)$
γ		$\omega_o\ L\Big/\left(\frac{1}{g_m} + R_B\right)$

LIST OF SYMBOLS (Contd)

Z	impedance	
e	voltage across hot wire	
U'	intensity of wind fluctuation	
$F(f)$	cf. equation (7)	
C	(output voltage)/(input voltage)	
C_o	C at $f = 0$	
E	output voltage	
ρ	$2\pi f\ RC$	
B, σ, m	cf. equation (13)	
P	amplifier output/input	
δ	R_1/R_2	cf. equation (15)
γ	$(R_1\ C_1)/(RC)$	

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APPENDIX I

Circuit Values in Fig.1

Resistances

R_1	510KΩ	$\frac{1}{2}$ W. Carbon
R_2	620Ω	$\frac{1}{4}$ W. Carbon
R_3	1000Ω	$\frac{1}{2}$ W. Carbon
R_4	30KΩ	1 W. Wire Wound
R_5	33KΩ	1 W. Carbon
R_6	33KΩ	1 W. Carbon
R_7	510KΩ	$\frac{1}{2}$ W. Carbon
R_8	620Ω	$\frac{1}{4}$ W. Carbon
R_9	370Ω	$\frac{1}{2}$ W. Carbon
R_{10}	20KΩ	1 W. Carbon
R_{11}	150KΩ	$\frac{1}{2}$ W. Carbon
R_{12}	12KΩ	$\frac{1}{2}$ W. Carbon
R_{13}	12KΩ	$\frac{1}{2}$ W. Carbon
R_{14}	250KΩ	Log Carbon Pot 2W
R_{15}	3300Ω	$\frac{1}{4}$ W. Carbon
R_{16}	820Ω	$\frac{1}{2}$ W. Carbon
R_{17}	270KΩ	$\frac{1}{2}$ W. Carbon
R_{18}	10KΩ	$\frac{1}{2}$ W. Carbon
R_{19}	62KΩ	1 W. Carbon
R_{20}	1000Ω	Log Carbon Pot 2W
R_{21}	Variable with frequency Range (see compn. cir. values)	
R_{22}	10Ω	$\frac{1}{2}$ W. Carbon
R_{23}	620Ω	$\frac{1}{4}$ W. Carbon
R_{24}	1500Ω	$\frac{1}{2}$ W. Carbon
R_{25}	20KΩ	1 W. Carbon
R_{26}	100KΩ	$\frac{1}{2}$ W. Carbon
R_{27}	10KΩ	$\frac{1}{2}$ W. Carbon
R_{28}	510KΩ	$\frac{1}{2}$ W. Carbon
R_{29}	3300Ω	$\frac{1}{4}$ W. Carbon
R_{30}	100Ω	$\frac{1}{2}$ W. Carbon
R_{31}	1MΩ	$\frac{1}{2}$ W. Carbon
R_{32}	10KΩ	$\frac{1}{2}$ W. Carbon
R_{33}	47KΩ	$\frac{1}{2}$ W. Carbon
R_{34}	3300Ω	$\frac{1}{4}$ W. Carbon
R_{35}	20KΩ	1 W. Carbon
R_{36}	5000Ω	$\frac{1}{2}$ W. Carbon
R_{37}	15KΩ	1 W. Carbon
R_{38}	510KΩ	$\frac{1}{2}$ W. Carbon
R_{39}	510KΩ	$\frac{1}{2}$ W. Carbon
R_{40}	1000Ω	$\frac{1}{2}$ W. Carbon
R_{41}	4700Ω	$\frac{1}{2}$ W. Carbon
R_{42}	4700Ω	$\frac{1}{2}$ W. Carbon
R_{43}	620Ω	$\frac{1}{4}$ W. Carbon
R_{44}	500Ω	Wire Wound Pot
R_{45}	390Ω	$\frac{1}{2}$ W. Carbon
R_{46}	2200Ω	$\frac{1}{2}$ W. Carbom
R_{47}	5000Ω	$\frac{1}{2}$ W. Carbon
R_{48}	510KΩ	$\frac{1}{2}$ W. Carbon
R_{49}	5000Ω	$\frac{1}{2}$ W. Carbon
R_{50}	390Ω	$\frac{1}{2}$ W. Carbon
R_{51}	120KΩ	$\frac{1}{2}$ W. Carbon
R_{52}	51KΩ	1 W. Carbon

Condensers

C_1	0.25 µF	350V
C_2	16 µF	350V
C_3	16 µF	350V
C_4	0.25 µF	350V
C_5	4 µF	350V
C_6	8 µF	350V
C_7	8 µF	350V
C_8	0.5 µF	350V
C_9	4 µF	350V
C_{10}	16 µF	350V
C_{11}	2 µF	350V
C_{12}	Variable with frequency range (see compn. cir. values)	
C_{13}	3 µF	350V
C_{14}	12 µF	350V
C_{15}	1 µF	350V
C_{16}	4 µF	350V
C_{17}	0.25 µF	350V
C_{18}	4 µF	350V
C_{19}	0.25 µF	350V
C_{20}	0.25 µF	350V
C_{21}	0.25 µF	350V
C_{22}	4 µF	350V
C_{23}	0.25 µF	350V
C_{24}	4 µF	350V
C_{25}	4 µF	350V

Compensation Circuit

Values

L_2 = 100 M.H.

Frequency range	L_1	R_{21}	C_{12}
(Kc/s)	(M.H.)	(KΩ)	
1.5	128	1.033	0.1 μF
3.1	64	2.26	0.025 μF
6.25	32	5.06	0.0063 μF
12.5	16	11.5	0.0016 μF
25	8	28.3	300 μμF
50	4	142	30 μμF

Valves

V_1	C.V.139		Min. Triode
V_2	C.V.138		Min. Pentode
V_3	C.V.1065	(V.R.65)	Pentode
V_4	C.V.1065	(V.R.65)	Pentode
V_5	"	"	"
V_6	"	"	"
V_7	C.V.1932	(6J5G)	Triode
V_8	"	"	"
V_9	C.V.1091	(V.R.91)	Pentode

Switches

S_1	One pole two way
S_2	Two pole six way rotary
S_3	Two pole two way
S_4	One pole three way
T	Thermojunction (Rated Current 2.5 m.a.)
m.a.	1-0-1 milliameter.

Neon Tube Voltage Regulators

N_1	C.V.1070
N_2	"
N_3	"
N_4	"

For a Low Frequency Cut-Off of 1.4 c/s

The following components are altered:-

Condensers C_3 and C_7 each replaced by two neon tube voltage regulators (C.V.1070), in series

R_5 changed to 15KΩ; R_6 to 13KΩ;
R_7 and R_{28} to 1MΩ; R_{12} to 10KΩ; R_{13} to 11KΩ
C_1, C_{19} to 5 μF; C_6 to 12 μF;
C_4, C_5, C_{16}, C_{24} to 8 μF; C_8 to 1 μF.

APPENDIX II

Apparent Noise Level of Various Valves as First Stage of Amplifier

Valve	3.1 Kc/s Range	6.25 Kc/s Range	12.5 Kc/s Range	25 Kc/s Range	50 Kc/s Range
C.V.139 (Min. Triode)	4.9 µV	14.5 µV	40 µV	109 µV	290 µV
C.V.138 as Triode	5.6 µV	14 µV	38 µV	97 µV	250 µV
A.C.100 Triode	7 µV	17 µV	42 µV	100 µV	250 µV
6SJ7 Triode		22 µV	47 µV	111 µV	270 µV
V.R.56 as Triode		13.2 µV	40 µV	97 µV	245 µV

