THE PERFORMANCE OF AMPLIFIERS.

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SUMMARY.

The paper describes the researches which have been carried out at the National Physical Laboratory for the Radio Research Board. A standard method of testing the amplification and input impedance of an amplifier is described, and the theory of the load introduced by the amplifier as well as by reaction is shown to agree with the observed results.

Some preliminary experiments on distortion are described, output wave-forms from audio-frequency amplifiers being analysed.

TABLE OF CONTENTS.

INTRODUCTION.

An amplifier consists of several valves and coupling components connected in cascade, so that the total amplification effect obtained is the product of the various amplifications obtained in the individual stages. This definition excludes cases where retroaction effects from output to input via inter-electrode capacities or coupling of any type materially affect the overall amplification. In such cases the product of stage amplification is increased or decreased by such " reaction " effect. Although the ultimate output of an amplifier is in the form of power, we may regard all stages except the last as being pure potential magnifiers.

Strictly, each stage of an amplifier should perform the same function, though not of necessity in the same way. For instance, several types of coupling might be employed between two valves used for high-frequency amplification, yet if each stage is designed to amplify high-frequency E.M.F.'s, the whole series of stages would be regarded as an amplifier.

The term, unfortunately, has been extended in practice to apply to any combination of valves used for the purpose of amplifying, note-magnifying and/or rectifying, and any combination of valves fulfilling these varied functions is commercially regarded as an amplifier. For the sake of clarity such an arrangement will be termed an " amplification system," this term being more explicit than " mixed amplifier." The term " amplifier " will be applied only to a combination of components fulfilling the purpose of pure high-frequency or low-frequency amplification. Unless otherwise stated, the terms " amplifier " or " amplification system " will include all battery and output connections, i.e. it is the complete assemblage and not merely the instrument devoid of its outside circuits.

An amplification system must be of one of the following types :—

(*a*) High-frequency stages followed by a detector.
(*b*) A detector followed by low-frequency stages.
(*c*) High-frequency stages, a detector, and low-frequency stages.

In the determination of the behaviour of any given amplification system, it is found expedient to split it up into its independent sections and treat each part separately. The factor of voltage amplification for both high-frequency and low-frequency sections must be obtained at the frequencies required, and the detector law connecting input voltage and rectified output must be stated. The internal behaviour cannot be analysed if an overall input-output expression only is given.

The performance of any amplifier must be expressed in terms of three distinct properties :—

(1) Its voltage amplification.
(2) Its effect upon the circuit to which it is connected.
(3) Its distortion of wave-form.

These three properties are intimately related to each other, but the amount of experimental work carried out has been insufficient for an attempt to be made to correlate any one property with any other. Valve noises, which in a multi-stage audio-frequency amplifier usually determine the limiting number of cascade valves, are a special property of amplifiers and will not be dealt with here. Such noises are more a matter of valve design. The three essential characteristics are therefore treated separately at present.

A method of determining the voltage amplification of high-frequency or low-frequency amplifiers is described in detail, and the effect of the amplifier on the input circuits is analysed. With reference to the distortion produced by low-frequency amplifiers, the results of some preliminary experiments are given, but more information is needed before a complete study of distortion can be attempted. This Section is therefore very fragmentary, and is given in order to demonstrate the types of distortion met with in practice and to show the magnitude of the distortion that may be anticipated in practical cases.

Section 1. The Measurement of Voltage Amplification.

(a) *Practical difficulties.*—At first sight it would appear a comparatively simple matter to inject known E.M.F.'s to the input terminals of the amplifier, and measure these E.M.F.'s for a constant known output, but there are many difficulties which render such an operation exceedingly difficult.

In the first place, since the voltage amplification is critically dependent upon the filament emission and the high-tension voltage, it is desirable to adjust each valve of a cascade amplifier individually to give its optimum voltage factor. In practice, several filaments are bunched together and controlled by a coarse rheostat. It is therefore usually impossible to obtain the maximum output from any given set of triodes. Every disturbance of the original circuit, such as will be produced by the insertion of measuring instruments, will modify the characteristics and, if this insertion takes place between the input and output, the disturbance so produced may be very serious. This forms one of the major difficulties of measurement. Again, actual stage amplification is not constant for all inputs but appears to increase with weak inputs.

The output has either to be determined or kept constant, and, whatever method be adopted, the output must be measured in some way.

The determination of the amplification of the system is of value only when the E.M.F.'s and currents with which it is dealing are of the same order as those encountered in practical operation on a receiving antenna. The current in the telephones for an average type of signal is only of the order of micro-amperes, and such instruments as the Duddell reflecting thermo-galvanometer and electrostatic voltmeters can only be used for loud signals, failing completely to measure the feeble outputs required. Indirect methods such as the valve or crystal rectifier and "slide back" method give rather doubtful accuracy and always introduce not only shunting loads but large earth capacities due to the batteries forming the appendages of such auxiliary measuring circuits.

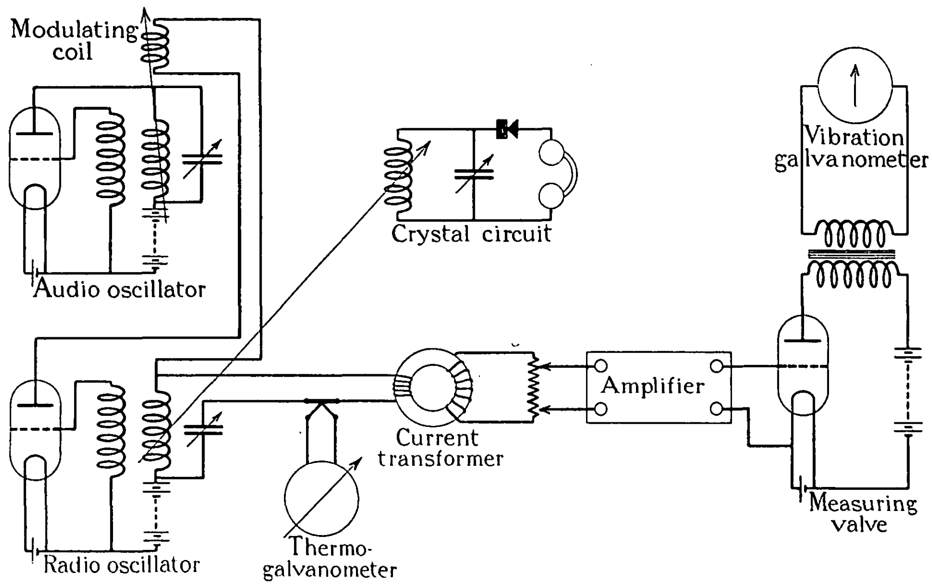

Fig. 1.

The method which has most often been adopted in this class of work consists of telephone comparisons. The difficulty of matching two sounds in intensity is well known, and limits the accuracy of such methods owing to the insensitivity of the human ear to small pressure-changes.

Again, perhaps the most serious difficulty in so matching telephone sounds lies in the fact that the pressure wave delivered to the ear is usually not sinusoidal and the type of wave given under the two balance conditions is dissimilar. It will be shown later that the output wave-forms from even the simplest type of single-stage amplifier are seriously distorted from the original sinusoidal input form, and it is quite true to state that the physiology of the human ear is so little understood that even if a balance is observed between two dissimilar waves, it is difficult to know what such a balance means.

Since such distortions of initial form take place throughout the amplifier, we are left with two methods of measurement :—

(i) The R.M.S. value of the output-current wave.
(ii) The value of the fundamental component of the complex wave.

Most measurements give (i), and it has been found only approximate to consider this value as representing the output. This determination requires also a knowledge of the wave-form to have much significance. However, if (ii) is measured, this does give the true amplification of the original wave due to the system, the harmonics produced being considered merely as the result of secondary effects which can be dealt with separately.

The methods of measuring amplification due to Jordan * and Napier-Smith † suffer by the adoption of a telephone comparison as the final limit of measurement. About 5 per cent. is the limit of accuracy with a trained observer, and many observations produce nerve strain upon the operator. The latter method of determination of small mutual inductances at high audio frequencies.

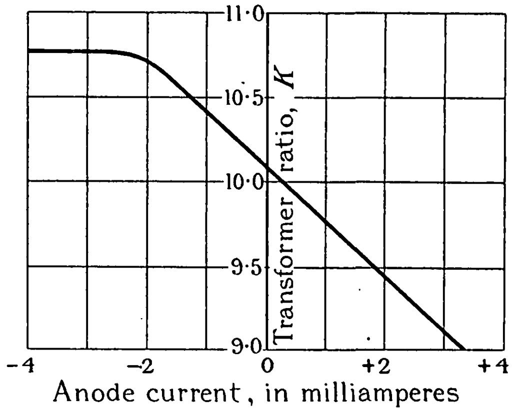

FIG. 2.

(*b*) *General method.*—The method adopted for measuring output employs a vibration galvanometer in connection with a current transformer, the resistance of the secondary of the transformer, which is in series with the galvanometer, being about equal to the sum of the motional and static resistances of the galvano-

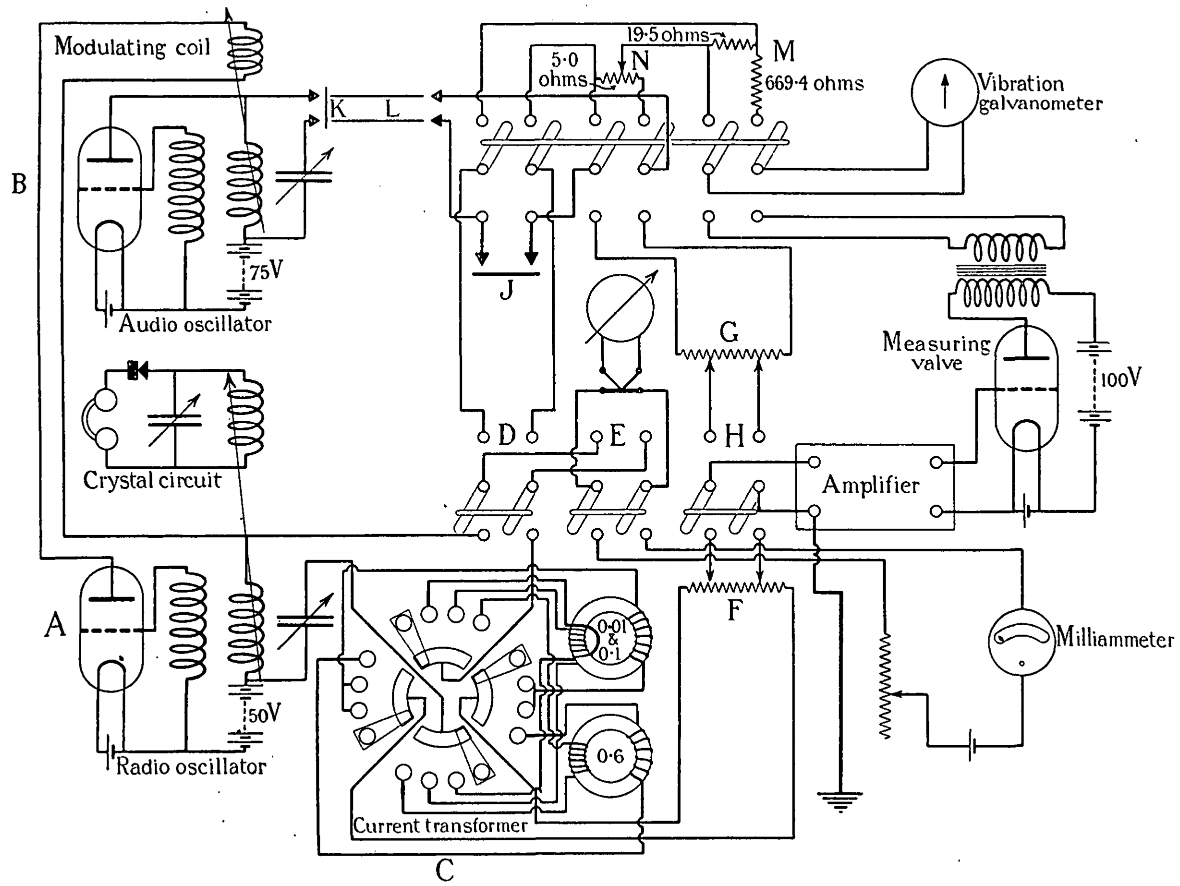

FIG. 3.

known mutuals cannot be applied to cases with very large step-up ratios, owing to the inaccuracy in the

* *Proceedings of the Physical Society of London*, 1919–20, vol. 32, p. 105.
† *Ibid.*, 1919–20, vol. 32, p. 116.

meter, the former being the largest portion of the effective galvanometer resistance.

Small, known E.M.F.'s cannot easily be obtained by a series of simple potentiometers, and thus a step-down radio-frequency current transformer * was adopted in conjunction with a calibrated high-frequency resistance potentiometer across the secondary. The current in the primary is measured by means of a thermo-junction and galvanometer. A ratio of E.M.F.'s of $1/10^5$ can be obtained by this method, the accuracy of measurement falling only towards the smaller values of injected voltage.

Since for the measurement of high-frequency amplifiers the output must be of audible frequency to operate the galvanometer, the radio output is modulated by means of an aperiodic coupling coil (coupled to an audio source) in series with the anode of the oscillator valve.

The general scheme of the apparatus is shown in Fig. 1. If the rectifier characteristic is required, a definite percentage of modulation is necessary. This is

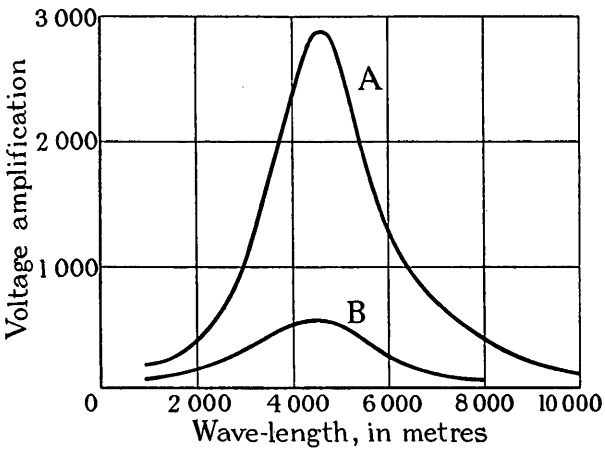

Fig. 4.

provided for by always setting the aperiodic coupling coil to give complete (or 100 per cent) modulation. The method of determining this condition is by means of a local tuned crystal receiving circuit coupled to the radio oscillator. When the source is over-modulated, a second harmonic is easily detectable in the rectified current as observed by telephones, and the point where this just vanishes gives the completely modulated condition. Tests with an electrostatic voltmeter demonstrate that this point can be determined audibly with accuracy.

The galvanometer can be calibrated directly from the audio source, and the current transformer is also calibrated for ratio, the combination forming a method of measuring the output current at the particular frequency of 1 000 which represents an average for telegraphic signals. The calibration of the transformer is dependent upon the d.c. anode current flowing through the primary, as the characteristic working point on the *B-H* curve is altered by such current. Fig. 2 gives the calibration of this transformer and shows what large

* D. W. Dye: "Producing Small Voltages at Radio Frequencies," *Journal I.E.E.*, 1925, vol. 63, p. 597.

changes in ratio can be expected from comparatively small polarizing anode currents.

For the determination of high-frequency voltage amplification a constant modulation is all that is required, the calibration of the galvanometer being necessary only for the absolute determination of the rectifier characteristic.

To determine the amplification factor of the audio stages, the audio source is injected directly by means of a potentiometer with a known shunt, and the output is measured as before. It was found that the current sensitivity of the vibration galvanometer varied considerably and thus a quick-switching arrangement was devised by means of which the galvanometer could be directly calibrated from the audio source in terms of a vacuo-junction deflection, which in turn could be instantly calibrated by direct current and a milliammeter. In this way, both input and output can be referred directly to a d.c. instrument, and errors due to inconstancy of calibration are eliminated.

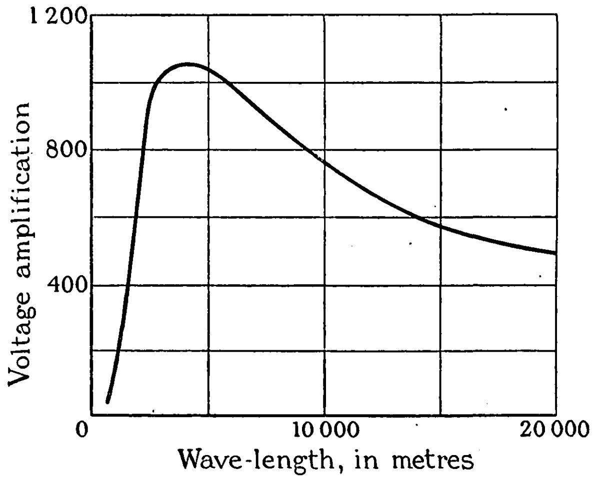

Fig. 5.