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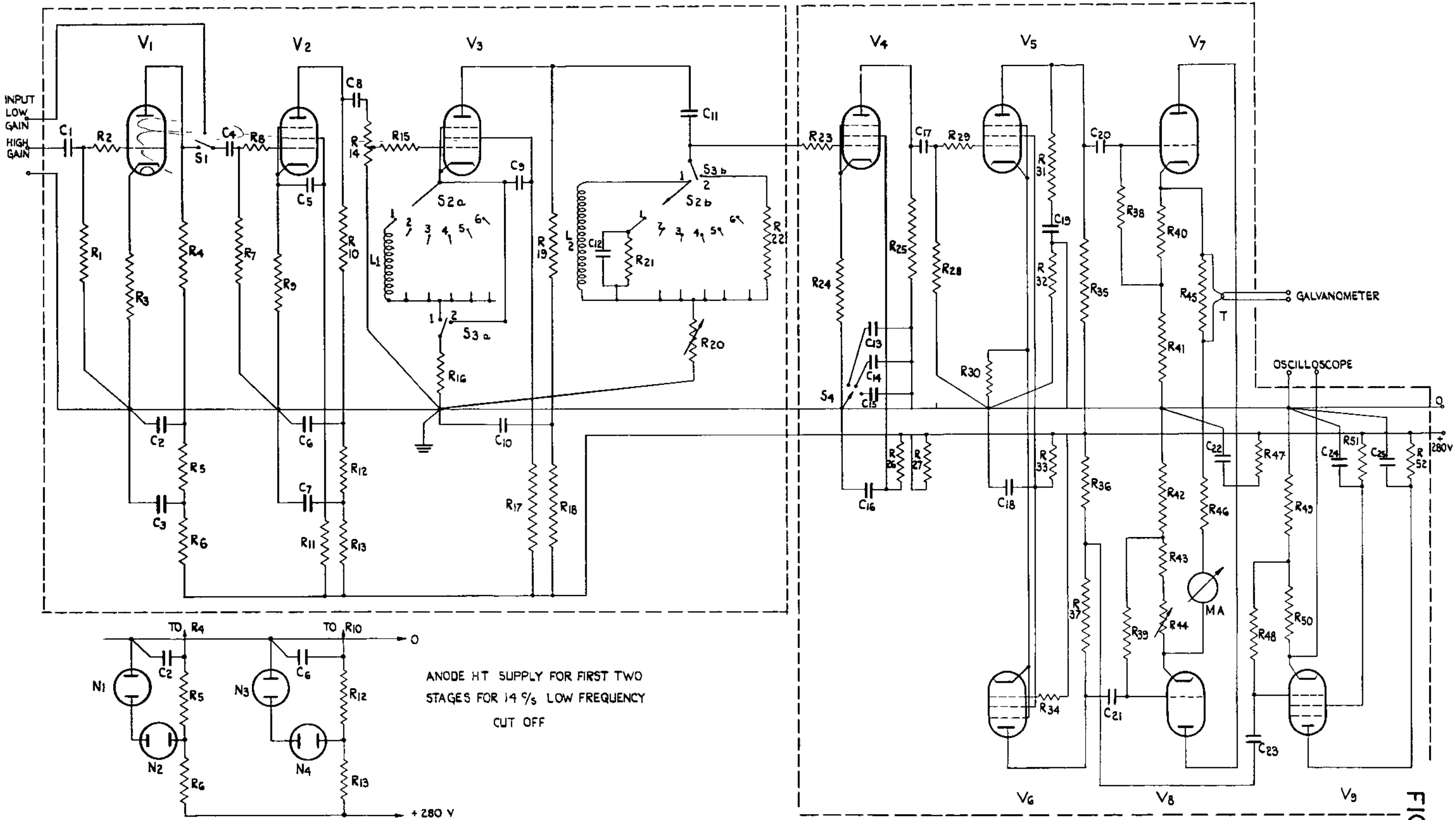


FIG.I

FIG.1(CIRCUIT DIAGRAM OF AMPLIFIER FOR 2·6 C/s TO 50,000 C/s

FIG. 2 & 4(a & b)

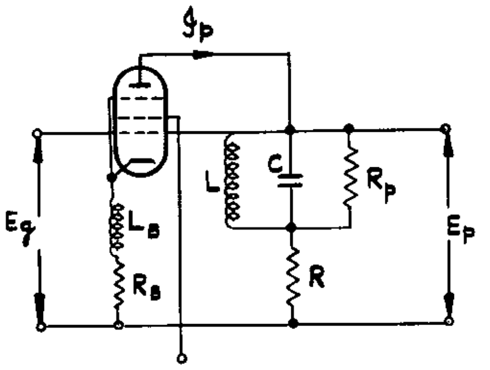
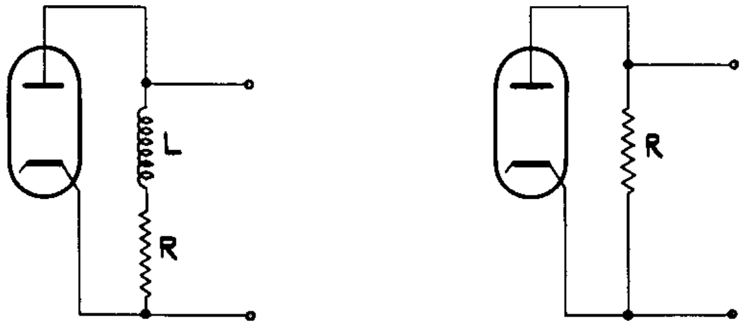


FIG. 2 SIMPLIFIED COMPENSATION STAGE.



(a) COMPENSATION "IN"

(b) COMPENSATION "OFF"

FIG. 4(a & b) COMPENSATION SWITCHING ARRANGEMENT.

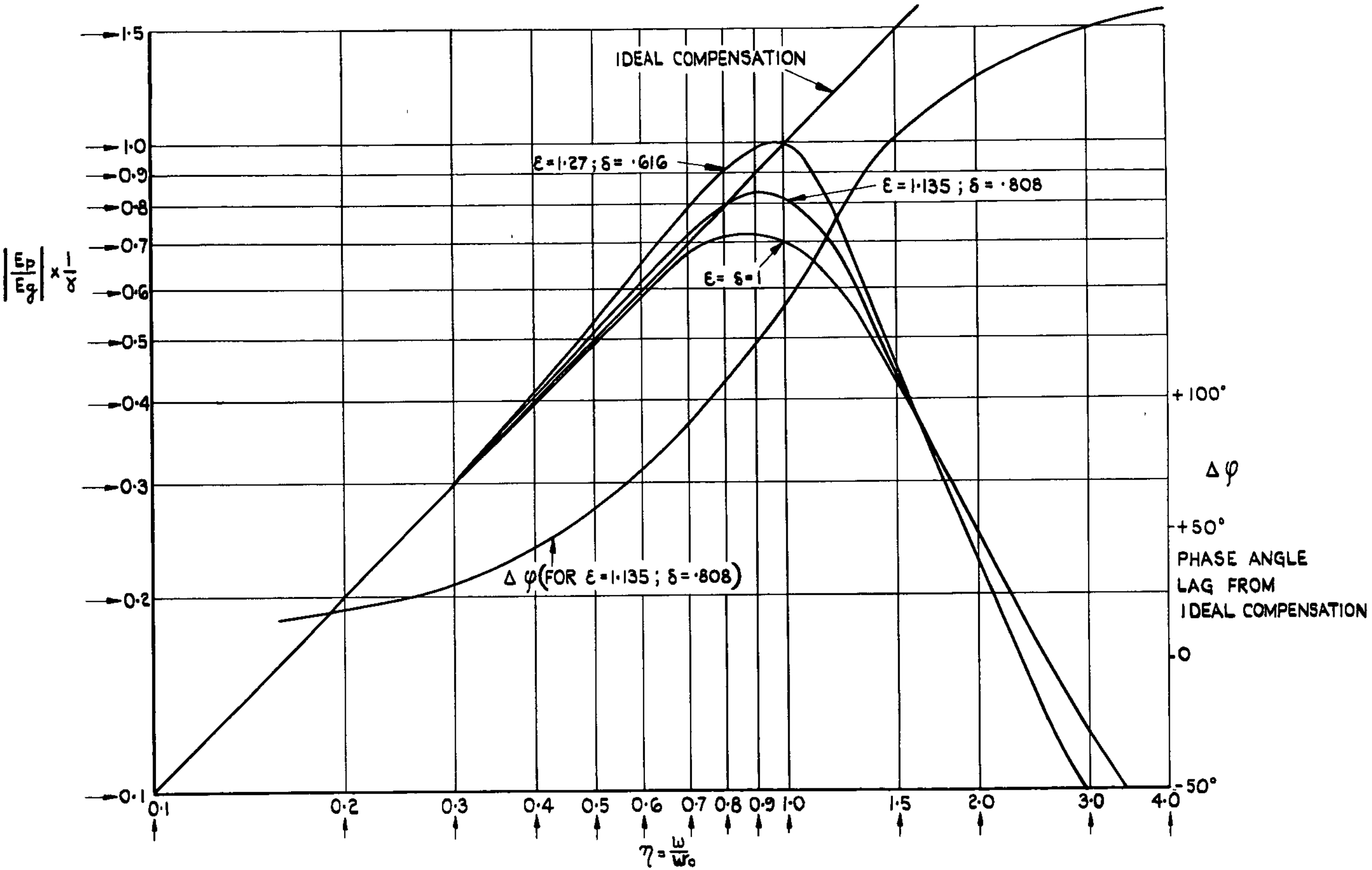


FIG. 3 CALCULATED FREQUENCY CHARACTERISTIC OF COMPENSATION CIRCUIT.

FIG. 3

FIG.5.6 & 7

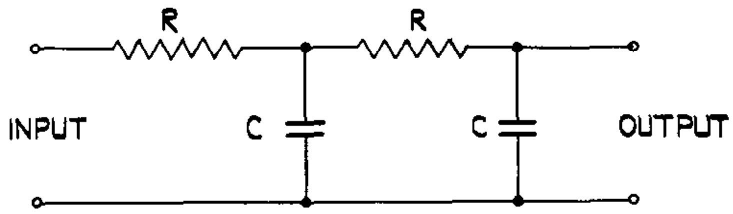


FIG.5 TWO STAGE R-C FILTER.

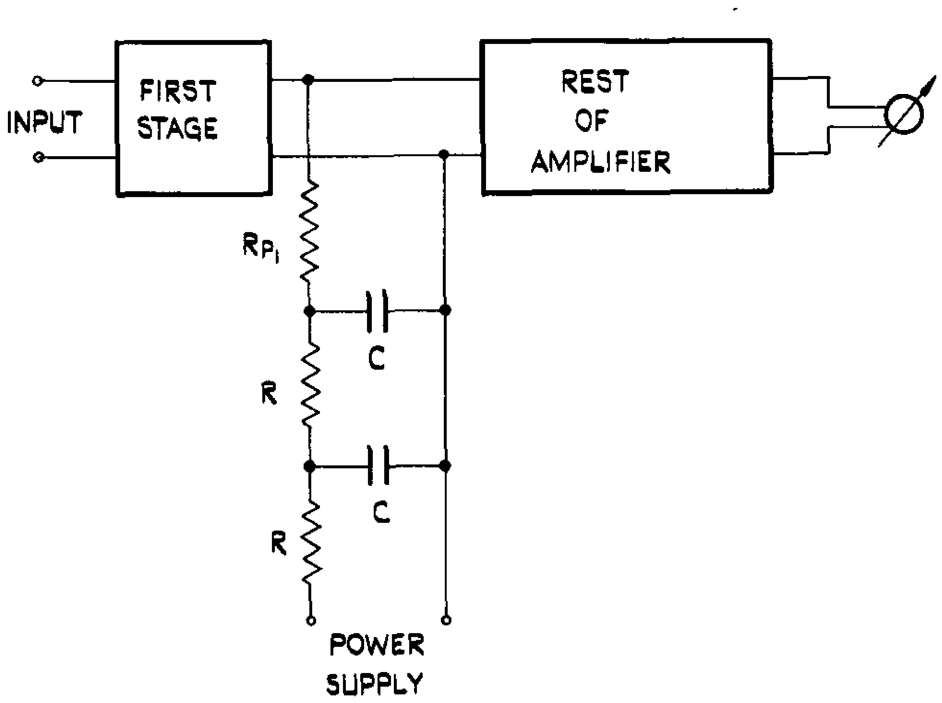


FIG.6 POSITION OF FILTER IN 1ST STAGE.

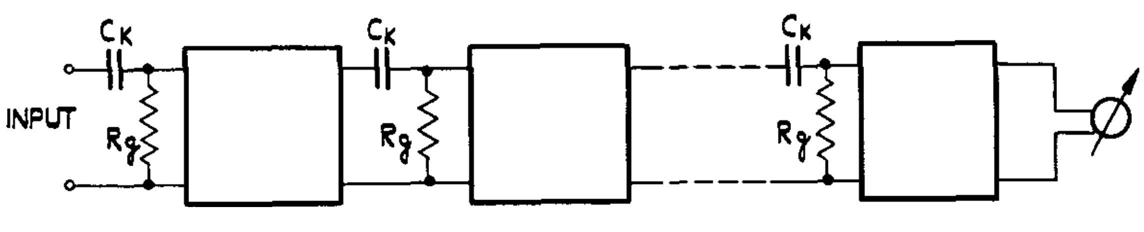


FIG.7 SUBSTITUTE DIAGRAM FOR R-C COUPLING IN AMPLIFIER.

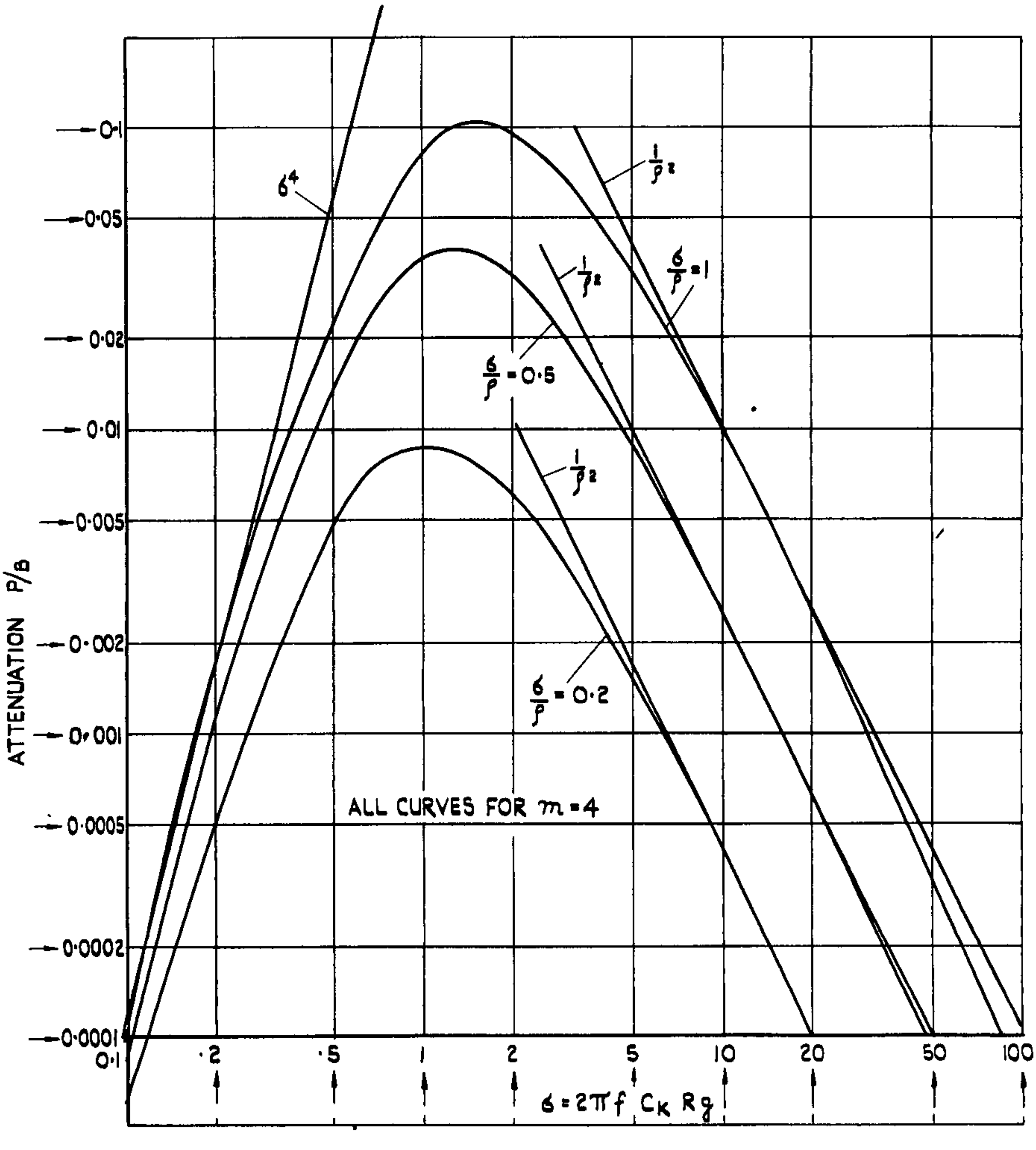


FIG. 8 FREQUENCY CHARACTERISTIC FOR ATTENUATION OF DISTURBANCES FROM A POWER SUPPLY (SEE SEC. 5.3)