The final arrangement with complete switchgear is shown in Fig. 3. The radio and audio oscillators are shown at A and B respectively. The three high-frequency transformer ratios are controlled by switch C. The thermo-junction can be inserted into either the radio or audio source by means of switch D, and can be calibrated by means of switch E. The radio potentiometer F or the audio potentiometer G can be switched on to the amplifier by means of switch H. When the three double-pole interlocked switches are in the lower position the galvanometer is connected to the output, whereas in the top position it is connected directly to the audio source for calibration. Switch J is closed for calibration and works on the interlock. Switch K closes the audio source for radio modulation and L permits the source to be used for audio injection or galvanometer calibration. The standard shunts are shown at M, and the potentiometer N is used for calibration.

Both high-frequency and low-frequency amplifiers forming part of an amplification system can be quickly measured by this means. The only difficulty lies in the direct induction due to the source at a considerable distance from the amplifier under test. This difficulty was almost entirely eliminated by sheathing all the radio oscillator leads in copper tubing.

(c) *Discussion of results obtained.*

High-frequency amplifiers.—So far as high-frequency amplification is concerned, it seems apparent from the results obtained that the net effect of the many factors which can only be approximated in design gives very variable figures for amplification. As an example, two apparently identical 3-stage amplifiers, transformer coupled, were measured, with the results shown in Fig. 4. In curve A, the factor per stage at a wave-length of 4 700 m is considerably greater than the factor of the triode. It is apparent that, in this case, retroaction effects combine to increase the overall amplification, whereas in curve B the phasing is such as to reduce the amplification. Since such retroactive effects form an inherent property of any amplifier and are dependent upon inter-electrode capacities, stray lead capacities and leaks, it is reasonable to expect large variations between amplifiers built to similar specifications.

Fig. 5 gives the overall voltage amplification of a 6-stage resistance capacity amplifier, from which it will be noticed that below 4 000 m the shunting effect due to the self-capacity of the anode resistances seriously reduces the amplification. The more gradual fall at higher wave-lengths is attributed to the fact that the coupling condensers are not large enough at the lower frequencies.

Fig. 6 gives the amplification of a 6-valve untuned transformer-coupled amplifier with various inputs on the grid, from which it will be observed that the amplification appears to fall with increasing input.

It has been stated by several authorities that the voltage amplification falls with weak inputs, but the inputs for which this effect is claimed are of the order of a few microvolts and are smaller than any input measured here. The curve shown in Fig. 6 may therefore bend back to the origin, but no measurements have been taken to confirm this. The evidence for this effect may depend upon distortion which will seriously affect the R.M.S. value of the current and may not be a genuine reduction of amplification of the fundamental. The discrepancies arising due to a neglect of the harmonics present may be, as shown later, very serious.

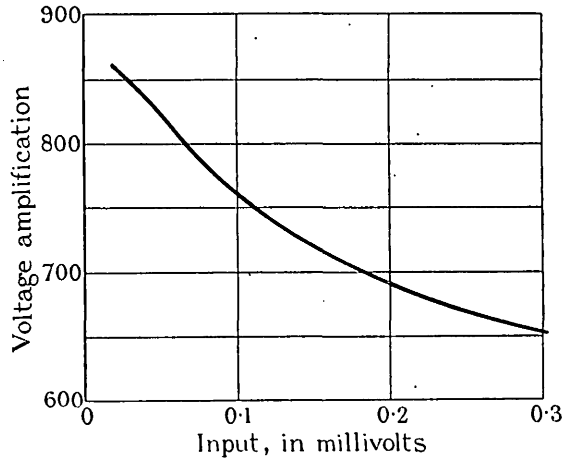

FIG. 6.

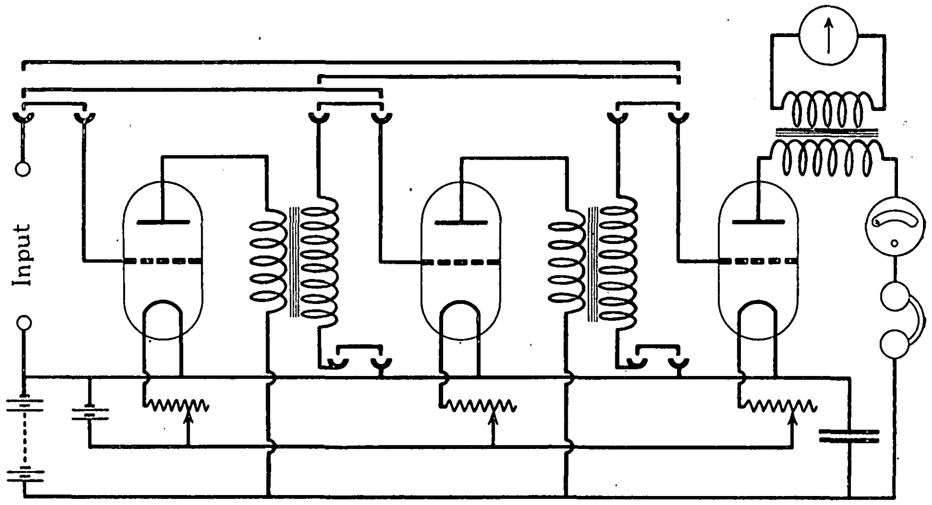

FIG. 7.

The behaviour of the detecting valve has been found in every case to depart only very slightly from the theoretical square law; in fact this law can in most instances be assumed.

Low-frequency amplifiers.—The measurement of the voltage amplification of a low-frequency amplifier presents less difficulty. The inter-electrode impedances at low frequencies are large and their shunting effects almost negligible. Induction can be entirely eliminated with care, and measurements to less than ½ of 1 per cent can be obtained.

Several standard audio amplifiers were tested at a frequency of 1 000, and it was found that the overall amplification of several cascade stages was less than the product of the individual stages. A special experimental 2-stage amplifier was built and with this it was found that very consistent results could be obtained.

The amplifier output was measured by means of a special calibrated measuring valve as shown in Fig. 7. By means of links and mercury cups, the input could be switched on to the measuring valve, stage 1 and the measuring valve, or stage 1, stage 2 and the measuring valve. The voltage amplification of each stage was in this way compared with the overall amplification of the two stages in cascade. With definite high tension, low tension and grid bias, the amplification of stage 1 was found to be 21·9, and of stage 2, 19·65. When these two stages were coupled together, the first gave 22·2 and the second 19·2, the overall amplification thus being 426 for the two stages in cascade.

This means a gain of 1 per cent on the first stage, due to retroaction from the second and to a weaker input, and a loss of 2 per cent on the second due to the fact that the input wave-form to this valve is now no longer sinusoidal. The overall loss for the two stages is 1 per cent, the theoretical figure being 433, the product of the two initial determinations.

The Smith-Napier method of testing gave 21 for each stage and thus shows good agreement with a poorer sensitivity. The effect of the high-tension condenser of several microfarads was found to be very pronounced, the amplification falling considerably when a smaller condenser was used. This effect is probably due to the resistance of the high-tension battery.

The effect of inserting a small capacity of 100–1 000 $\mu\mu$F between the two windings of the transformer is slightly to increase the amplification, due to the increase in the electrostatic coupling between the windings. A capacity of 1 000 $\mu\mu$F increased the amplification by 5 per cent.

These tests show that it is possible to construct a 2-stage amplifier in which little loss takes place, if the components are judiciously separated. The maximum figure of 420 may be obtained, if separate high-tension batteries be used for each stage without the use of a high-tension condenser. Separate low-tension batteries produce an increase of 4 per cent in overall amplification.

Section 2. The Input Impedance of an Amplifier.

(*a*) *Discussion of methods of measurement.*—The effect of the amplifier upon the tuned input circuit is twofold, viz.—

(*a*) To increase or decrease its effective resistance, due to the power taken from (or delivered to) this circuit by the valve amplifier.

(*b*) To alter the tuning of the circuit due to the shunt capacity of the input circuit of the amplifier.

The amplifier may be looked upon as an impedance load across the tuned circuit. To determine this load it is necessary to find the effective change in the high-frequency resistance of the resonant circuit as well as the shift in the resonant frequency due to the amplifier.

The usual method of determining the high-frequency resistance of the tuned circuit consists of inserting a known non-inductive resistance into the circuit and determining the fall of current in that circuit, or the fall in voltage across the circuit. If the voltage across the condenser is V before insertion and V_r when a resistance R is inserted, we have

$$\frac{V}{V_r} = \frac{R_e + R}{R_e}$$

where R_e is the circuit resistance.

Very inconsistent results were obtained with this method, often of the order of 100 per cent. These errors are attributed to the fact that the mechanical shape of the tuned circuit is modified by the insertion, and the effective E.M.F. in the circuit was so varied.

It appears that with large currents and low amplification the E.M.F. can be inserted virtually at one

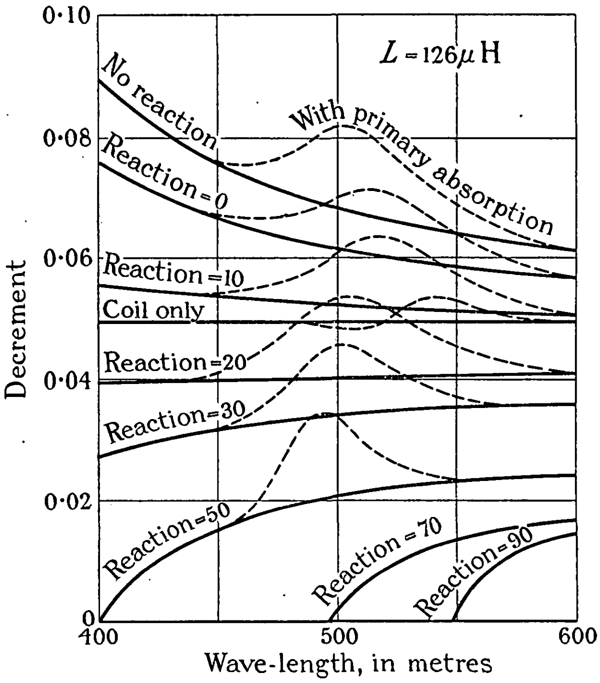

FIG. 8.—Decrement curve: stud 2.

point in the resonant circuit (as in the case of a deliberately inserted inducing coil), thus approaching the ideal theoretical conditions, but when the injected E.M.F. is very small and is picked up by a stray field in the neighbourhood of the amplifier, the injected E.M.F. will vary materially with any changes in the mechanical formation of the circuit. The "feed-back" effect due to retroaction is dependent upon the resistance of the input circuit, and any artificial change in this resistance will modify the amplifier condition.

When a 6-stage high-frequency amplifier is used, the injected E.M.F. is so small that direct pick-up induction from the oscillator is sufficient to give large outputs. In this particular case the injected E.M.F. was of the order of 1 mV to give a weak signal of about 6 μA in the output circuit, the field from a weak oscillator 15 ft. away being sufficient for this output. Such distant injection has the advantage that the tuned circuit is in no way modified by local coupled circuits.

The inserted-resistance method had therefore to be abandoned when such weak signals were being dealt with. A resonant method of determining the high-

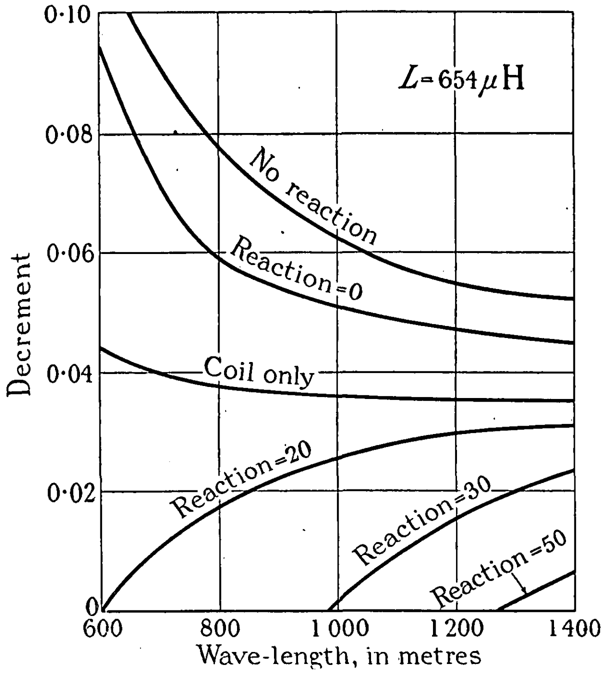

FIG. 9.—Decrement curve: stud 3.

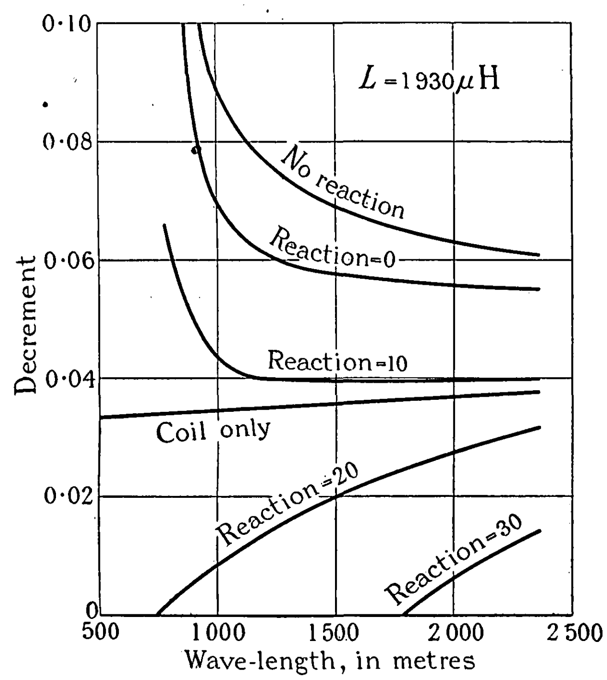

FIG. 10.—Decrement curve: stud 4.

frequency resistance had therefore to be resorted to and it was found that this method gave very excellent results.

(*b*) *The resonance method of measuring the effective resistance of an oscillatory circuit.*—If the resonance curve of a tuned circuit is obtained, the decrement of the circuit is given by either of the following formulæ:—

$$\delta = \pi\frac{C_r - C}{C}\sqrt{\frac{1}{(I_r/I)^2 - 1}} \quad . \quad . \quad . \quad (1)$$

where C_r and I_r are the values of capacity and current

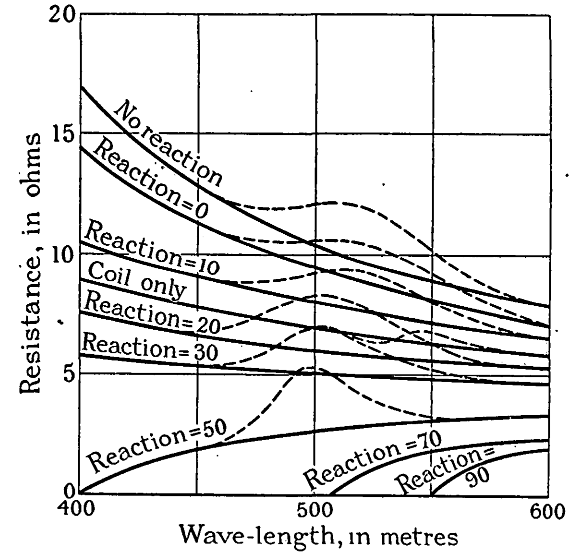

FIG. 11.—Resistance curve: stud 2.

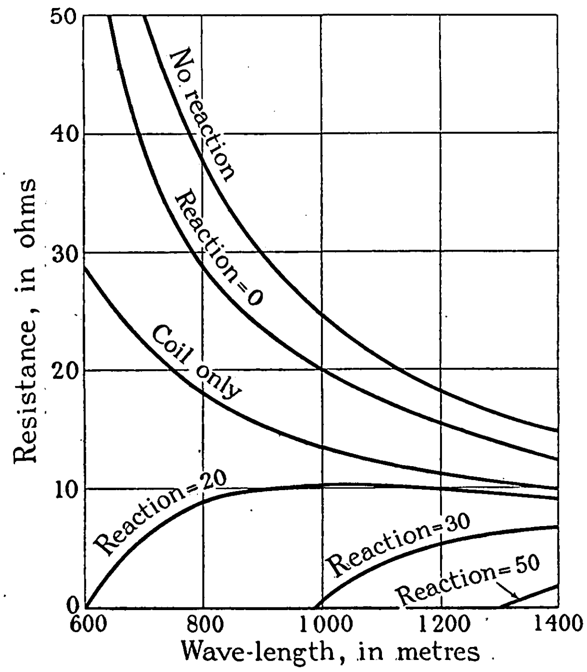

FIG. 12.—Resistance curve: stud 3.

at resonance, and C and I are values at any other point on the curve, or

$$\delta = 2\pi\frac{f - f_r}{f_r}\sqrt{\frac{1}{(I_r/I)^2 - 1}} \quad . \quad . \quad . \quad (2)$$

where f_r and f are the frequencies at resonance and any other point respectively.