FIG. 9

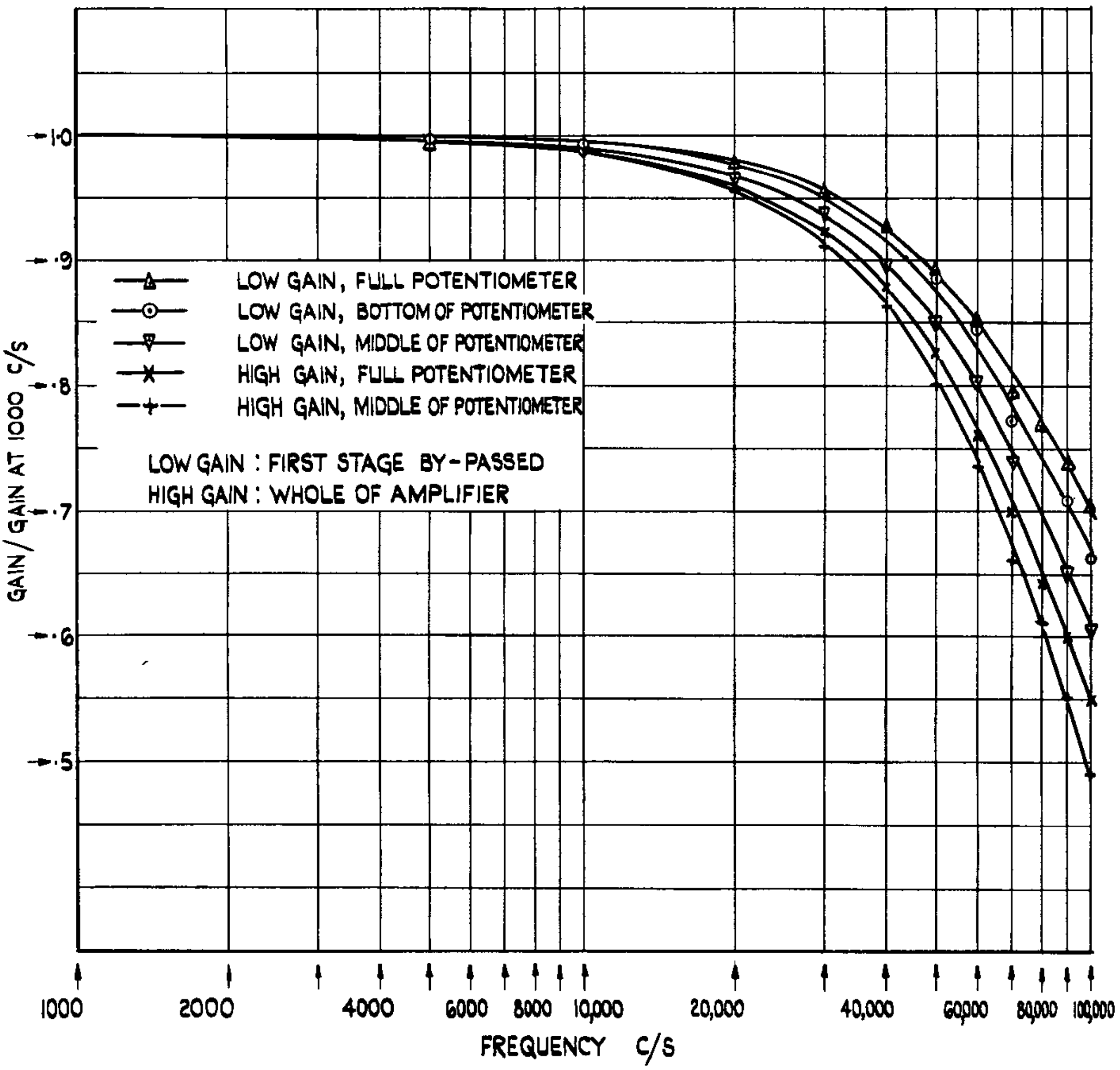


FIG.9 FREQUENCY CHARACTERISTIC OF UNCOMPENSATED AMPLIFIER AT HIGH FREQUENCIES

FIG.10 & 11

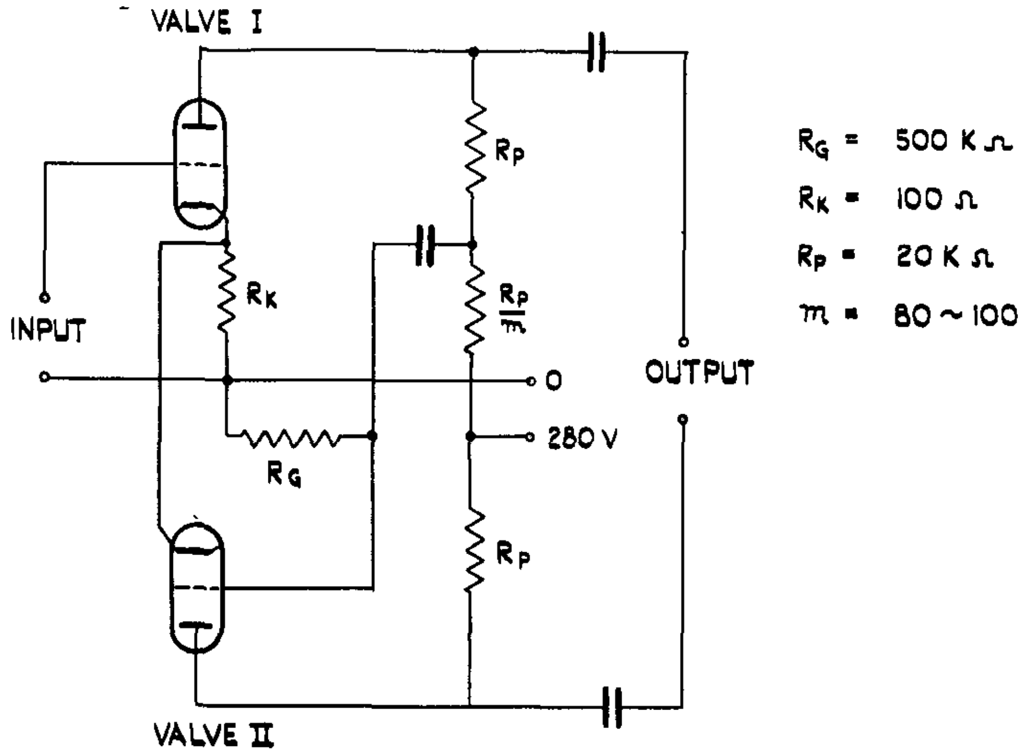


FIG.10 PHASE CONVERTER STAGE ORIGINALLY USED.

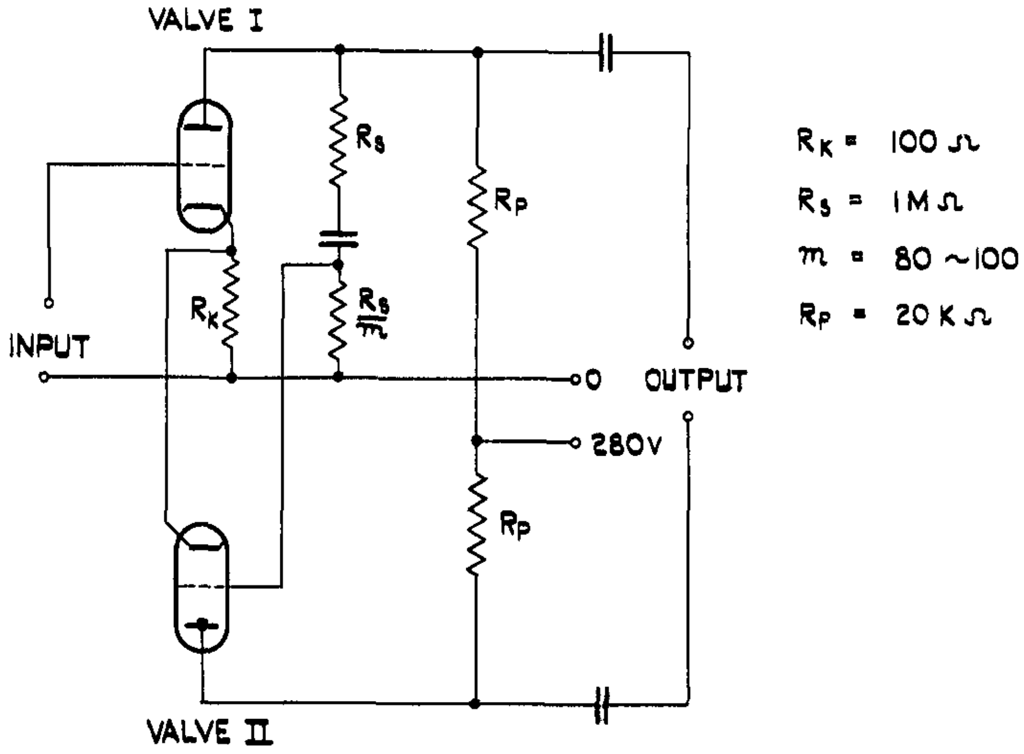


FIG.11 PHASE CONVERTER STAGE FINALLY USED.