If a constant-frequency source be applied to the tuned circuit, and its tuning condenser be altered, a

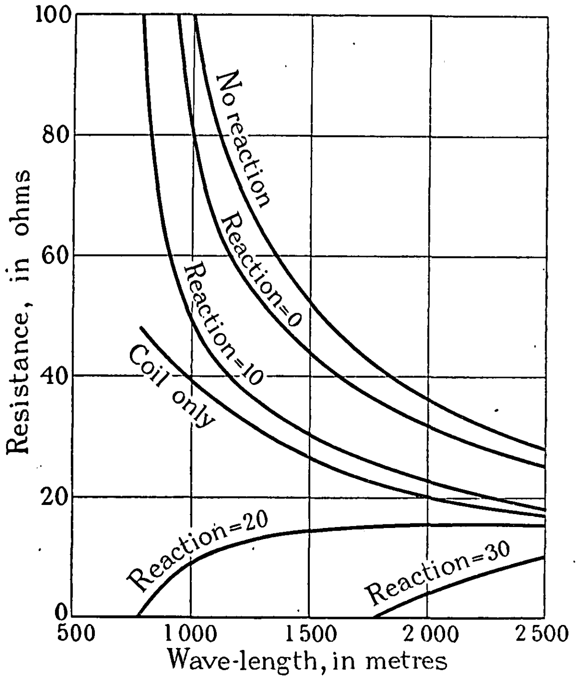

FIG. 13.—Resistance curve: stud 4.

resonance curve can be plotted. This method, however, means a calibration of the tuned circuit condenser, which forms part of the losses to be measured and also

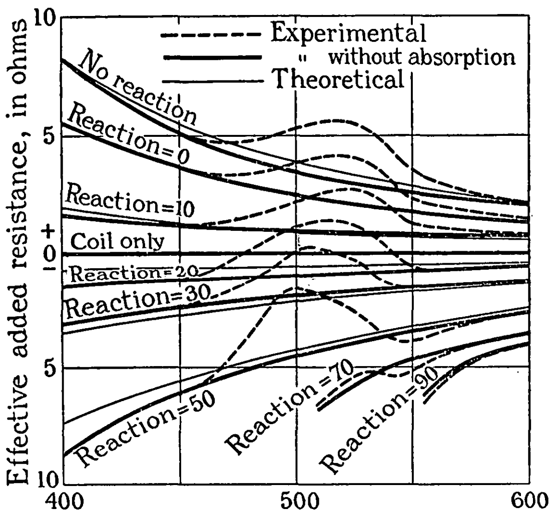

FIG. 14.—Effective added resistance due to amplifier: stud 2.

slightly disturbs the amplifier conditions. The proximity of an operator also seriously modifies the injecting field.

For these reasons, therefore, it was thought preferable to keep the test-circuit constant and to vary the input frequency. As the resonance curve is obtained with changes of less than 1 per cent in frequency, great accuracy of oscillator constancy and calibration is required.

An oscillator was therefore built with a standard condenser and a special 40 $\mu\mu$F condenser in parallel. This condenser was controlled at a distance of several feet and was calibrated to $0 \cdot 1$ $\mu\mu$F. The self-capacity of leads and coils was measured and thus the value of C_r was accurately known. The rectifier was found to follow a square-law curve to within $\frac{1}{5}$ of 1 per cent and therefore the vibration galvanometer scale was modified to a square law, thus saving much labour in calculation.

It was found possible to plot resonance curves with this apparatus quickly and with a remarkable accuracy.

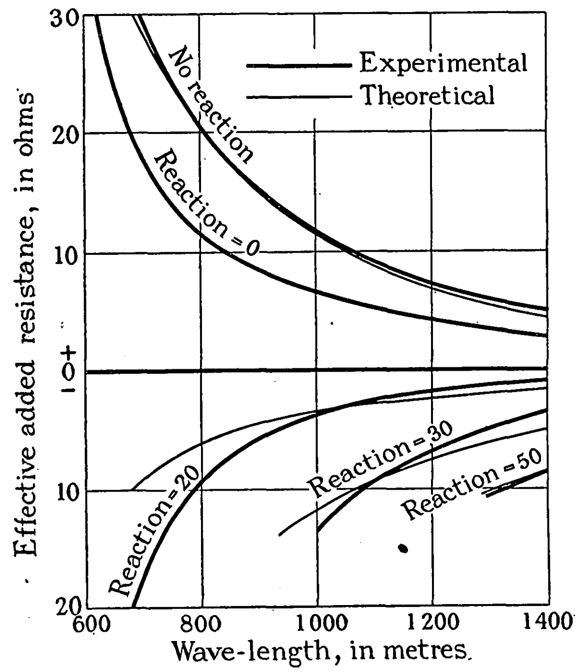

FIG. 15.—Effective added resistance due to amplifier: stud 3.

Of a total of about 300 such curves, the average error between several determinations of decrement from one curve was not greater than 1 per cent and the individual error was never greater than 5 per cent. Many interesting and important points would have been missed if a more approximate method had been adopted.

(c) *The effective load on the resonant circuit due to the amplifier.*—Decrement curves obtained for three inductance ranges are shown in Figs. 8, 9 and 10. These curves do not diverge by more than $\frac{1}{2}$ of 1 per cent from the actual points taken. In Fig. 8 a peculiar absorption is noted at a wave-length of 505 m, which occurs at all settings of reaction. This is due to the natural wave-length of a very loosely coupled aerial tuning coil which forms part of the tuning panel.

The decrement of the tuned circuit without an amplifier is also shown, this being determined by plotting resonance curves as before with a vacuo-junction in series as a recording instrument, the source being a powerful calibrated oscillator.

From these curves the resistance of the circuit was plotted, since $\delta = R/(2fL)$, where R = resistance, f = frequency, and L = inductance of tuned circuit, in henrys. These curves are shown in Figs. 11, 12 and 13. By taking the resistance of the circuit (without the amplifier) as datum and plotting the change in effective resistance with various reaction settings, the curves shown in Figs. 14, 15 and 16 are obtained. They represent the effective added positive or negative resistance produced by the amplifier for different settings of the reaction coil and at different frequencies.

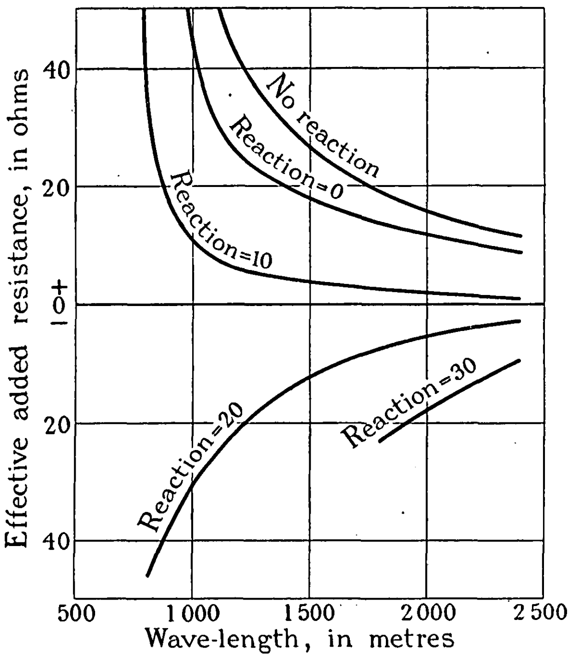

FIG. 16.—Effective added resistance due to amplifier : stud 4.

The following points are at once noticed :—

(1) The effective resistance load cannot change sign at varying frequencies.
(2) All curves appear to bear a definite mathematical relationship to each other.
(3) The departures from the mean form of the curves occurs only near to oscillation, when instability occurs.

In most of the cases given, oscillation may be obtained when the tuning condenser is very small, i.e. the curve may suddenly bend back and give a negative resistance. As this period was always unstable, it was deemed unwise to consider these conditions in the curves.

(*d*) *Theoretical treatment.*—Miller's analysis * of the effect of an amplifier on an outside circuit cannot conveniently be adapted to frequency variations. The theory has therefore been attacked from first principles, and practical expressions have been obtained for the particular cases under consideration.

The amplifier may be considered as a resistance and capacity in series acting as a load across the tuned circuit. Since the effect of this load is always positive without reaction, the resistance must also be positive. Let R_1 and C_1 be the effective resistance and capacity respectively of the amplifier input circuit. We have to find R_1 and C_1 in terms of the effective increase of resistance, ΔR, in the tuned circuit, the initial high-frequency resistance of which is R. In the vector diagram shown in Fig. 17, E_c and I_1 represent the E.M.F. and current in the branch circuit, the leading angle being ϕ_1. The main current I will equal the vectorial sum of I_1 and $I_c = E_c\omega C$. The increased E.M.F. due to the load is $I\Delta R = E_c \sin\theta$, and the resonant condition is fulfilled when $\omega LI = E_c \cos\theta$, the effect of the load thus being to alter the value of C to tune to any definite frequency.

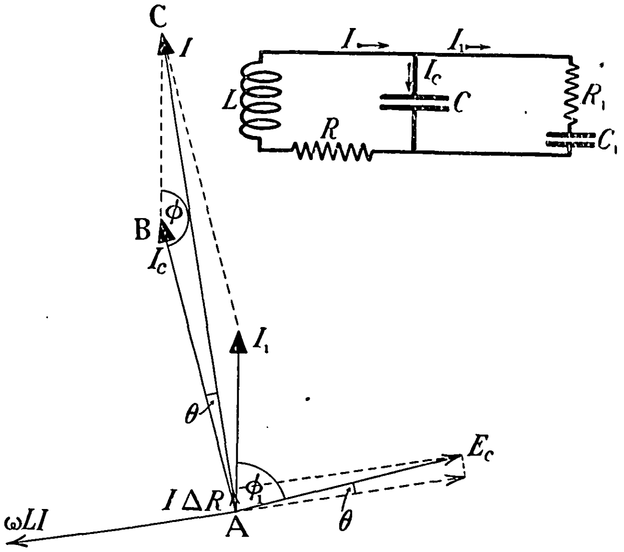

FIG. 17.

From the triangle A B C we have

$$\frac{I_1}{I} = \frac{\sin\theta}{\sin\phi} = \frac{\sin\theta}{\cos\phi_1} \text{ (since } \phi_1 = \phi - \tfrac{1}{2}\pi)$$

$$I_c = E_c\omega C = I_1 Z\omega C$$

where $Z = \sqrt{[R_1^2 + (1/\omega C_1)^2]}$ and $E_c \cos\theta = \omega LI$ at resonance,

$$E_c = \frac{\omega LI}{\cos\theta} = I_1 Z$$

$$\therefore \frac{I_1}{I} = \frac{\omega L}{Z\cos\theta} = \frac{\sin\theta}{\cos\phi_1}$$

Now $$\sin\theta = \frac{\Delta R}{\sqrt{[\Delta R^2 + (\omega L)^2]}}$$

$$\cos\theta = \frac{\omega L}{\sqrt{[\Delta R^2 + (\omega L)^2]}}$$

and $$\cos\phi_1 = \frac{R_1}{\sqrt{[R_1^2 + (1/\omega C_1)^2]}} = \frac{R_1}{Z}$$

$$\therefore \frac{\omega L}{Z} = \frac{\sin\theta\cos\theta}{\cos\phi_1} = \frac{\Delta R\omega LZ}{\{\Delta R^2 + (\omega L)^2\}R_1}$$

$$\therefore R_1\{\Delta R^2 + (\omega L)^2\} = \Delta RZ^2$$

$$\therefore \Delta R^2 R_1 - \Delta RZ^2 + R_1(\omega L)^2 = 0$$

* "Dependence of the Input Impedance of a Three-Electrode Vacuum Tube upon the Load in the Plate Circuit," *Scientific Papers of the Bureau of Standards*, No. 351.

Solving this quadratic, we get

$$\Delta R = \frac{Z^2 \pm \sqrt{[Z^4 - 4(R_1\omega L)^2]}}{2R_1}$$

$$= \frac{Z^2}{2R_1}\left[1 \pm \left\{1 - 4\left(\frac{R_1\omega L}{Z^2}\right)^2\right\}^{\frac{1}{2}}\right]$$

and, since $\left(\frac{R_1\omega L}{Z^2}\right)^2$ is small compared with unity

$$\Delta R = \frac{Z^2}{2R_1}\left[1 \pm \left\{1 - 2\left(\frac{R_1\omega L}{Z^2}\right)^2\right\}\right]$$

$$= \frac{Z^2}{2R_1} \times \frac{2(R_1\omega L)^2}{Z^4}$$

$$= \frac{R_1(\omega L)^2}{Z^2}$$

if the plus sign $\left(\text{which gives } \Delta R = \frac{Z^2}{R_1} \doteq 10^9\right)$ is neglected,

$$\therefore \Delta R = \frac{R_1(\omega L)^2}{R_1^2 + [1/(\omega C_1)]^2}$$

To find R_1 and C_1 for given values of ΔR, L and ω, we solve the two simultaneous equations given by

$$R_1^2\Delta R - R_1(\omega L)^2 + \Delta R/(\omega C_1)^2 = 0$$

In Fig. 14, taking the curve of no reaction, we find that $\Delta R = +\,8\cdot25$ ohms at 400 m and $+\,2\cdot15$ ohms at 600 m. From these values we get $R_1 = 20\ 800$ ohms, and $C_1 = 9\cdot9\ \mu\mu$F.

Substituting these values in the general expression we obtain a theoretical curve; the correlation with the experimental being within 10 per cent.

A few of the values obtained are given in Table 1.

TABLE 1.

Wave-length	ΔR (theoretical)	ΔR (experimental)
m		
400	8·25	8·25
450	5·50	5·20
500	3·90	3·50
550	2·87	2·60
600	2·15	2·15

TABLE 2.

Wave-length	ΔR (theoretical)	ΔR (experimental)
m		
700	28·95	29·0
800	20·8	20·4
900	15·03	15·4
1 000	11·92	11·8
1 100	9·26	9·2
1 200	7·28	7·3
1 300	5·82	6·0
1 400	4·67	5·2

In Fig. 15 we get $R_1 = 87\ 600$ ohms and $C_1 = 9\cdot0\ \mu\mu$F. The values obtained from them and the theoretical curve are given in Table 2.

The positive load introduced by the amplifier can therefore be expressed in terms of a definite resistance and capacity, this capacity appearing to remain constant at all frequencies and values of the inductance in the resonant circuit. However, the resistance values obtained were found to differ for various values of L as follows :—

L	R_1
$\mu\mu$H	ohms
126	20 800
654	87 600
1 930	249 000

The value of R_1 increases with L and approximately follows the law $R_1 \propto L^{0\cdot8}$.

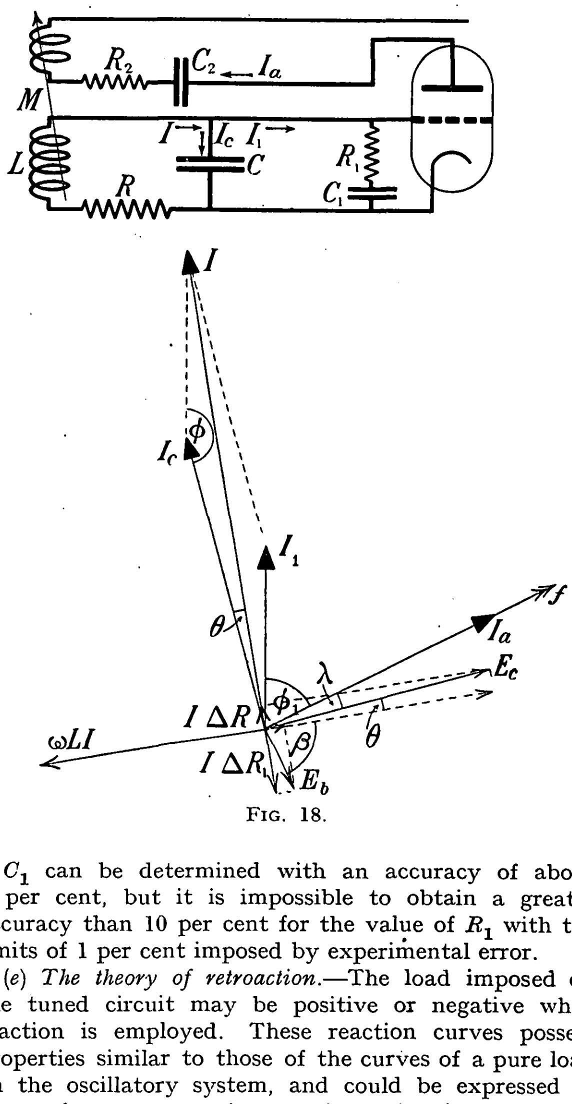

FIG. 18.

C_1 can be determined with an accuracy of about 5 per cent, but it is impossible to obtain a greater accuracy than 10 per cent for the value of R_1 with the limits of 1 per cent imposed by experimental error.

(e) *The theory of retroaction.*—The load imposed on the tuned circuit may be positive or negative when reaction is employed. These reaction curves possess properties similar to those of the curves of a pure load on the oscillatory system, and could be expressed in terms of a constant series capacity and resistance shunt. However, the results obtained would serve no more useful purpose than the diagrams themselves. It was thought preferable to express the reduction in the effective load due to reaction in terms of the actual electrical constants of the anode circuit, in order to show whether the fundamental theory would explain the experimental results.

In Fig. 18 the plate-circuit impedance is represented by a capacity and resistance in series, the resistance consisting of the anode-filament resistance of the triode and the capacity (the self-capacity of the iron-cored intervalve transformer), which will probably form a lower reactance at these frequencies than the inductance.

A fourth E.M.F. vector E_b is thus inserted into the resonant circuit which has two components, the one in phase with I producing a reduction of the effective resistance, and the other quadrature component altering the resonant conditions slightly.

The phase angle in the anode circuit is denoted by the angle λ, and the reduction of circuit resistance is given by $\Delta R_1 = (E_b/I) \sin \beta$.

The resonant condition gives from the vector diagram

$$\omega LI = \Delta RI \cot \theta + \Delta R_1 I \cot \beta$$

$$\therefore \omega L = \Delta R \cot \theta + \Delta R_1 \cot \beta$$

$$\therefore \Delta R_1 = \frac{\omega L - \Delta R \cot \theta}{\cot \beta}$$

Now $\cot \beta = \tan (\theta + \lambda)$.

Assuming $R_2 >> 1/(\omega C_2)$, and knowing from experiment that $\tan \theta \doteqdot \Delta R/(\omega L) << 1$, we have

$$\tan \theta = \theta \propto \Delta R/\omega = (p/\omega)\Delta R$$

and

$$\tan \lambda = \lambda \propto (1/\omega) = q/\omega$$

$$\therefore \tan (\theta + \lambda) = \theta + \lambda = (p\Delta R + q)/\omega = \cot \beta$$

$$\therefore \Delta R_1 = \frac{\omega L - \Delta R\omega/(p\Delta R)}{(p\Delta R + q)/\omega}$$

$$\therefore \Delta R_1 = \frac{\omega^2[L - (1/p)]}{p\Delta R + q}$$

where p and q are constants for any given curve.

From Fig. 14 (reaction = 0) we get

$$p = 7\,930, \text{ and } q = -0 \cdot 117 \times 10^6$$

and the equation of the curve is given by

$$\Delta R_1 = \frac{0 \cdot 00607 Y^2}{0 \cdot 117 - 0 \cdot 00793 \Delta R}$$

where $Y = \omega/10^6$.

This curve, when plotted against the experimental values, gives very close agreement, as shown in the figure, and demonstrates that the results can be expressed theoretically. Similarly, in Fig. 15 (reaction = 0) we get

$$p = 1\,530 \text{ and } q = -0 \cdot 1733 \times 10^6$$

and the equation of the curve is given by

$$\Delta R_1 = \frac{0 \cdot 1957 Y^2}{0 \cdot 1733 - 0 \cdot 00153}$$

where $Y = \omega/10^6$.

Since $\tan \lambda = X_a/R_a = q/\omega$

X_a is small compared with R_a. The anode circuit thus consists virtually of a small inductance in series with R_a, and the impedance of this circuit will now be considered to be sensibly that of R_a.

(*f*) *The determination of the mutual inductance between the reaction and primary.*—It is now necessary to determine the value of the mutual inductance at various settings of the reaction coil. A known high-frequency current at a frequency of 300 000 p.p.s. was passed through the reaction coil, and the open-circuit E.M.F. of the untuned primary was determined by means of a calibrated amplifier. The values of M and the coefficient of coupling so obtained are shown in Fig. 19. The relationship between M and the angular position of the coils is very nearly a sine relationship, as would be expected, but the law varies with different primary coils. The maximum coupling is only 32 per cent.

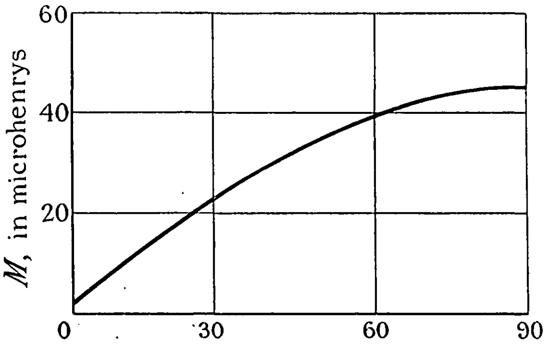

FIG. 19.—Experimental determination of M: stud 2.

From Fig. 18 we obtain the following relationships

$$E_b = \omega M I_a$$

$$I_a = uE_c/Z_a$$

where u is the voltage factor of the tube, and

$$Z_a = \sqrt{[R_2^2 + (1/\omega C_2)]^2}$$

$$\Delta R_1 I = E_b \sin \beta$$

$$= \omega M I_a \cos (\theta + \lambda)$$

$$= \frac{\omega M u E_c}{Z_a} \cos (\theta + \lambda)$$

$$= \frac{\omega M u I_1 Z}{Z_a} \cos (\theta + \lambda)$$

$$\therefore \Delta R_1 = \omega M u \frac{I_1}{I} \frac{Z}{Z_a} \cos (\theta + \lambda)$$

Now

$$\frac{\sin \theta}{I_1} = \frac{\sin \phi}{I} = \frac{\cos \phi_1}{I}$$

$$\therefore \frac{I_1}{I} = \frac{\sin \theta}{\cos \phi_1}$$

$$\therefore \Delta R_1 = \frac{\omega M u Z}{Z_a} \frac{\sin \theta}{\cos \phi_1} \cos (\theta + \lambda)$$

Now $\cos (\theta + \lambda) \doteqdot 1$, $\cos \phi_1 = \dfrac{R_1}{Z}$ and $\tan \theta \doteqdot \sin \theta$

$$\therefore \Delta R_1 = \frac{\omega M u Z}{Z_a} \cdot \frac{\tan \theta}{R_1} Z$$

and $$\tan\theta \doteq \frac{\Delta R}{\omega L}$$

$$\therefore \Delta R_1 = \frac{\omega M u Z \Delta R Z}{Z_a R_1 \omega L}$$

$$= \frac{M u Z^2 \Delta R}{Z_a R_1 L}$$

From Fig. 14 (reaction = 10) we get $M = 6 \cdot 12\ \mu$H, where

$Z_a = 13\ 000$ ohms (determined experimentally)
$u = 4 \cdot 92$ (determined experimentally)
$Z = R_1 + j/(\omega C_1)$

where $R_1 = 20\ 800$ ohms and $C_1 = 9 \cdot 9\ \mu\mu$F

$$L = 126\ \mu\text{H}$$

The experimental determination gave 10 μH.

Assuming the ratio of changes in M given by experiment, theoretical curves for each reaction position were obtained and are shown for two values of L in Figs. 14 and 15. The agreement shows how nearly the experimental results agree with the theoretical treatment. The tailing-off of each curve when near oscillation is due to unstable amplifier conditions. The reason for the 40 per cent error between the measured and calculated values of M can be roughly explained, since in the measuring case the field is due only to the current in the mutual coil, whereas when the actual measurements were taken the mutual inductance formed part of a complex field generated at a considerable distance from the coils, and in addition the primary current would seriously modify the field form. The amplifier used consisted of a simple rectifier followed by two audio stages. The valves used were dull-emitters.

(*g*) *Summary of results.*—The amplifier may be considered as a resistance and capacity in series forming a load across the resonant system. The value of this capacity appears to be sensibly constant under all conditions, whereas the value of the resistance is dependent upon the value of the tuning inductance. The effects due to reaction can be expressed in terms of the known theoretical conditions.

SECTION 3. DISTORTION IN AUDIO-FREQUENCY AMPLIFIERS.

(*a*) *Errors in measurements due to distorted waves.*—It has been shown that the output wave-form given by a 2-stage amplifier is nearly sinusoidal with very weak outputs, but if these amplification figures are extended to signals of about $\frac{1}{2}$ mA (R.M.S. value) as in loud-speaker work, the voltage ratios have little value, for the wave is no longer sinusoidal.

It is generally assumed that if the valve is operated with no grid current and upon a linear part of its v_g/i_a characteristic, the output wave-form is sinusoidal. However, R.M.S. determinations of output have shown severe discrepancies, for the vibration galvanometer measures the amplification of the fundamental only, whereas the R.M.S. instrument gives a power determination including the energy in the harmonics that may be present.

It was soon noticed that the audible strength of a signal did not appear to be proportional to the R.M.S. value of current through the instrument. If harmonics were present, the same apparent sound intensity could be obtained with R.M.S. values of current but one-sixth of the current required if the wave was sinusoidal. Since the ultimate object of amplification tests is to indicate the relative strengths of the output *sound* intensity, it is necessary to establish the type of wave given by an amplifier under various conditions with a sinusoidal input.

Great amplification can be obtained if reaction is pushed near its limit, but the distortion may be so great that the output signal may be of little value. For telegraphic signal reception the presence of the harmonics may be no disadvantage, but for telephonic reception it seems necessary to postulate a definite maximum departure from the sinusoidal form and to obtain the amplification under these conditions.

The 2-stage audio amplifier shown in Fig. 7 was used for the following investigations. The distortion was soon found to be so large that one transformer only was used. It may be stated that these transformers were known to be well above the average in performance.

(*b*) *Low-frequency determination of wave-form.*—At frequencies below 300 p.p.s. an Einthoven galvanometer was used as shown in Fig. 20. This galvanometer had a 14 μ copper string and the main d.c. anode current component was balanced out. Photographic results were obtained on a high-speed paper camera which ran at 6 m/sec. Records were obtained at low frequencies lying between 130 and 300 p.p.s. The output was about $0 \cdot 6$ mA (peak value) and showed a great departure from the sinusoidal form. The input was obtained from a filter circuit and when

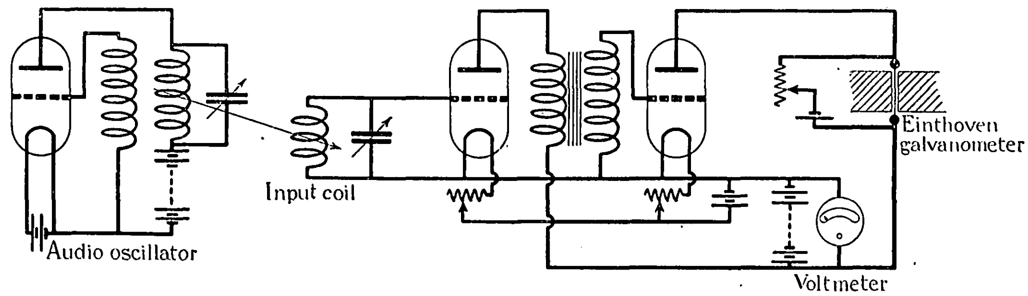

FIG. 20.

photographed was found to be sinusoidal. The distortion is a minimum with large negative grid bias, but is still very appreciable. The decrement of the string was about 0·3 and its natural frequency about 800 p.p.s. Although it did not seriously affect the wave-forms obtained, the method could not be extended to the higher-frequency cases.

(*c*) *Higher-frequency determinations of wave-form.*—Since the amplification measurements were all performed at a frequency of 1 000 p.p.s., it was necessary to obtain a more complete series of results at that frequency. A cathode-ray oscillograph was used as the recording instrument and was connected as shown in Fig. 21. The difficulty when using this oscillograph is to obtain a large enough undistorted voltage replica of the weak anode-current changes. This, however, was effected by introducing a non-inductive resistance of 20 000 ohms into the anode circuit and suitably raising the high-

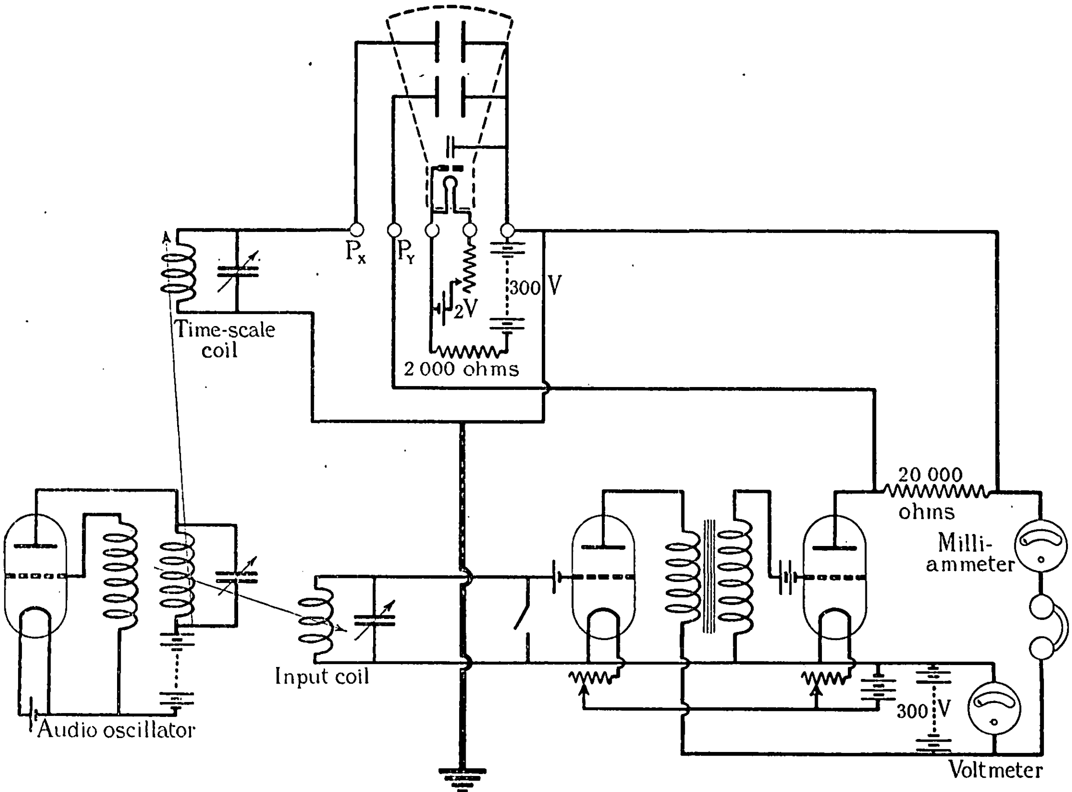

FIG. 21.

TABLE 3.