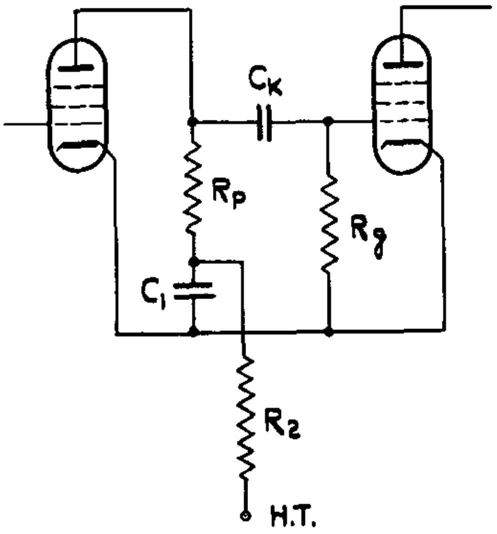


FIG. 12 AN AMPLIFIER STAGE WITH POWER SUPPLY FILTER AND R-C COUPLING.

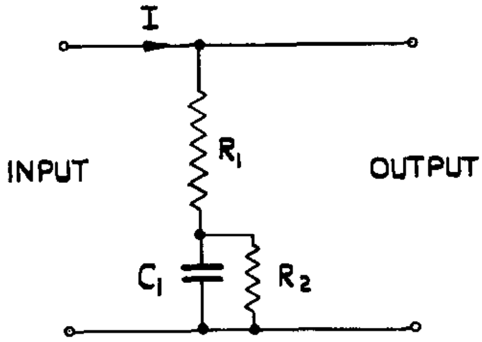


FIG. 13 LOW FREQUENCY COMPENSATING CIRCUIT

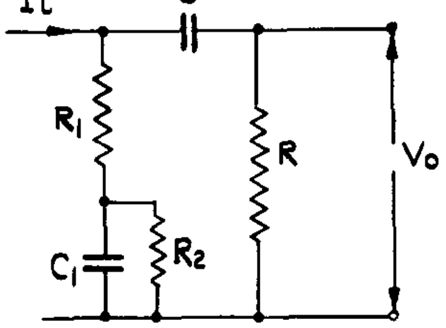


FIG. 14 LOW FREQUENCY COMPENSATING CIRCUIT PLUS R-C COUPLING.

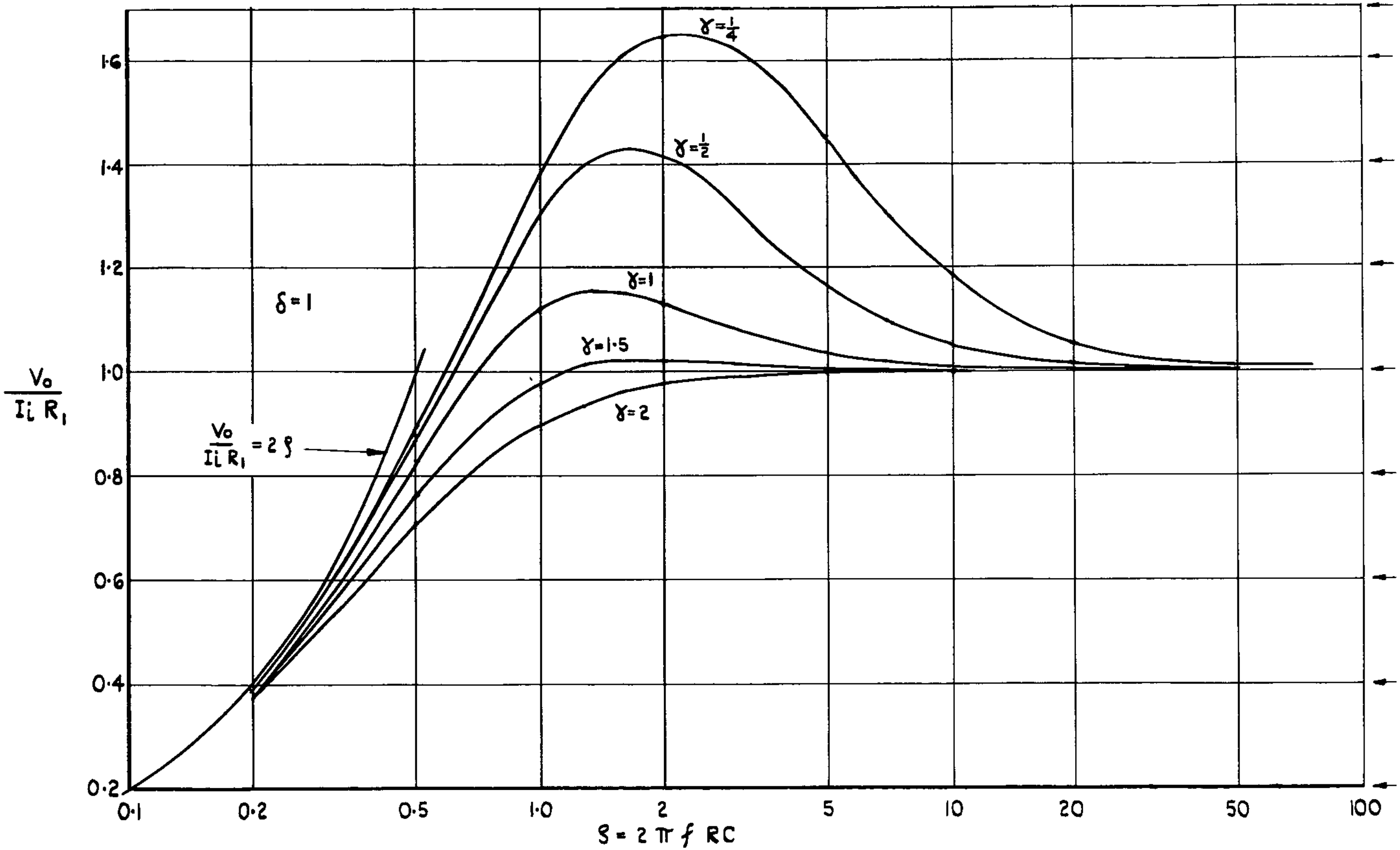


FIG. 15 FREQUENCY CHARACTERISTIC OF CIRCUIT OF FIG. 14 .