Curve number	R.M.S. current	First harmonic	Second harmonic	Third harmonic	Fourth harmonic	Fifth harmonic	Sixth harmonic	Form factor	Peak / Fundamental peak	Peak / R.M.S. peak	D.C. component of anode current in transformer primary
	mA	per cent	per cent	per cent	per cent	per cent	per cent				mA
1	0·6	100	54·6	23·0	—	—	—	1·135	1·37	1·23	2·3 (?)
2	0·6	100	48·0	16·5	—	—	—	—	—	—	1·7
3	0·6	100	42·2	9·5	0·5	0·5	—	1·22	1·4	1·32	1·12
4	0·345	100	55·8	29·1	10·0	2·5	10·0	1·24	2·08	1·75	3·4
5	0·645	100	31·2	10·4	—	—	—	1·18	1·57	1·34	2·83
6	0·276	100	16·8	9·2	—	—	—	1·17	1·25	1·21	2·83
7	0·181	100	16·5	8·6	—	—	—	1·17	1·2	1·2	2·83
8	0·507	100	1·2	2·25	4·4	3·6	1·75	1·125	1·0	1·04	2·25
9	0·407	100	6·3	2·8	—	—	—	1·13	1·06	1·065	2·25
10	0·203	100	6·25	8·3	—	—	—	1·127	1·14	1·09	2·25
11	0·654	100	17·5	3·7	7·9	2·0	2·0	1·28	1·21	1·19	2·25

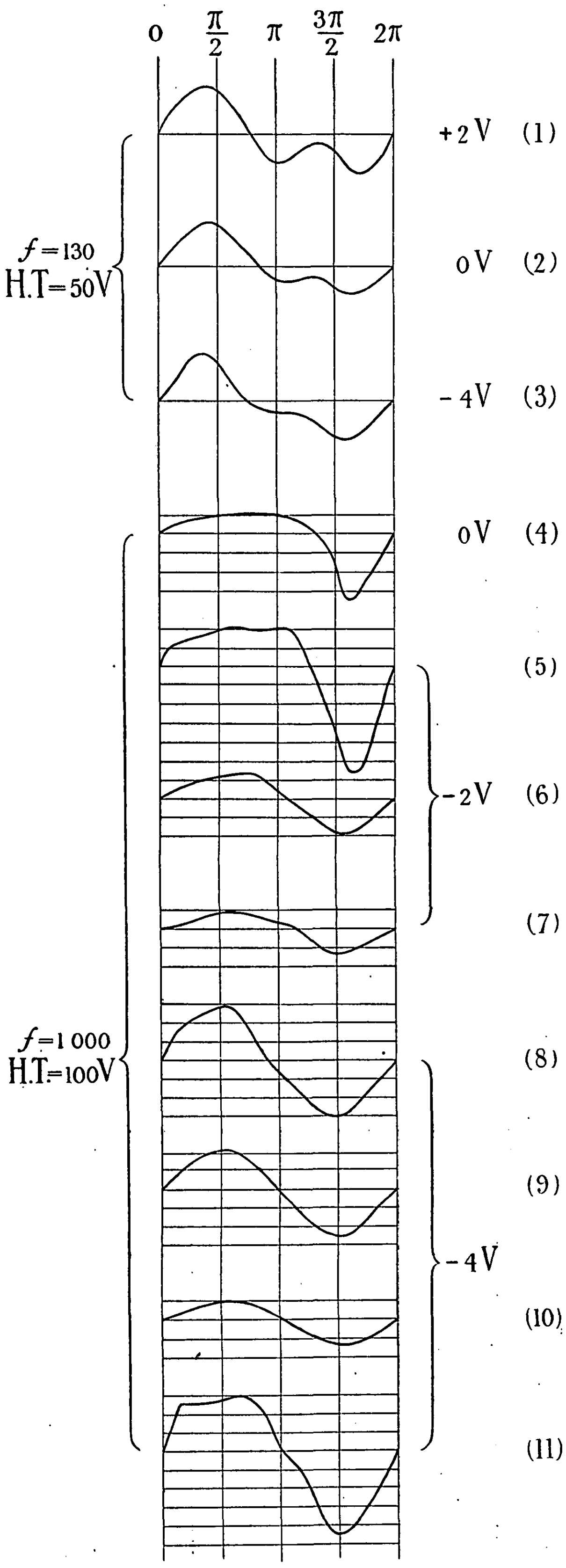

FIG. 22.

tension battery voltage until the plate voltage measured electrostatically was the same as before the insertion of the resistance. In this way a voltage of 10–15 was obtained for the overall changes, and the normal drop across the resistance was balanced out.

The input to the amplifier was the voltage across a tuned circuit very loosely coupled to the audio oscillator. The wave-form was found to be sinusoidal. The output across the anode resistance was taken to one pair of the cathode-ray tube plates, the other pair being connected across another tuned circuit loosely coupled to the same audio source. The magnitude of the input E.M.F. could be varied by adjusting the coupling of the input coil, and any convenient width of time scale can be obtained by adjusting the coupling of the time-scale coil. The sensitivity with 250 volts on the anode of the tube was about 1 mm scale deflection per volt.

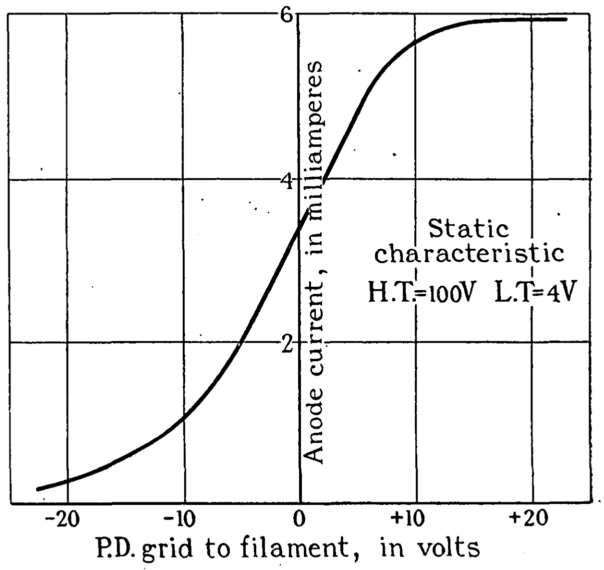

FIG. 23.

Photographic results were obtained by exposing bromide paper held against the screen. The Lissajous figures so obtained were analysed and the most important of the curves of wave-form deduced from them are shown in Fig. 22. The details of the Fourier analysis are given in Table 3.

(*d*) *Discussion of some observed cases.*—From a study of these curves it will be seen that the number and magnitude of the harmonics is considerable, and that the actual peak value may be as much as 75 per cent greater than the assumed peak value obtained from the R.M.S. value.

The grid-voltage variation is therefore in all these cases greater than would be given by a R.M.S. determination.

The output was never great enough to give a grid current in the cases with 2 or 4 volts negative bias on the grid, as seen from the static characteristic in Fig. 23. The following conclusions can be drawn from these results, remembering, however, that they must be considered only as provisional, considerably more experimental work being necessary to confirm the general conclusions so far obtained.

(i) The effect of *increasing output* is to modify the wave-form seriously. In general, the harmonics increase in magnitude far more rapidly than the fundamental.

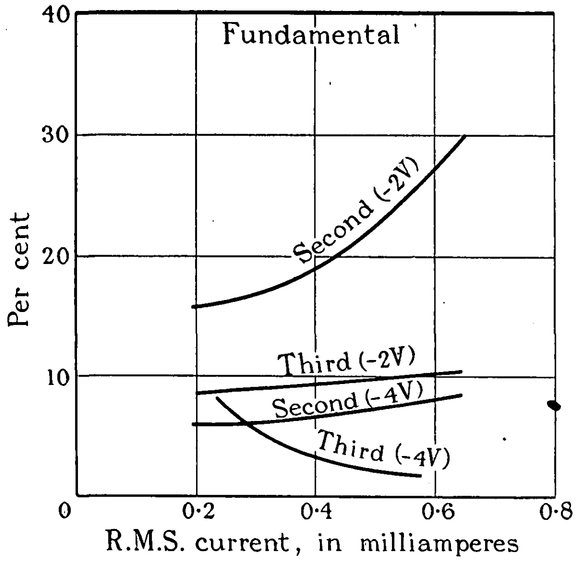

FIG. 24.—Percentage harmonics, with different grid potentials.

(ii) As the *frequency* is lowered, the distortion becomes much more serious. It is safe to say that at 150 p.p.s., the fundamental may be almost completely eclipsed by the harmonics with outputs of about 1 mA.

(iii) The effect of *negative grid bias* is to reduce the

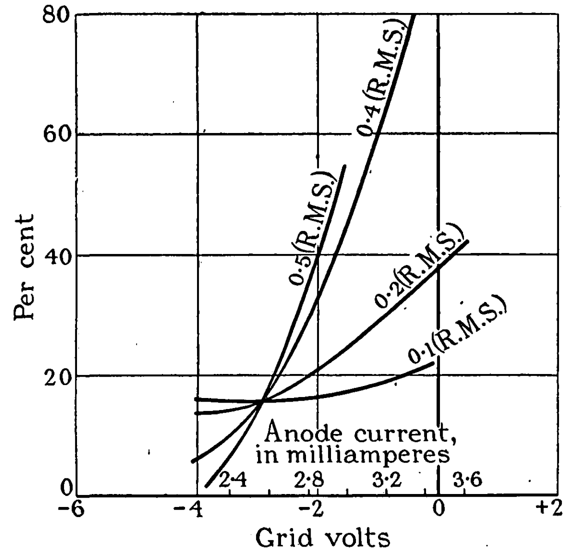

FIG. 25.—Ratio (Peak/Fundamental peak) expressed as a percentage greater than 1.

magnitude of the second and third harmonics and to introduce small harmonics of a higher order.

(iv) The *form factor* remains sensibly constant under most conditions.

(v) In curve 11 (Table 3), it will be seen that the rapid growth of the higher harmonics, the fourth, the fifth and the sixth, produces a critical distortion. This was noticed in many cases. The shape of the Lissajous figure quite appreciably changes with a very small increment of current beyond a given critical value.

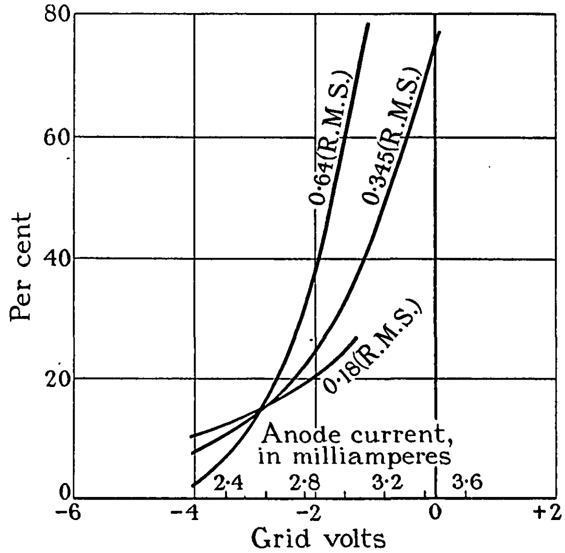

FIG. 26.—Ratio (Peak/R.M.S. peak) expressed as a percentage greater than 1.

The form factor and other ratios are seriously upset in this case, and do not fall into the final inferences with smaller outputs.

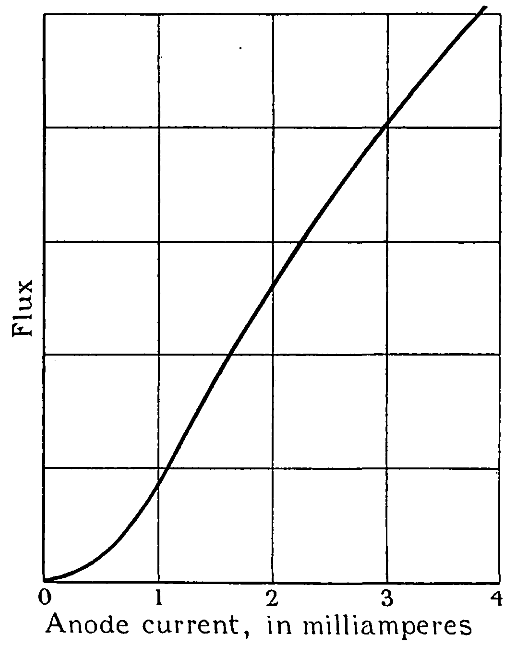

FIG. 27.

(vi) In Fig. 24 the percentages of the second and third harmonics are given for various outputs with different grid potentials. It will be seen that the rate of growth of the harmonics is much greater than that of the fundamental, thus demonstrating the rapid wave-form change as the amplitude of the sinusoidal input is increased.

(vii) In Fig. 25 the ratio of the actual peak to the fundamental component peak is plotted for various output currents and mean grid potentials and is expressed as a percentage greater than unity. These curves all intersect at a point corresponding to a mean negative grid potential of 2·9 volts. This means that the waveform is *not altered* by increasing the magnitude of the output, and this condition is valid only at this point.

Further, there is a *definite distortion* leading to an error of 18 per cent *which apparently cannot be removed by reducing the signal amplitude.*

(viii) The ratio of the actual peak value to the peak of a sine wave of the same R.M.S. value is plotted in Fig. 26, from which a precisely similar result is obtained at the same mean grid-voltage condition. It seems probable that this condition is one defined by the normal d.c. anode-current component in the primary of the transformer rather than any loading effect on the secondary, due to grid-filament impedance, which will be very large in all the cases we have considered.

This grid voltage corresponds to 2·6 mA primary current. In Section 1 it has been shown that the transformer voltage ratio is materially affected by the normal d.c. anode current, thus supporting this opinion. The shape of the B–H curve for the transformer is shown in Fig. 27, from which it will be seen that the polarizing flux brings the normal working point just at the beginning of the saturation bend. It is not easy, however, to observe any definite properties at this point.

(*e*) *Summary of results.*—It is apparent that the error between an R.M.S. determination of output and a fundamental wave determination as given by a resonant instrument may be often as much as 20 per cent. Further, the grid variation is much in excess of the theoretical as given by an R.M.S. measurement.

The general observations point to peak values giving the chief measure of output sound effect upon the human ear, and if this can be established it is clear that much modification will be necessary in our measurements of signal intensity.

These investigations were carried out for the Radio Research Board under the Department of Scientific and Industrial Research, and the author wishes to acknowledge his indebtedness to Sub-Committee D1 of the Board for their useful advice throughout the experiments.

He also wishes to acknowledge his indebtedness to Mr. J. Hollingworth, M.A., B.Sc., for his valuable co-operation in the early part of the work, to Dr. R. L. Smith-Rose, M.Sc., for much useful advice and assistance, and to his assistant, Mr. G. Warren, for his valuable aid in all the latter portion of the work.

Discussion before the Wireless Section, 2 December, 1925.

Prof. C. L. Fortescue: The use of the vibration galvanometer in the measurements described in Section 1 of the paper suggests that the amplitude of the output is much greater than that required for reception by telephone. A method of measurement more nearly equivalent to the ordinary telephone receiver will be necessary if the properties of the amplifier are to be investigated down to outputs as small as that of a just-audible signal. The observed increase of magnification with decrease of output amplitude is no doubt due, as suggested by the author, to change of waveform, and this confirms the view that the amplitudes at which the measurements have been made are rather high. For loud-speaker amplitudes the vibration galvanometer is no doubt quite suitable if its indications are properly interpreted. The author points out in Section 2 the difficulties arising from the disturbance of the amplifier by changes of the geometric form of the input circuit, but in Section 1 he appears to have taken no precautions to avoid inserting switches in the "high tension" side of the apparatus used for applying the small voltage to the amplifier input terminals. It seems likely that capacity effects may have been appreciable and that they may explain the differences in the behaviour of amplifiers of apparently identical construction. The screening arrangements, also, appear to have been inadequate and the re-designed testing apparatus mentioned by the author in reading the paper will be a great improvement though even now it is doubtful whether they are sufficiently complete. With regard to the three conclusions on page 261, the author should make quite clear under what conditions the first of them is applicable, as there is a general belief that with many forms of amplifier the reaction on the input circuit may change sign. The theoretical treatment given by the author assumes that the valve may be regarded as equivalent to a resistance in series with a capacity—both at the grid and the anode. This assumption neglects cross-capacity effects which are almost always of fundamental importance, and the observed fact that the resistance R_1 is found to vary from 20 000 to about 290 000 ohms for different values of the inductance in the input circuit seems to be directly attributable to this omission. For the same reason the author's vector treatment of the subject cannot be regarded as even approximately complete. Unfortunately the data given in the paper are not sufficient to enable the effects of cross-capacity to be computed for the apparatus in use but it would, no doubt, be possible for the author to investigate the effects. The wave-forms of output in Section 3 bear out the results obtained by other observers when the amplitudes are as great as the 10–15 volts given in the paper. Up to 5 volts and with frequencies of 1 000 there should be no serious distortion if the valves are suitable and suitably adjusted. It would appear that a great deal more work is required in connection with this part of the paper.

Mr. L. B. Turner: The behaviour of amplifiers is a subject which calls emphatically for exact measurements. Amplifiers of various types are in very common use and give very varied overall performances; confident but nevertheless meaningless or obscure statements about amplification and distortion are met on all sides;

and it is far from easy for even serious experimentalists to analyse quantitatively the phenomena they observe qualitatively. Consequently the report of an orderly and painstaking research such as that of the present paper should be given an eager welcome. The author has elected to make output measurements throughout at an acoustic frequency and employs a vibration galvanometer registering sensibly only the amplitude of the component of fundamental frequency. His method of acoustic 100 per cent modulation of the high-frequency input is ingenious. He states on page 256 that the modulation is readily adjusted to 100 per cent by the ear's recognition of the second harmonic of the modulating frequency when 100 per cent is exceeded. I should be glad if he would give an account of the method and observations by which he was able to establish the accuracy of this easy way of adjusting to 100 per cent modulation. The modulation method is inspired presumably by the desire to make as much as possible of his plant serve for both high-frequency and low-frequency amplifiers. Whilst I appreciate the value of the vibration galvanometer for the low-frequency amplifiers, it does not appeal to me as the best method for high-frequency amplifiers. It does not in any way discriminate between the fundamental and harmonics of the high-frequency output of the amplifier, since the 1 000-cycle current passed to the galvanometer is proportional to the square of the *virtual* value of the P.D. on the rectifier.* It is said on page 257 that "the discrepancies" (in high-frequency voltage amplification) "arising due to a neglect of the harmonics present may be, as shown later, very serious"; but this method cannot investigate these discrepancies. If virtual voltage, and not the fundamental component only, is to be dealt with, a Moullin thermionic voltmeter or its equivalent, without acoustic modulator or vibration galvanometer, seems to have everything to recommend it on the score of simplicity. The author is mistaken, I think, when he says (see page 254) that the valve rectifier is objectionable on account of large earth capacities. It is precisely as unobjectionable in this respect as his own "measuring valve" (Figs. 1 and 3), whose place it would take. If it is desired to take cognizance of the fundamental alone of the high-frequency input, a possible method would be to produce the acoustic frequency for the vibration galvanometer, not by the author's acoustic oscillator, but by a high-frequency oscillator used as a heterodyne. A few practical details in the apparatus call for comment. Fig. 2 is very puzzling to me. First, it is surely a very poorly designed current transformer whose ratio is so sensitive to change in the magnetic condition of the core; and in this connection I should like to ask why (as stated on page 255) the secondary of the transformer was given a resistance equal to the total resistance of the galvanometer. Secondly, how is it that the curve relating transformation ratio with the polarizing current in the primary is not symmetrical about zero current? In Fig. 3, the high-frequency potentiometer F is shown with two sliders, the right one of which is connected to earth. Motion of this slider thus changes the earthed point in the high-frequency transformer secondary circuit. This seems to invite errors, particularly as the transformer primaries are, surprisingly, connected in the non-earthed side of the radio oscillator A. Fig. 6 shows a rapid fall of amplification with increasing input. No details of this amplifier are given; and I venture to suggest that perhaps here, as elsewhere, not enough account has been taken of grid damping. Were all the grids of this amplifier adequately negative in potential? If not, there need be no mystery as to the cause of the inconstancy of amplification. The series of curves in Figs. 8–16 are very interesting, but it is not clear to what amplifier they refer. Was it the six-stage amplifier mentioned at the end of page 258 or some simpler arrangement, as seems rather to be implied in the paragraph on the theory of retroaction? Whatever it was, one would like to have full details of the amplifier under examination. The later portions of the paper deal with distortion in low-frequency amplifiers, and are full of interest. I venture to think the sources of distortion are not so hard to find as the author seems to suggest. He says (see page 264): "It is generally assumed that if the valve is operated with no grid current and upon a linear part of its v_g/i_a characteristic, the output wave-form is sinusoidal." I hope to be able to continue to assume this, except, of course, in the presence of unsuitably designed iron-cored chokes and transformers. I think that in some at least of tests 1 to 11 of Fig. 22 there *were* grid currents, and the straight-line region of the triode characteristics was *not* adhered to. In tests 1 to 3 the output current was 0·6 mA through a negligible impedance, so that (judging from Fig. 23) the grid amplitude was some 2 V to 3 V. This would produce asymmetric grid damping in tests 1 and 2, but not in 3. But the large magnetizing current in any ordinary amplifier transformer, when used at a frequency as low as the present 130 cycles per sec., may well be credited with the distortion here. In tests 4–11, which were at 1 000 cycles per sec., the iron effect was doubtless much less. But here a resistance of 20 000 ohms was inserted in the anode circuit, across which a P.D. of 10–15 V amplitude was produced. Fig. 23, unfortunately, does not show the amplification constant of the triode; but taking it as 5, I calculate that the grid amplitude would be 6 V when that of the anode was 15 V. This would produce severe grid current in all the tests, and in some would reduce the anode current to values dangerously near the curvilinear region. In conclusion, I think we often ask too much of the last triode on our low-frequency amplifiers. The anode joined to an ordinary room loud-speaker may easily suffer an amplitude of some 50 V, and its grid (say) 8 V: it should be fed with grid and anode voltages accordingly. If the author had been more generous with his grid and anode voltages—say − 8 V and + 150 V—we should, I think, have had more shapely curves in Fig. 22.

Mr. P. W. Willans: The author in Section 1 of the paper gives under heading (*a*) a summary of the practical difficulties of measuring voltage amplification, and outlines a few general methods of making this measurement. In the course of this summary he

* See E. B. MOULLIN and L. B. TURNER: *Journal I.E.E.*, 1922, vol. 60, p. 708.

remarks that the output of the amplifier must be either determined or kept constant, and whatever method be adopted the output must be measured in some way. I am venturing to bring forward a general method which does not depend upon such a determination of output or upon its constancy, but only on a comparison between the output and input voltages of the amplifier. The basis is a null observation, and not only is a comparison between the scalar values of the input and output voltages obtained but also the phase angle between these voltages. The method of making the observation may conveniently be considered in relation to Fig. A.

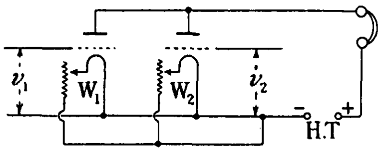

FIG. A.

Here W_1 and W_2 are two valves the filaments of which are controlled by separate rheostats. The anodes of these valves are connected in parallel through a pair of telephones and a source of high-tension current, and to the grids of the valves are applied alternating voltages v_1 and v_2, of the same frequency, from any source whatever. Then it is clear that if the valves have linear characteristics and identical mutual conductances, and if v_1 and v_2 are equal and in opposition of phase, then no sound will be heard in the telephones. In practice the valves can be so

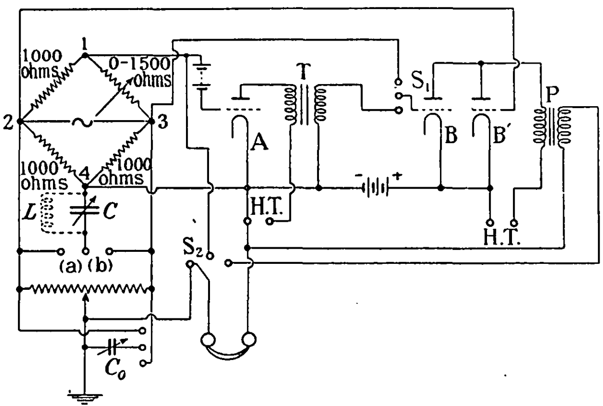

FIG. B.

adjusted that their mutual conductances are equal, by first arranging that the applied voltages are exactly equal and in opposition of phase and then adjusting the filament resistance of either W_1 or W_2 until no sound is heard in the telephones. If, then, one of these voltages, say v_1, be replaced by a voltage which varies in conformity with the adjustments of any measuring apparatus, we can bring this voltage into equality and opposition of phase with v_2 by effecting an extinction of sound in the telephones. It is worth noting that such an extinction will, in practice, only be attainable with the fundamental frequency of the applied voltages if their wave-forms are not identical. This is an advantage, since it helps to separate the effects of amplification on different frequencies. To apply a detecting device of this type to the measurement of voltage amplification it is convenient to use a bridge arrangement as illustrated in Fig. B. This shows the measurement of a single-stage transformer amplifier consisting of a valve A followed by an intervalve transformer T, and has been used mainly in the development and testing of audio-frequency intervalve transformers. The valves B and B′ correspond to the two valves shown in Fig. A, the anodes being connected in parallel and to the primary winding of a telephone transformer P. To the grid of the first valve is applied a fraction of the input voltage to a bridge which consists essentially of four arms, three of 1 000 ohms resistance and one, in general, slightly different from that value. Further, either of the ratio arms of the bridge can be shunted by a variable condenser. Referring to Fig. B, it will be seen that the condenser marked C can be connected either across the arm 2, 4. or across 3, 4; simultaneously we can throw the bridge out of balance in respect of resistance by adjustment of the arm 1, 3, which is variable from 0 to 1 500 ohms. The grid of the valve B′ is permanently connected to point 2 on the bridge, and the grid of B can be connected either to the output of the voltage amplifier or to the point 3 on the bridge, a switch S_1 being provided for this purpose. In order to effect the measurement we must first ensure that the mutual conductances of the valves B and B′ are the same. For this purpose we connect the grid of valve B to the point 3 on the bridge, balance the latter exactly, thus making the applied voltages equal and opposite, and by means of the filament resistances of these valves reduce the sound heard in the telephones to zero. Having made this adjustment we throw over the switch S_1 to the output of the voltage amplifier, and then displace the balance of the bridge until the output voltage is such that no sound is heard in the telephones. We then know that the output voltage of the transformer is equal and opposite to the voltage across the arm 2, 4 of the bridge and the input voltage to the amplifier is equal to the voltage across the diagonal 1, 4. Consequently the amplification ratio is equal and opposite to the ratio of the voltages across 2, 4, and 1, 4, respectively. These voltages can very readily be calculated. The resistance R_0 and the condenser C_0 constitute a Wagner earth connection, the arrangements being such that we can reduce to zero the voltage between the point 4 of the bridge and earth under all conditions of measurement. The resistance R_0 is of a total value of about 10 000 ohms, and the condenser C_0 consequently requires to be roughly one-tenth of the value of the capacity across the ratio arms, though it will deviate slightly from this value due to the stray capacities of batteries, etc., for which it is required to compensate. The switch S_2 enables the telephones to be connected to the bridge terminals direct, to the earth bridge, or to the output of the valves B and B′. In Fig. B an inductance L is shown as a dotted line across the condenser C. This may be used for the purposes of frequency measurement, the resonant circuit $L\,C$ being shunted across either ratio arm and the condenser and variable resistance arm being adjusted for exact balance of the bridge. It is important to note the conditions of measurement, namely, that there is, practically speaking, no impedance either in the input grid circuit or in the output anode circuit. In the first case the total impedance of the bridge is of the order of 1 000 ohms, which is negligible in comparison with the grid filament impedance of the valve at even fairly high frequencies. In the second case, since the adjustment is made in such a way that there is zero alternating current flowing through the telephone transformer windings, there is no alternating voltage on the plates of these valves and, in consequence, no retroactive effect on the amplifier. This reduces the conditions of operation to the simplest possible terms, and if it is required to observe the effect of input or output impedances these can be deliberately introduced in such a manner as not to interfere with the measuring apparatus. The calculation of the amplification ratio differs according to the position of the condenser C. Referring to Fig. C, which is a simplified diagram of the

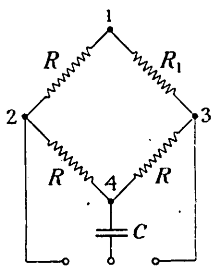

FIG. C.

bridge itself, if we denote the two positions of the switch as (a) and (b) and the voltages across 2, 4; 1, 4, etc., by v_{24}, v_{14}, etc., the formulæ can readily be established. Thus, for the switch in position (a)

$$\frac{v_{24}}{v_{14}} = \frac{R' + R}{R' - R - j\omega R^2 C}.$$

And for the switch in position (b)

$$\frac{v_{24}}{v_{14}} = \frac{R' + R}{R' - \dfrac{R(1 - \omega^2 R^2 C^2)}{1 - \omega^4 R^4 C^4} + j\,\dfrac{\omega R^2 C}{1 + \omega^2 R^2 C^2}}$$

ω being of course the angular frequency of the applied alternating voltage. In by far the greater number of practical cases the second formula can be simplified by neglecting $\omega^4 R^4 C^4$ in comparison with unity in the real term, and $\omega^2 R^2 C^2$ in comparison with unity in the imaginary term. We then have, as an approximate formula with the switch in position (b)

$$\frac{v_{24}}{v_{14}} = \frac{R' + R}{R' - R + \omega^2 R^3 C^2 + j\omega R^2 C}$$

This method of measurement has been employed mainly on the investigation of audio-frequency intervalve transformers, where it has given results in excellent agreement with theory. I believe that work on multistage amplifiers has also been carried out on the same lines by other investigators, but I am not in possession of any results obtained. The advantages which I suggest are obtainable from the use of a general method of this type in measuring voltage amplification are threefold. First, in a number of cases it is possible to obtain more information regarding the performance of the amplifier under test if the vector ratio of output to input voltage is measured. This has certainly proved to be the case in respect of intervalve transformer work. Secondly, we are enabled to carry out measurements at very small output voltages, as, for example, $\frac{1}{4}$ volt or less at any frequency, without the use of calibrated apparatus. Lastly, the use by this method of a phase-splitting device as input makes it possible for a correction to be applied for the stray E.M.F. picked up by the amplifier, and this reduces the necessity for an elaborately screened source. In this last connection, referring again to Fig. B, we may disconnect the valve B′ in any manner and then reduce the output of the amplifier to zero by adjusting the bridge (with valve B connected to the amplifier) until no sound is heard in the telephones. If there is no stray E.M.F. picked up by the amplifier, the bridge will be exactly balanced under these conditions; if such an E.M.F. exists, a counter E.M.F. will be required at the input end of the amplifier and the bridge will then be unbalanced. We may then make a measurement of amplification as previously described and the input E.M.F. is reckoned as the vector difference of the *apparent* input E.M.F.'s in the two cases (the phase of the bridge E.M.F. v_{23} being counted as the same for both observations). The amplification ratio will then be corrected for the stray pick-up of the amplifier. The only condition for the success of this method is that v_{23} must be the same for the two observations, and this is substantially true in the case of measurements on powerful amplifiers, inasmuch as the bridge impedance varies only slightly for a small displacement of the balance.

Mr. J. Hollingworth: Having been associated with this work since its inception I do not propose to put forward any criticism of it, but rather to state briefly some of the early history of the investigation which occurred before, or very soon after, the author came to the laboratory. In this way, I think, the perspective of the whole can be more clearly seen. The matter arose out of a discussion in committee on two points. The first was that, whilst a great deal of mathematical work had been done on the subject of amplifiers, it had not in general been followed up by a consistent quantitative examination of any actual piece of apparatus in order to see whether the assumptions necessarily made during the mathematical work were justified in actual fact, and what values should be given to the actual constants which arose. Secondly, it was hoped to see what prospects there were for devising anything in the nature of routine tests for amplifiers in general, which would satisfy the usual conditions for such tests; namely that they should be capable of reasonably accurate repetition and at the same time should give a result really representing the behaviour of the amplifier under working conditions. The present paper is the commencement of an answer to these questions. With regard to the technical aspect, the vibration galvanometer was decided upon after considerable discussion in committee as offering on the whole, in spite of its obvious limitations, the best method of attack. The other principal feature, the separation of the test into two parts, first the amplification of the instrument alone, and then the consideration of the effect upon its associated circuits, was derived from the work then being done upon signal-strength measuring apparatus, which had brought home very strongly the vital importance of the latter factor. This separation has been described as somewhat artificial, and doubts have been expressed as to its validity when applied to the complete apparatus; but both the results in this paper and those obtained by using the same principle in the signal-measuring apparatus during the past two years, seem to have answered this question satisfactorily. It can also be defended on theoretical grounds, but space does not permit of that. The only reservation is that there must be no stray inductive effects from the outside circuits to the intermediate circuits of the amplifier; if this occurs no real test is of course possible, as all results would be dependent on the chance arrangement of the outside circuits. Actually this has involved extremely elaborate screening, especially when an amplifier of five or six stages is under test, in spite of the fact that with this method it is no longer necessary to induce an accurately known E.M.F. into an oscillating circuit, for which the precautions would be even more severe. Considering the results obtained, the author has shown definitely, I think, that, if sufficient precautions are taken, results can be repeated to a degree of accuracy not often reached previously in this type of work; but that the precautions involved are very severe, and such small practical factors as a change of valves may have a considerable effect. He has also shown that the amplifying power, subject to these precautions, can be stated mathematically; but that it invariably involves reference to the associated circuits right back to the receiving aerial or coil. Again the results can only be expressed in the form of a vector impedance if they are to give numerical results in any way consistent with actual performance, so that it seems to follow that the results of any tests on an amplifier involving radio frequency can only be expressed in an elaborate mathematical form; and that any simplification of the mathematics would inevitably lead to results so different from those actually obtainable by experiment as to have very little value for purposes of classification. The use of the crystal circuit referred to in the paper for the determination of 100 per cent modulation is based on the following idea. Tests on the radio-frequency oscillator used showed that the curve between the high-tension voltage and radio-frequency current was, within the limits employed, a straight line which did not pass through the origin but cut off almost abruptly at a critical positive value of high-tension voltage. Consequently, if an audio-frequency E.M.F. were superimposed on the direct-current and so adjusted that the d.c. voltage exceeded the peak value of the audio-frequency voltage by this critical value, complete modulation should be obtained. At first all these voltages were measured directly in every case, but as this became very laborious when varying intensities were required, the crystal method was tried and was found successful. It is based on the idea that if the audio-frequency E.M.F. is too great, so that during part of the cycle the resultant E.M.F. becomes less than the critical value referred to above, the radio-frequency current ceases abruptly, and consequently the rectified wave-form will at once contain a second harmonic. Tests as described above and also with a cathode-ray oscillograph have shown that the accuracy is about 5 per cent, but it should be noted that the E.M.F.'s should be adjusted to the correct order before the crystal is used, as extreme forcing may bring in this harmonic again due to entirely different causes.