FIG.15

FIG.16

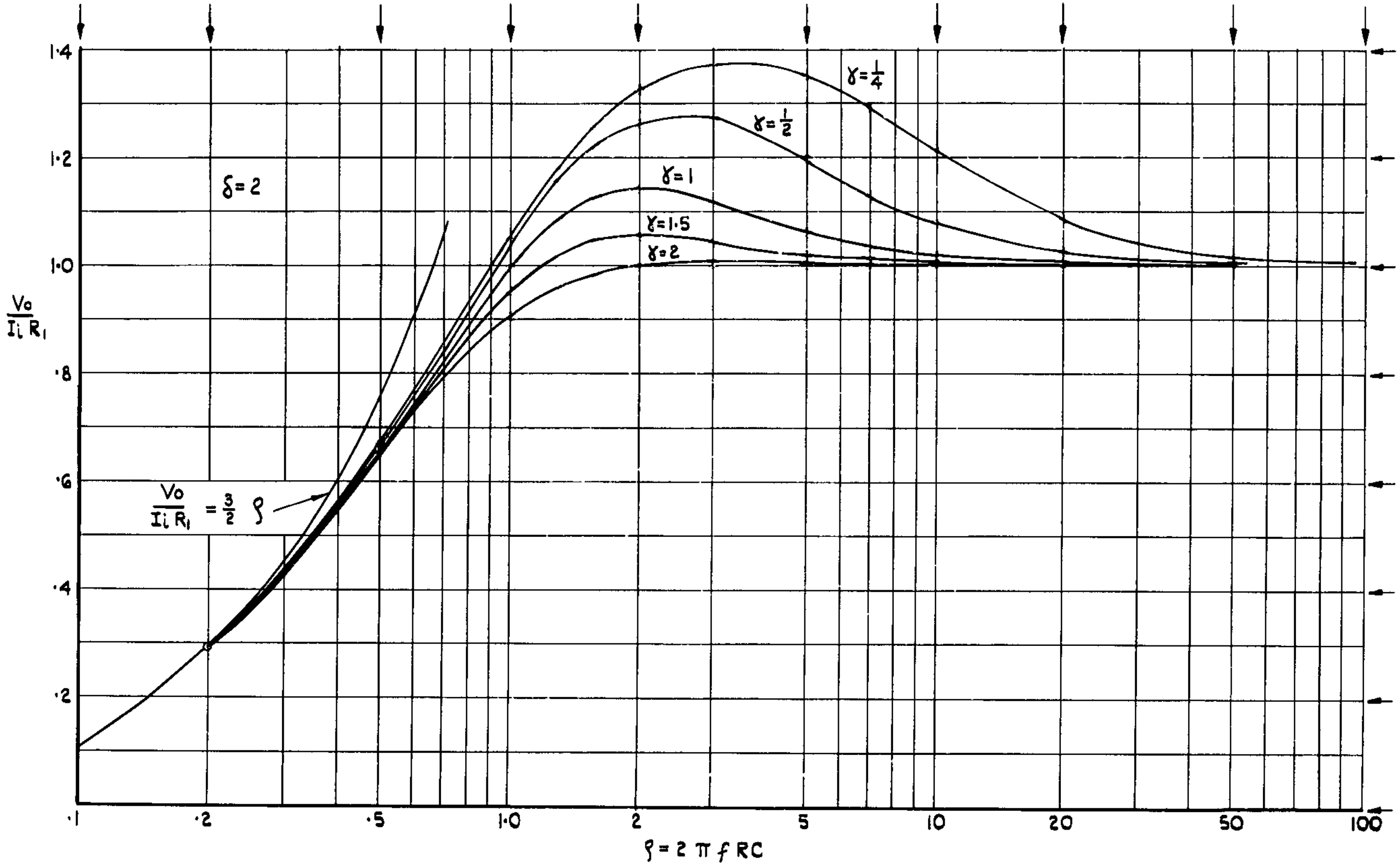


FIG. 16 FREQUENCY CHARACTERISTIC OF CIRCUIT OF FIG. 14

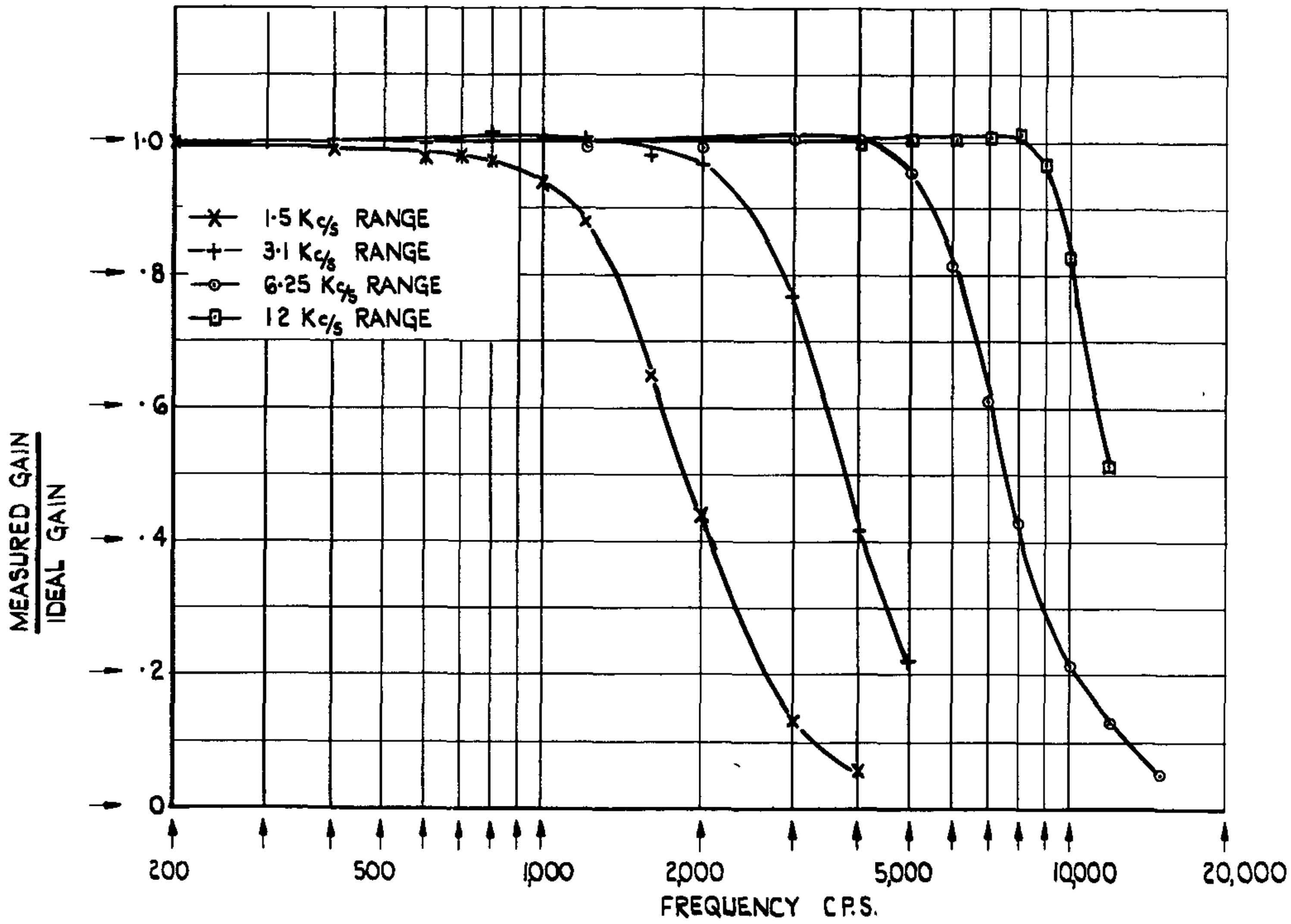


FIG. 17 FALLING OFF IN AMPLIFICATION FOR DIFFERENT FREQUENCY RANGES. (TIME CONSTANT IN AMPLIFIER 5·0m.s.)

FIG.17

FIG.18

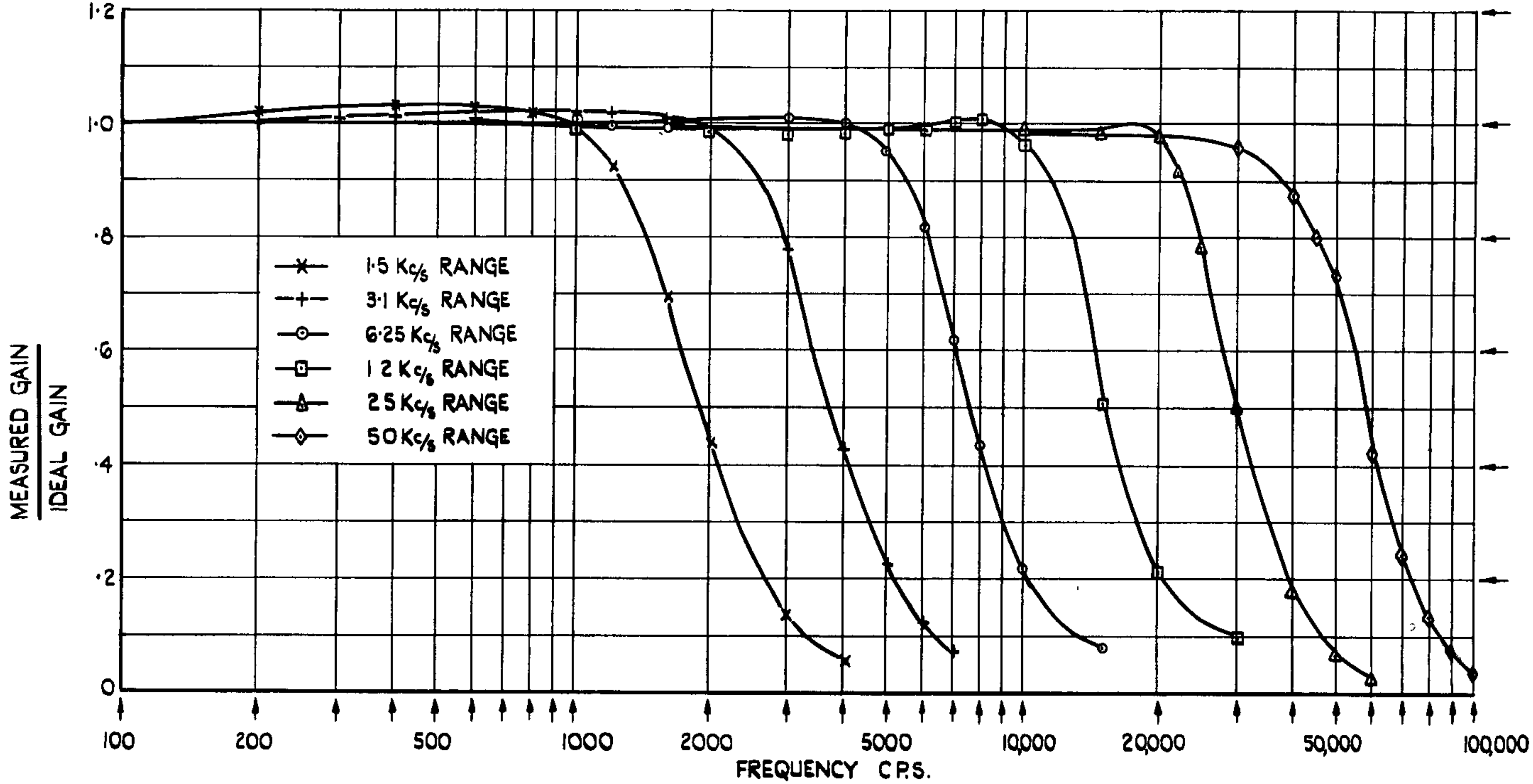


FIG. 18 FALLING OFF IN AMPLIFICATION FOR DIFFERENT FREQUENCY RANGES.
(TIME CONSTANT IN AMPLIFIER 1·0 m.s.)