Major A. G. Lee: The chief point upon which I propose to touch is the measurement of the decrement of the input circuit when retroaction is present in the amplifier, the results of which are described in Figs. 8 to 16. The method adopted by the author was to use an input of constant amplitude, the frequency of which could be varied, and to plot the response in the input circuit of the amplifier in the form of a resonance curve. The response at the peak is assumed to be inversely proportional to the effective resistance of the circuit, and the response at any other portion of the curve is dependent upon the effective impedance of the circuit at the frequency of the point of the curve. From these details Equation (2), giving the decrement, is derived. Now, in a simple circuit without retroaction, the variation of impedance with frequency is given accurately by the expression $Z = \sqrt{\{R^2 + [\omega L - (1/\omega C)]^2\}}$. When retroaction is present, however, the effect of retroaction is to make both the resistance and reactance of the circuit a less simple function of the frequency. For example, the author mentions at the commencement of Section (2) that the effect of an amplifier upon the input circuit is to alter the tuning of the circuit. The subject has been dealt with in great detail by Bennett and Peters,* who show for a case somewhat similar to that of the author that both the resistance and reactance of a retroacted circuit are somewhat complicated functions of the frequency. It would seem, therefore, that the simple expression for the decrement in Equation (2) would not give the decrement accurately. A further point in connection with these measurements is that a strong input oscillator was used in order to get thermocouple readings in the input circuit. A question which arises in this case is whether the retroaction conditions of the amplifier were disturbed by this strong input, and whether the retroaction would have been the same with weak inputs. With strong inputs, for example, there is a danger of grid currents being produced at various points in the amplifier chain, and this would result in a reduction of the retroaction. The following are some minor points in the paper to which I should like to call attention. In Section 3 (a), paragraph 3, the statement is made that "the same apparent sound intensity could be obtained with R.M.S. values of current." I do not find this clear, and perhaps the author could amplify the statement. In the same Section, which deals with *audio*-frequency amplifiers, paragraph 4 refers to reaction being pushed near its limit, but, so far as I am aware, retroaction is not intentionally used in audio-frequency amplifiers.

* "Resistance Neutralization," *Journal of the American Institute of Electrical Engineers*, 1922, vol. 41, p. 234.

Lieut.-Col. K. E. Edgeworth: The point in the paper that particularly interested me was the question of distortion in audio-frequency amplifiers. Some time ago I was trying to compare the input and output of a 2-stage amplifier, and I found that the musical note was so altered in character that a reasonably accurate comparison was out of the question. I formed the opinion that the distortion due to the production of harmonics was at least as important as the distortion due to unequal amplification. Only small currents were used and valve distortion was probably absent. When a valve is worked in such a manner that the grid is positive during a portion of the oscillation, there is a large variation in the input impedance of the valve, and the consequences of this change of impedance are increased by the use of transformers with a high transformer ratio. This effect has already been referred to by Mr. Turner. I believe that it is fairly well understood, and that it is generally accepted that the correct remedy is to employ a valve with large emission worked under suitable conditions. On the other hand there appears to be very little definite knowledge as to the distortion produced by the iron core of the transformer, and the best method of dealing with the trouble is by no means obvious. It would appear that several of the curves in Fig. 22 were taken under conditions which must involve distortion due to the valve as well as distortion due to the transformer, and it is difficult to separate the two effects. I suggest that research in the immediate future should be devoted to the investigation of the distortion produced by the transformer, this being the problem about which least is known. Experiments might be carried out with valves of high emission worked under such conditions that valve distortion is inappreciable. Such an arrangement would not only reduce the complexity of the effects to be interpreted but would enable larger currents to be used and would facilitate the question of measurement. There appears to be a tendency to assume that uniformity of amplification is the only condition which a transformer has to fulfil, whereas in fact transformers which give very uniform amplification may cause excessive distortion owing to a large production of harmonics. The best transformer is probably one which provides a compromise between the two conflicting sets of requirements. I feel very strongly that further knowledge in regard to transformer distortion would lead to a definite improvement in the reproduction of speech by audio-frequency amplifiers.

Mr. P. K. Turner: According to the paper very inconsistent results were obtained with the ordinary resistance-variation method of trying to find the input impedance of a valve, and these inconsistent results were ascribed largely to the fact that this method altered the geometry of the circuit; but I do not quite understand why it is that the substitution, say, of an inch or two of 47 S.W.G. Eureka wire in the exact location of an inch or two of 40 S.W.G. copper wire, should make a sufficiently important alteration in the circuit. It is standard practice, of course, to use exactly similar links, merely substituting Eureka wire for copper wire. Another difficulty is the fact that obviously the amplification of all high-frequency amplifiers is so greatly governed by retroaction effects. Twice in the paper the author brings out the point that the amplification on the high-frequency side appears to diminish as the input increases. A tendency towards a constant output has been found by an American writer. The statement on page 261 as to the effective resistance load not changing its sign with varying frequencies has already been mentioned. I take it that that refers purely and simply to a resistance-coupled amplifier. Of course it is generally recognized now that in all cases where some sort of tuned coupling is being used between valves that theory no longer holds good at all, and that whenever the anode circuit becomes reactive in the positive sense there is a tendency towards regeneration which may eventually lead to oscillation. Another point which has already been admirably dealt with is that, with the large distortion shown in experiments on audio-frequency amplification, the author has hardly been fair to his own circuit. Noting the characteristics shown in Fig. 23 at 100 volts, and comparing them with the grid inputs and R.M.S. currents produced in Fig. 22 (though the grid characteristic of that valve is on rather a small scale), it appeared to me obvious that the larger input could not be dealt with even by working the valve down on the lower portion of its curve by increasing the grid bias. The saturation current of this valve is of the order of 6 mA, and for swings of the amount given, as far as I can make out from rough measurements from the curves and Table 3, one would need a saturation current of 12 mA and a considerably lengthened curve before one could hope to get distortionless amplification.

(*Communicated*): Since the date of the meeting I have looked further into the matter of measuring input impedance and find some interesting points: (1) If the effect of reaction can be represented as simply a change in the input resistance of the first valve, without the introduction of a reaction E.M.F. into the tuned input circuit, then there is no difficulty. (2) If the effect of reaction can be represented by an E.M.F. (a function of the input voltage), then *if* this E.M.F. is in phase with the input E.M.F. the resistance-variation method may be modified to function, but the reaction variation method will not be satisfactory. If, in addition, the reaction E.M.F. is proportional to the input E.M.F., the ordinary resistance-variation method will suffice. (3) If the reaction E.M.F. is *not* in phase with the input E.M.F., then all the usual methods fail. The analysis on which these rather sweeping statements are made is quite simple and is merely omitted to save space.

Dr. R. L. Smith-Rose: I should like to take this opportunity of justifying the attitude which the National Physical Laboratory has had to adopt in regard to the testing of commercial wireless receiving sets. From time to time we are asked to carry out tests not only of amplifiers of high or low frequency, but also of complete receiving sets. We are requested to give some sort of certificate of merit of performance of the instrument. I think that the present paper, and also the discussion thereon, has emphasized the great difficulties there are in the way of obtaining consistent results in dealing with the amplifier alone, without adding receiving circuits to the front end of it, as would be the case in the complete receiving set.

The National Physical Laboratory has a reputation to maintain, and in the absence of any consistent method of measuring the various factors which it is necessary to measure in the receiver, we have had to confess that we do not know how to test these receivers so as to give some satisfactory certificate of merit of performance of the instrument. The paper shows, however, that an investigation has been commenced with a view partly, at any rate, to arriving at some satisfactory method of testing a receiving set. In view of Prof. Fortescue's remarks I feel that some explanation is necessary in regard to the screening that has been adopted recently, more particularly since I have been partly responsible for the screening methods adopted. I showed some time ago that in order to get complete screening of a radio-frequency field it was necessary to use tin-plate, and to solder up all joints round about the lid of the box in which the instrument to be screened was located. As that was, of course, very impracticable, methods of partial screening have been adopted, and a way has been discovered of fitting on lids to make adequate contact round the side. In continuing this work Mr. Barfield showed that wire netting gives moderately good screening for many purposes, provided care is taken to use netting of a fairly small mesh, and also to bond over all the joints. He also showed that the field inside a 1 in. mesh wire netting screen could be reduced to something like 4 per cent of what it is outside at wave-lengths of from 500 to 7 000 metres. In discussing what we should do in regard to putting these amplifiers in screens, we considered first of all the question of making big tin boxes, i.e. boxes large enough to crawl about inside. But in view of the fact that the radio oscillator and all leads therefrom are already screened with tin-plate, it was considered that if the stray field were reduced to about 4 per cent of its original value, that would eliminate any error due to direct induction from the oscillator. I believe that the author's recent measurements on that particular point have justified the adoption of a whole-room screen of wire netting in place of a small-space screen of tin-plate. I was very interested in Mr. Willans's method of testing low-frequency amplifiers and hope to study that in more detail later. The ideal method of testing low-frequency amplifiers should, I think, be one in which telephone receivers could be dispensed with. It is very difficult to make good telephone measurements at and below 250 cycles per second, yet, as we all know, the characteristics of the amplifier are required at frequencies down to something like 50 cycles per second.

Mr. R. C. Clinker (*communicated*): In connection with the paper, and also with Mr. Willans's contribution to the discussion, it may be of interest to describe a method of measurement due to Mr. C. G. Garton and used in the laboratory of the British Thomson-Houston Co., Ltd. This method can be applied to the determination of the amplification ratio of a low-frequency amplifier of any usual number of stages. It is used regularly for obtaining the frequency/ratio curves of low-frequency transformers, and has proved simple and accurate. In Fig. D (from which some items are omitted for clearness), T is the transformer under test. Its characteristic is to be determined when working with valves V_1 and V_2. The principle employed is to balance the voltage output from the secondary S against the drop across a known resistance R_2 which is placed in series with R_1 and carries a current measured by A. As the secondary voltage is out of phase with the drop across R_2, a mutual inductance M is inserted to provide a quadrature component and give a balance. Valve V_2 has its grid negatively biased, and serves as amplifier for headphones, H. A known audio-frequency voltage from source G is applied to the grid of V_1 by the drop across R_1. When a balance is obtained, the total amplification of one stage, consisting of valve V_1 and transformer T, is equal to $[(R_1 + R_2)^2 + M^2]/R_1$, and the tangent of the phase angle is $pM/(R_1 + R_2)$, where $p = 2\pi f$. For low frequencies a vibration galvanometer may be substituted for H, and a condenser shunted across R_1 for M. Section 3 of the paper shows some distortion effects obtained with the particular valve

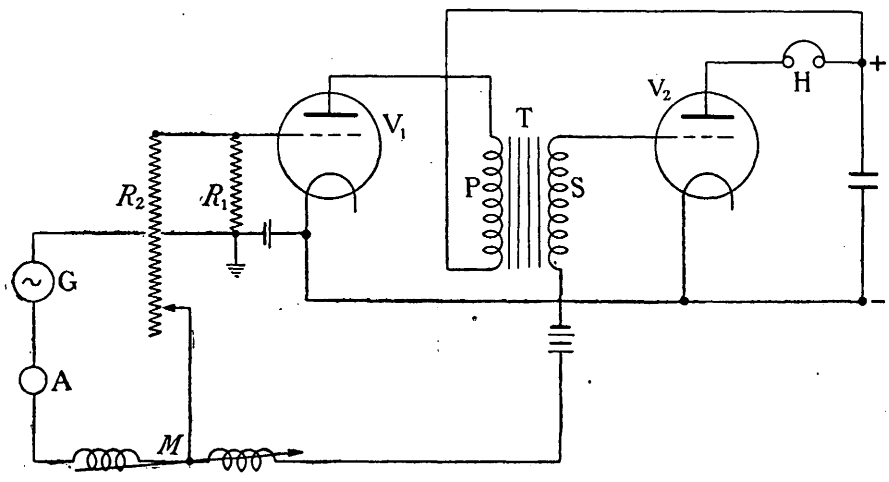

Fig. D.—Method of measurement of low-frequency amplification.

and transformer used, but although a curve is plotted in Fig. 23 no indication of the value of anode impedance of the valve is given. It would seem, however, that as distortion increased rapidly with the lowering of the frequency, the impedance of the valve must have been high in comparison with that of the transformer primary.

Mr. K. Sreenivasan (*communicated*): After everything is taken into consideration, the galvanometer method of measurement is decidedly superior to the telephone method from considerations of accuracy and sensitivity. Perhaps some simplification in the circuit and the apparatus used could be secured by either of the two following modifications: (*a*) Instead of using an audio oscillator for modulation purposes, a rotating contact breaker (or commutator) inserted in the oscillating circuit of the radio-frequency oscillator and driven at any required speed by a motor would do away with any necessity for the crystal circuit in order to detect the presence of harmonics. In this case an ordinary d.c. microammeter or galvanometer of the required sensitiveness will replace the vibration galvanometer. As the author remarks, a d.c. instrument keeps its calibration far steadier than a vibration galvanometer. (*b*) If an audio oscillator is indispensable, it would be a good plan to adopt a tuning-fork generator with the necessary arrangements in the output circuit. In this case a small 6-volt battery is all that is necessary. A tuning-fork generator not only works far more steadily than a tube oscillator, but is also remarkably free from harmonics, which are generally sources of trouble. The output will then be of constant frequency of great steadiness. The curve for the voltage amplification of a six-stage capacity-resistance amplifier is obviously obtained without any reaction introduced in the circuit. The average maximum amplification per stage comes to about 3·2, which is rather low. In view of the difficulties in working a resistance-capacity amplifier of more than four stages without self-oscillation, it appears to me that any steadying arrangements in this connection will reduce, more or less seriously, the individual, and so the overall, voltage amplification. It would be of some interest to know the amplification of a 2-, 3- and 4-stage resistance-capacity amplifier in order to have some idea of the fall in amplification per stage with an increase in the number of stages. Another aspect of resistance-capacity amplifiers about which one wishes to have more information is their behaviour with capacity reaction, say, between the grid of the first tube and the anode of the second, third or fourth tube. In a case like this it will naturally be difficult to reconcile experimental results with theoretically obtained values. The author's remarks in Section 2 regarding the resistance-variation method are very interesting. Experiments conducted in the Radio Laboratory at the Indian Institute of Science, Bangalore, with this method have given reasonably consistent results, variations from 5 per cent to 20 per cent being common, and 100 per cent extremely rare. These extreme variations were attributed to errors in reading the instruments. The resonance method, though very accurate, seems to be cumbersome and rather elaborate. I do not understand what "Reaction = 20," "Reaction = 30," etc., mean. Do these stand for any definite quantities or do they merely indicate the dial readings of the reaction coil? I should like to know if it was found necessary to adopt any system of shielding in order to avoid interference due to other radio or audio sources in the neighbourhood. This question arises because the author has used inputs of the order of those generally met with in reception. The adoption of the tuning-fork generator in the distortion experiments would have been of great advantage with regard to purity of wave-form. As a result of this investigation, I would ask the author if he can suggest any further remedies in minimizing the effects due to distortion. In the case of an amplification system consisting of a high-frequency amplifier, a detector and a low-frequency amplifier, how are the distorting effects due to the three individual portions related to the overall distortion? It is to be hoped that the author will give us later, comparative figures of the best performances of amplifiers of all the three types for a good range of frequencies. These would be extremely valuable to all interested in the design and building up of efficient and reliable amplifiers.