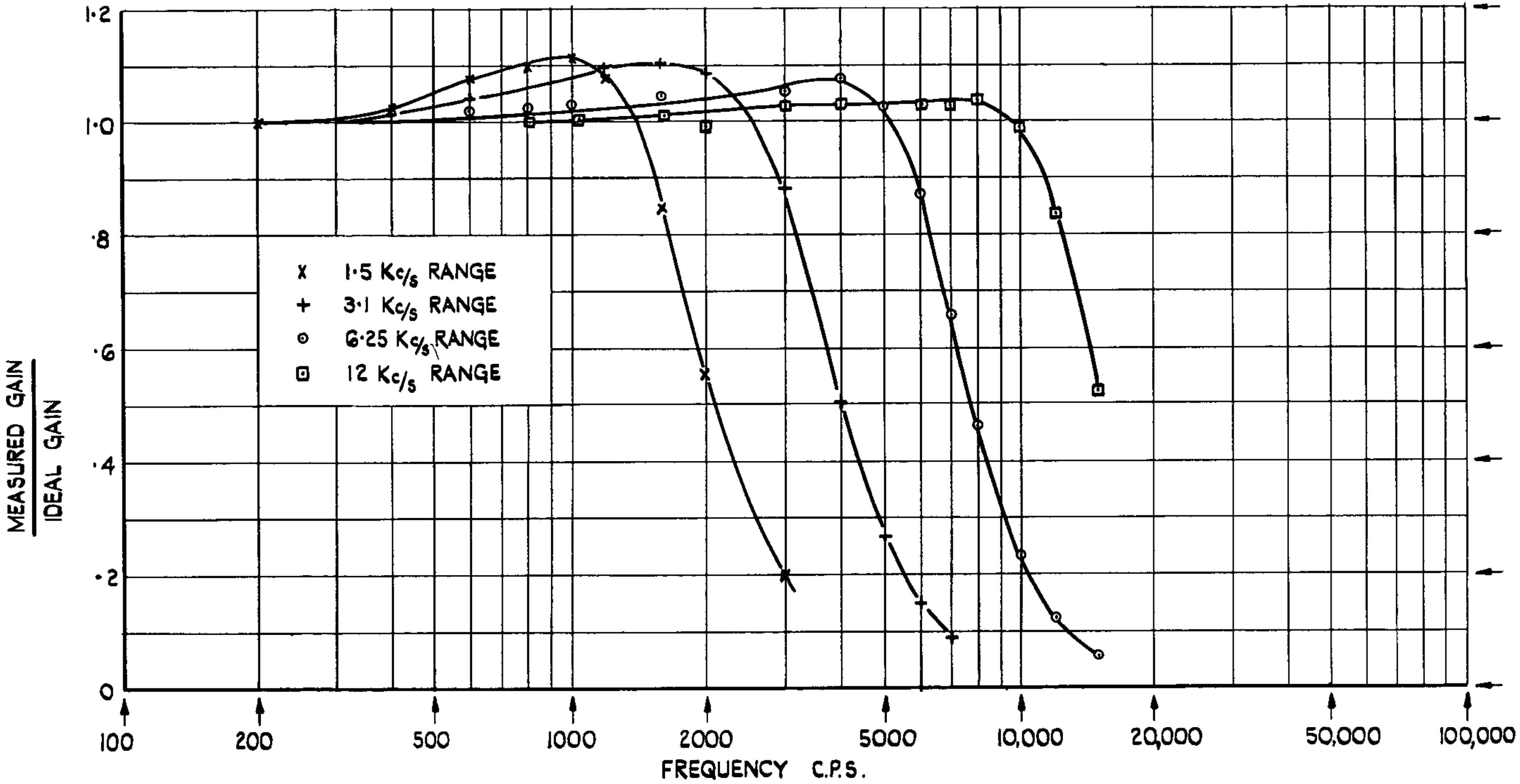


FIG. 19 FALLING OFF IN AMPLIFICATION FOR DIFFERENT FREQUENCY RANGES (TIME CONSTANT IN AMPLIFIER 0·2 m.s.)

FIG. 20

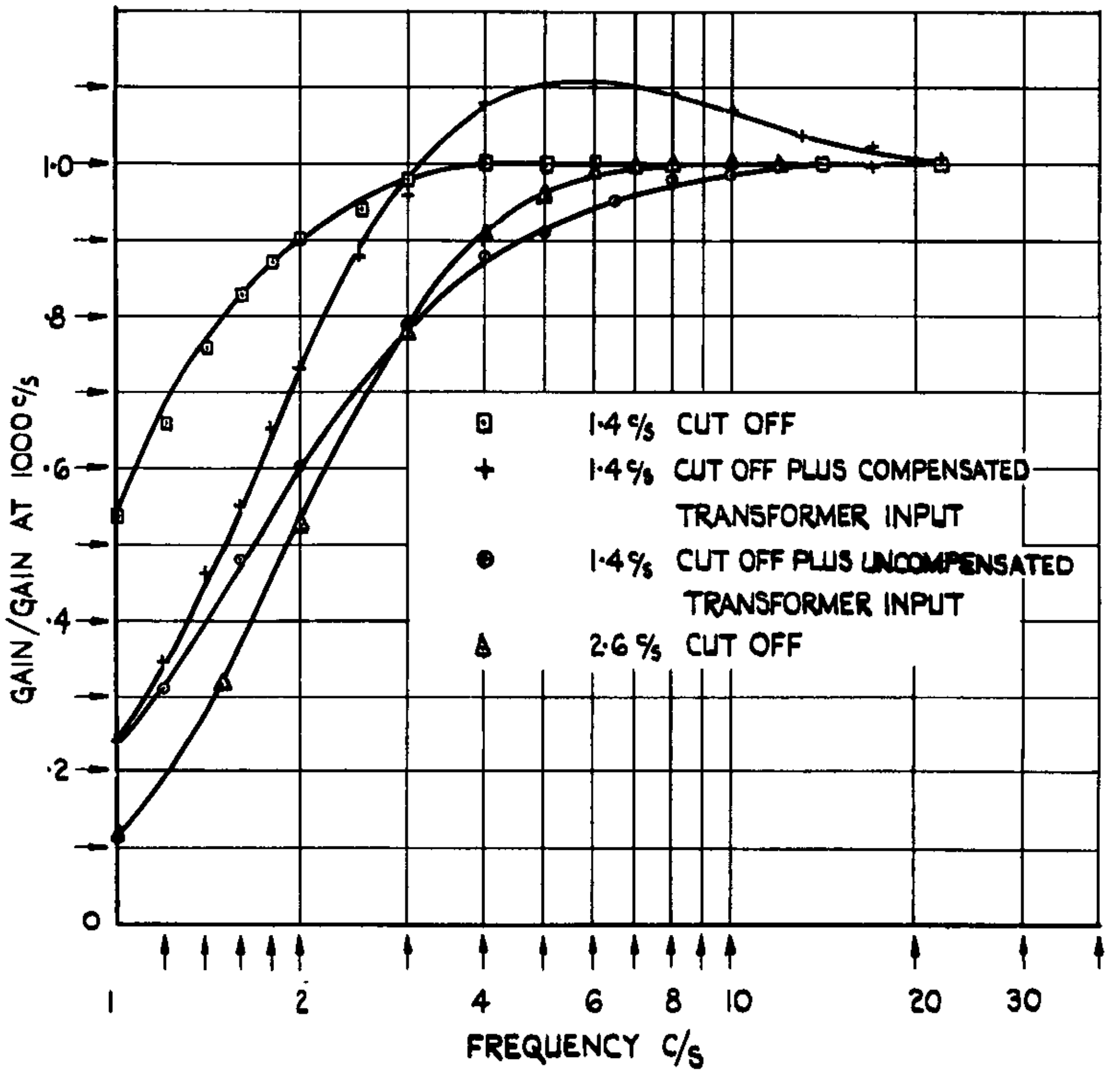


FIG. 20 LOW FREQUENCY CHARACTERISTICS OF AMPLIFIER.

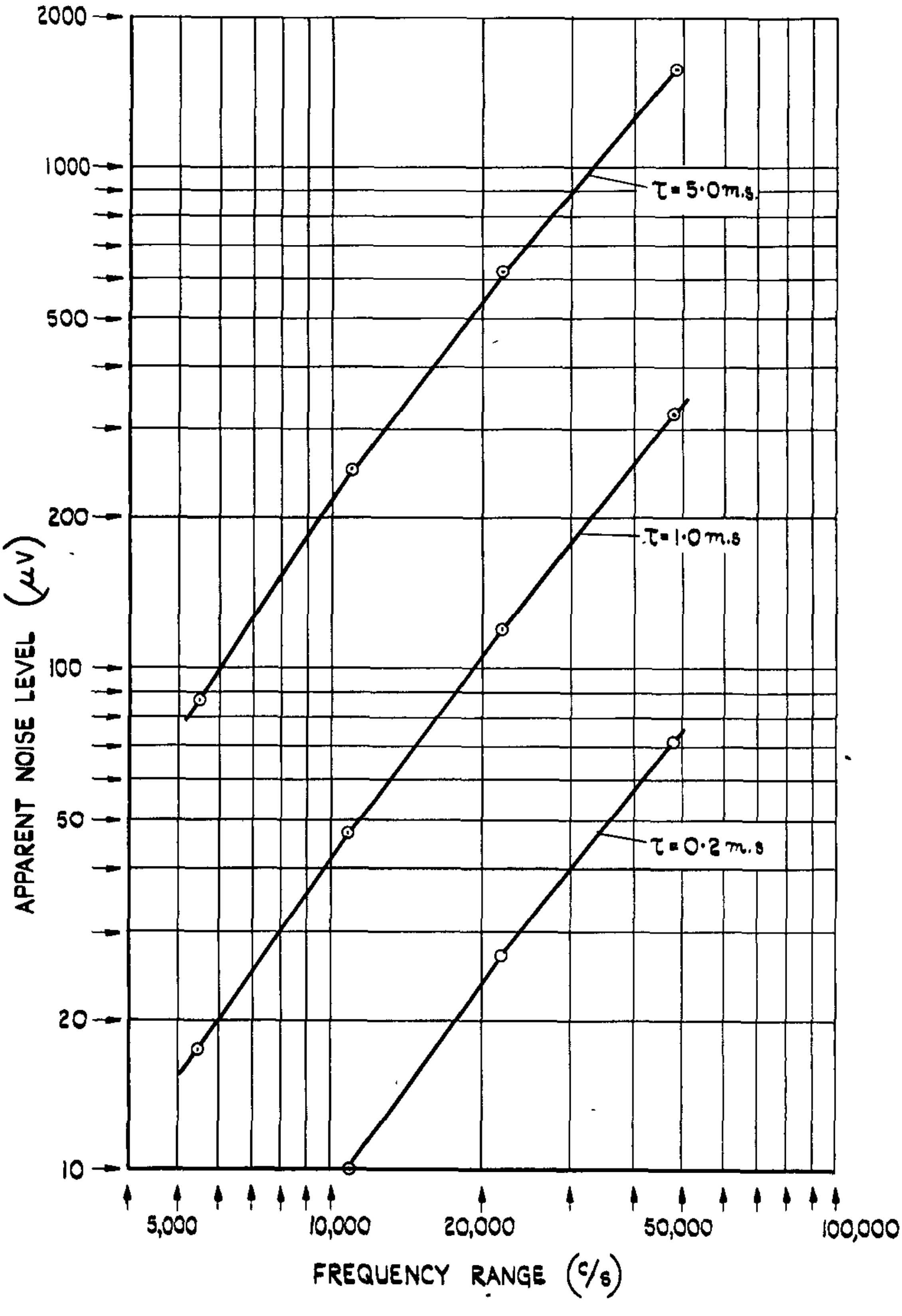


FIG. 21 APPARENT NOISE LEVEL OF AMPLIFIER

FIG 22

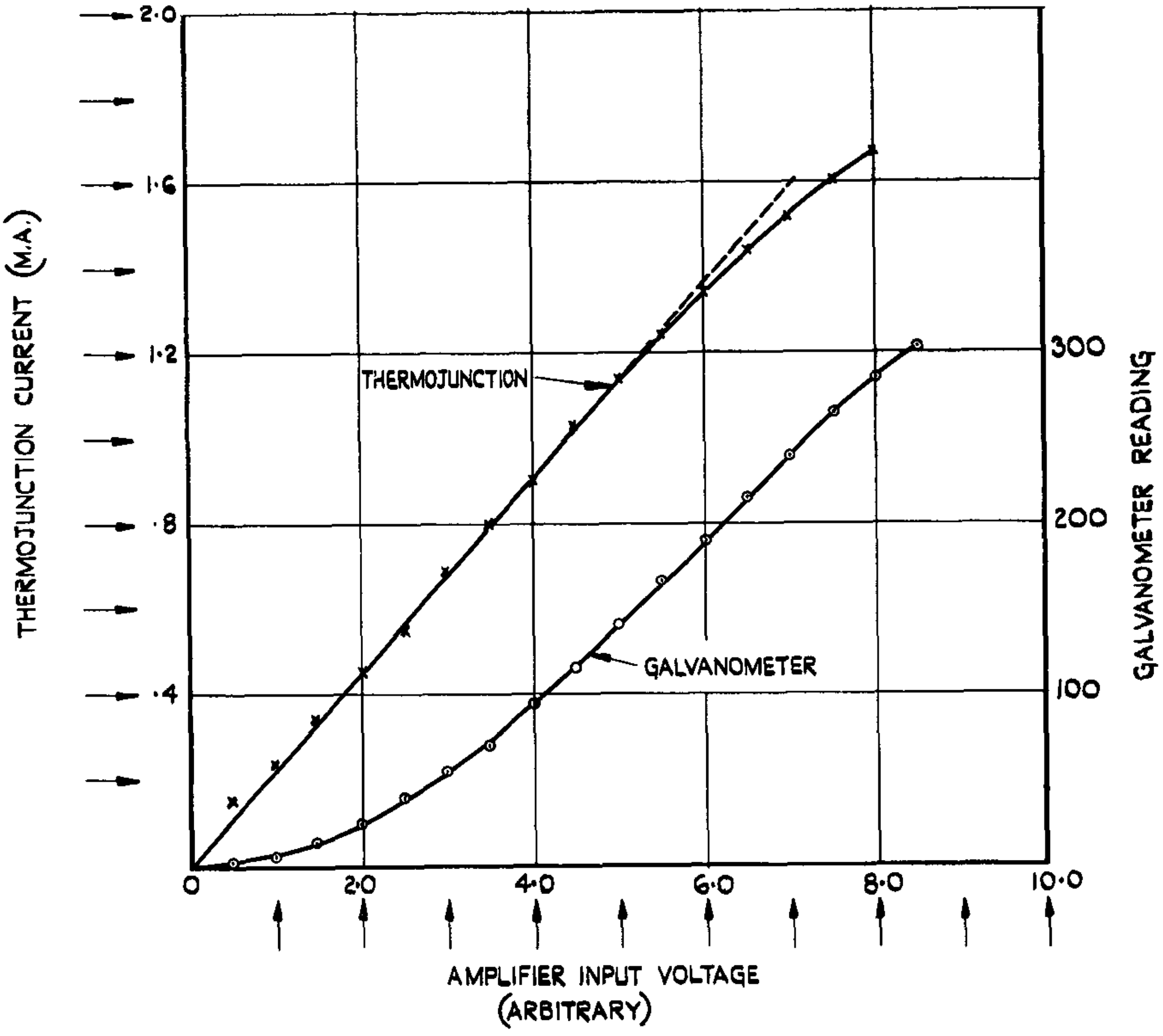


FIG.22 AMPLITUDE DISTORTION OF AMPLIFIER.

C.P. No. 198
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