Mr. H. A. Thomas (*in reply*): With reference to the remarks of Prof. Fortescue, I would point out that the vibration galvanometer is capable of measuring an output of 6 μA, which is the current value for a medium telephone signal. The sensitivity range of this instrument is in fact that of weak telephone signals, and the galvanometer cannot be used for strong signals unless it is heavily shunted. I know of no other instrument which could be used for current measurement below 1 μA under the existing conditions.

In Section 2 I refer to the detrimental effect produced by inserting switching arrangements in the tuned input circuit, but in Section 1 there is no input circuit and the switches are permissible, as we are merely applying a small, known voltage to the amplifier input directly. Capacity effects have been calculated for this case and have been found negligible, as all leads are most carefully spaced. The screening methods adopted have been adequately defended by Dr. Smith-Rose, whose remarks answer the points raised.

The conclusions arrived at on page 261 are only meant to apply to the special case under investigation. In the absence of further comparative information it is not possible to extend these conclusions to other cases. In this particular case the observed results can be expressed mathematically if the amplifier input circuit is considered as a condenser and resistance in series, the chief merit of this conception of the input impedance being that the capacity component appears to remain sensibly constant under all conditions.

Mr. L. B. Turner asks for a more detailed account of the method of determining audibly the completely modulated condition for radio injection. I would refer him to Mr. Hollingworth, who has already given a statement of the method.

The minimum high-frequency output which can be measured by the use of the rectifier, audio amplifier and vibration galvanometer is 5 mV, taking the maximum sensitivity of the vibration galvanometer as 10 μA. If a thermionic tube voltmeter were used, the maximum sensitivity would need to be 5 mV, and this could be obtained with a balanced pointer instrument in the anode circuit. However, I do not see how this method has any advantages, since it will only give R.M.S. values, and will not help in the determination of the amplification of the fundamental alone. A high-frequency resonance instrument or cathode-ray oscillograph is necessary for this purpose.

I think that the measurement of coupling values and currents would be so indirect that a heterodyne method of obtaining an audio output would give little accuracy. The frequency of both the injecting radio source and the heterodyne would have to be perfectly constant to give a constant-frequency beat note, thus requiring fork-driven circuits. However, since the resonant frequency of the vibration galvanometer is constantly changing, and is difficult to keep in adjustment, the audio source is very slightly variable to allow the galvanometer resonance condition to be tuned to. With constant oscillator and heterodyne the output beat note is inflexible in frequency, and thus the galvanometer would require adjustment for every reading.

I admit that the current transformer used is not a particularly good one, although the reason is not easy to find, as the iron section is large. The curve shown in Fig. 2 is merely given as the ratio calibration of the particular transformer used.

I wish to thank Mr. Turner for his helpful suggestion concerning the potentiometer and the current transformers. Small errors have been observable in this transformer, and the removal of the primary winding from the high-potential end of the oscillator has given greater accuracy. As the screening methods are improved it is found unnecessary to earth any point, in which case the whole system is effectively screened.

The amplifier used to obtain the curve shown in Fig. 6 was of the 3-stage tuned-transformer type, using bright R valves and 100 volts high tension, and, as is usual with such an amplifier, the grids were connected to the negative end of the filament. Negative bias causes oscillation when several stages are coupled in cascade and tuned.

I wish to thank Mr. Hollingworth for his remarks, which materially help to give a clearer concept of the purpose of the work. He has also effectively given the reasons why the audible 100 per cent modulation determination is comparatively accurate.

I am glad the experience of Col. Edgeworth tallies so well with my own. I am pleased to say that I hope in the near future to progress along lines such as he suggests. Large valves will be used and special transformers of known constants adopted for the purpose of determining the production of harmonics by the iron core.

With reference to the remarks of Major Lee, the case given in the paper before the American Institute of Electrical Engineers by Bennett and Peters is not a parallel case to the one I have cited. In my case the grid is directly connected to the tuned circuit, and retroaction takes place from the anode circuit into this tuned circuit. Surely, however, the best reply I can give is that, since the resonance curves obtained gave the same value of decrement for all cases taken on the curve, these curves *do* represent the condition of a circuit which has a constant apparent resistance for small changes of frequency. If rapid changes in resistance and reactance values had occurred over a small change in frequency, the resonance curves could not have given one value only for the effective high-frequency resistance.

I would point out that the input voltage applied to the amplifier for these tests was of the order of 10 μV, the oscillator used being 15 ft. away from the tuned receiving circuit. A powerful oscillator was used only for the determination of the normal high-frequency resistance of the circuit without an amplifier, and thus the suggestion that grid currents existed can only apply to the case of the weak input. In this case there was a 3-volt negative bias on each valve and the last valve had an input of only 200 μV upon its grid.

In the advance copies of the paper there was a slight error in the text in Section 3 (*a*), paragraph 3. I have now altered this to read: "If harmonics were present, the same apparent sound intensity could be obtained with R.M.S. values of current but one-sixth of the current required if the wave was sinusoidal." In paragraph 4 of the same Section I mean to infer that with an amplification system consisting of a rectifier followed by audio stages, great amplification due to high-frequency retroaction can be obtained, but the distortion due to the overloading of the audio amplifier may be so great that the output signal is of little readable value.

Dr. Smith-Rose has adequately stated the position that the National Physical Laboratory must adopt regarding the testing of commercial radio goods. Until we can interpret the behaviour of an amplifier in terms that will be of immediate practical utility to the manufacturer, we do not feel justified in testing apparatus of this kind. He has also answered the questions raised by Prof. Fortescue in connection with the screening methods adopted. As a result of some recent tests it has been found that 96 per cent of the external field is eliminated at a wave-length of 350 m and 94 per cent at a wave-length of 10 000 m. When one considers that the main oscillator is efficiently screened in a completely lined metal box, reducing the field to about 10^{-4} or 10^{-5} of the original, I think it must be admitted that the screening, although not perfect, is quite sufficient for most purposes.

The reasons for abandoning the inserted-resistance method raised by Mr. P. K. Turner are dealt with in the paper. The effect of this inserted resistance is to modify the amplifier conditions. It would, of course, be possible to duplicate the mechanical shape in copper and then in resistance wire, if that were the only difficulty. However, since I know of no one who claims high accuracy for this method when applied to the measurement of the high-frequency resistance of a tuned circuit the resistance of which is partly neutralized by the retroaction of an amplifier, I felt justified in obtaining more accurate results by the resonance method which, although complicated, yielded very excellent and consistent results. The curves given for the load introduced by the amplifier apply only to the case of a rectifier followed by audio stages. The question of the effect of high-frequency stages has not yet been dealt with. It is apparent from a perusal of Fig. 18 that the grid voltage vector E_c is *not* in phase with the retroacting E.M.F. E_b.

The remarks of Mr. Willans are more of the nature of a separate statement of a method of measuring stage amplification than a criticism of the paper. However, the method which he has given is not without interest.

I cannot see why screening the oscillator is deemed unnecessary. Surely induction effects between the two valves used cannot be separated from the actual amplification of the system. The output valve is not working under normal conditions. The secondary of the transformer has certainly the load due to the grid-filament impedance of a triode, but this triode has no output impedance and, as Miller has shown, the input impedance will be modified seriously by this departure from actual conditions.

The method is essentially limited by the sensitivity of the human ear to pick out zeros of the fundamental in the presence of harmonics. At low acoustic frequencies, e.g. those below 200, this is very difficult, as pointed out by Dr. Smith-Rose. I cannot see that the apparatus is simple. A bridge of the type shown is essentially a complex piece of apparatus. I feel that more care should be taken over the many leads with their capacity and inductive effects. He speaks of a $\frac{1}{2}$ volt as being a small output voltage. I personally consider this to be very large, my measurements rarely exceeding 5 mV on the output valve.

Mr. Clinker's remarks, like those of Mr. Willans, do not bear very definitely upon the main subject of the paper. He describes a method of measuring the stage amplification of one audio valve and transformer, and adds yet another method to the many already in use. I would point out first what is surely a mathematical error. The amplification of the stage must be

$$\{(R_1 + R_2)^2 + (\omega M)^2\}/R_1$$

and not $\{(R_1 + R_2)^2 + M^2\}/R_1$ as he gives it.

This method requires the calibration of a mutual inductance and two variable resistances and appears to be unduly complicated. The calibration of the mutual inductance over a wide range of frequencies is by no means a simple matter and the final result is dependent upon a zero telephone balance which at low frequencies gives a rather poor sensitivity. Finally, the last valve is not working under normal conditions, since there is no oscillating current in the anode circuit. If the amplifier is modified by the insertion of the suggested apparatus, the amplification figure will be sensibly different from the normal case of a loaded output and an absence of the measuring gear. It has been my experience that any insertion of measuring apparatus intermediate to the input and output terminals may completely modify the performance of any amplification system.

Whilst I appreciate the suggestions made by Mr. Sreenivasan, I feel that the modification suggested would lead to an unnecessary complication of the apparatus rather than a simplification. If the radio oscillations were chopped in the manner suggested, the resultant envelope wave-form of the modulated continuous-wave output would seriously depart from the original rectangular wave-form, and the d.c. instrument in the last stage of the amplifier would of course give the R.M.S. value of this wave. It would consequently be difficult to interpret the amplification, as the output wave-form would depend upon the number of stages used in the amplifier. Charging effects, time-lags, and transient starting and stopping conditions of the high-frequency oscillations would all tend to distort the original rectangular wave-form. I think that a tuning-fork arrangement for providing the audio modulation would not give the output required, especially in those cases where the audio oscillator is used to supply the input to a pure audio amplifier. A master control of the main oscillator could be arranged, operated by a self-maintained fork, but this constancy in frequency is not required for this class of work, as the vibration galvanometer itself does not preserve its resonant frequency accurately and the audio oscillator has to be slightly varied in frequency to tune to the galvanometer for every reading.

It must be remembered that the one oscillator is used for a dual purpose :—

(*a*) As a modulator for high-frequency injection.
(*b*) As the direct injecting agent for low-frequency injection.

I agree that the maximum permissible stage amplification before oscillation occurs falls as the number of high-frequency stages is increased. Unfortunately I have no comparative figures to give definitely, but I have not noticed that the first stages give a greater factor than the last. All seem to be equally affected.

The problem of intervalve coupling and its effect upon overall amplification is an exceedingly difficult one, which is to be more fully investigated in the near future.

The resonance method is admittedly more complicated than the inserted-resistance method, but is justified on the score of accuracy. It is possible to obtain an accuracy of 1 per cent with this method, and this is, as the speaker states, greater than the experimental accuracy of other methods.

"Reaction = 20," "Reaction = 30," etc., are meant to signify the settings of the reaction coil in terms of the particular scale used. The amplifier is completely screened in a special room, the radio oscillator is screened with metal plate, all leads are well spaced and screened in metal-lined trunks, and finally the measuring control panel itself is shortly to be enclosed in a large metal-gauze screen, thus forming the final link in a completely screened piece of apparatus.

It is early to consider remedies to minimize distortion in low-frequency amplifiers, the causes of such distortion being as yet an unsolved problem. When the causes are understood, methods of elimination will be considered. The distortion so far considered is entirely that occurring in the audio side of the amplifier.

A special cathode-ray oscillograph equipment, nearly completed, will examine the high-frequency distortion produced. It has also been demonstrated recently that distortion takes place in the rectifier due to the modulated nature of the applied input.

I would point out in conclusion that the many combinations that require examination are such that the final statement of the observed results cannot be given until much more work has been done. Only by a careful examination of each case can a thorough understanding be obtained, and the results must of necessity be slow in appearing.

INSTITUTION NOTES.

Faraday Medal.

The Council have made the fifth award of the Faraday Medal to Colonel R. E. B. Crompton, C.B., Honorary Member and Past-President of the Institution.

North Midland Centre.

Mr. H. Cecil Fraser has been appointed Hon. Secretary of the North Midland Centre, to fill the vacancy caused by the death of Mr. J. D. Bailie.

Informal Meetings.

The Smoking Concert which was to have been held on the 15th March at the Engineers' Club has been cancelled by the Informal Meetings Committee.

The following Informal Meetings have been held :—

71st Informal Meeting (26th October, 1925).

Chairman : Mr. R. A. Chattock (President).

Subject of Discussion : " How can the Cost of Distribution be cheapened " (introduced by Mr. R. A. Chattock).

Speakers : Messrs. P. Rosling, W. Brown, A. F. Harmer, T. Rich, W. E. Rogers, G. H. Stevens, W. P. Fanghanel, H. Richardson, N. W. Prangnell, D. G. Hurlbatt, W. F. Andrews, E. S. Ritter, J. S. Rann, C. D. King, J. Coxon.

72nd Informal Meeting (9th November, 1925).

Chairman : Mr. A. H. Allen.

Subject of Discussion : " Modern Developments of Telephone Cables " (introduced by Mr. E. S. Ritter).

Speakers : Messrs. W. E. Twells, T. W. Riley, A. C. Rosen, W. Day, G. C. Marris, S. M. Catterson, J. Coxon, A. F. Harmer, F. Tremain, M. D. Hart, J. W. Wheeler, H. T. Werren, Major A. G. Lee, Mr. A. H. Allen.

73rd Informal Meeting (23rd November, 1925).

Chairman : Mr. J. Coxon.

Subject of Discussion : " The Testing of Large Electric Plant " (introduced by Mr. E. E. Tasker).

Speakers : Messrs. F. Creedy, M. D. Hart, W. E. Highfield, J. F. Shipley, W. E. Rogers, J. Coxon, J. R. Bedford, W. A. Erlebach, R. Samphier, A. Barraclough, W. J. Minton, R. D. Gifford, D.Sc., C. L. Lipman, D. G. Hurlbatt.

74th Informal Meeting (7th December, 1925).

Chairman : Mr. P. Dunsheath, O.B.E., M.A.

Subject of Discussion : " Design and Performance of Protective Relays " (introduced by Mr. C. L. Lipman).

Speakers : Messrs. R. D. Gifford, D.Sc., A. G. Hilling, F. E. Ockenden, J. F. Shipley, E. S. Ritter, G. N. Wright, F. H. Nalder, — Laws, H. S. Petch, H. Lloyd Williams, F. Pooley, P. Dunsheath, O.B.E., M.A., Col. K. Edgcumbe.

75th Informal Meeting (11th January, 1926).

Chairman : Mr. A. G. Hilling.

Subject of Discussion : " The Electrical Installation in the Rockefeller Building, University College " (introduced by Mr. W. C. Clinton, B.Sc.).

Speakers : Messrs. H. T. Young, J. R. Bedford, W. E. Rogers, G. C. Allingham, E. H. Freeman, C. L. Lipman.

76th Informal Meeting (25th January, 1926).

Chairman : Mr. C. L. Lipman.

Subject of Discussion : " Impressions of my Visit to America, mainly about Switchgear " (introduced by Mr. H. W. Clothier).

Speakers : Messrs. H. Trencham, M. D. Hart, A. F. Harmer, R. C. Andersen, — Ferguson, G. M. Davies, Col. K. Edgcumbe, Messrs. D. Kingsbury, C. L. Lipman.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 December, 1925–25 January, 1926 :—

	£	s.	d.
Abbott, A. J. (London)		5	0
Abraham, F. H. (Bradford)		5	0
Adams, G. H. (London)		10	0
Addis, E. (Crewe)		3	6
Alabaster, E. O. (Hong-Kong)		5	0*
Alabaster, H. (Eastbourne)	2	2	0*
Aldridge, D. W. (Prescot)		5	0
Aldridge, T. H. U. (Shanghai)	5	0	0*
Allan, R. H. (Swansea)		5	0
Allen, A. H. (London)	1	1	0*
Allen, R. G. (Leigh-on-Sea)		3	6
Allen, S. T. (Wolverhampton)	1	0	0*
Allom, G. F. (London)	1	1	0*
Allsop, D. (Manchester)		3	6
Ambrose, E. (London)		5	0*
Andersen, R. C. (London)	1	0	0
Anderson, A. (Motherwell)	1	0	0
Anderson, E. W. (Bristol)		5	0
Anderson, H. M. (Glasgow)		15	0
Anderson, J. (Birmingham)	1	5	0
Andrew, T. S. (Hebburn-on-Tyne)		10	0
Andrews, A. E. D. (London)		3	6
Andrews, O. M. (London)	1	1	0
Angold, A. E. (Birmingham)	1	1	0*
" Anonymous "	1	0	0
" Anonymous "		3	6

* Annual Subscriptions.