# Load Carrying Capacity of Amplifiers

By F. C. WILLIS and L. E. MELHUISH

SYNOPSIS: This paper describes the adaptation of the cathode ray oscillograph to the determination of the overload point of vacuum tube amplifiers. Using the input voltage to produce a horizontal deflection, and the output voltage or current to produce a vertical deflection, the amplifier performance is readily determined by noting the resulting figure on the fluorescent screen. So long as the figure is virtually a straight line or an obviously undistorted ellipse, it was found that the amplifier output is free from harmonics. As soon as overloading begins, the oscillogram shows either a sharp bend at either or both extremities of the line or apparent distortion of the ellipse. The method has the advantage of being quick.

IN any device used for the amplification of a complex electrical wave such as that necessary for the transmission of speech or music, distortion may arise in two ways. (a) The amplification may not be the same for all frequencies in the band to be transmitted. (b) The relationship between input voltage and output current may not be such as can be described by a straight line when r.m.s. values are plotted against each other.

Considering the distortion due to cause (b) alone it is true that for most practical devices the relationship between input and output can be described by a curve which is approximately straight for a portion of its length but as the amplitude of the wave to be transmitted increases, operation is over a longer portion of the curve and it ceases to be possible to regard the characteristic curve as straight. It therefore becomes necessary to determine for any design the maximum energy that the system can carry without noticeable distortion from this cause. For a system intended to transmit speech or music the final decision as to how much distortion is permissible must depend upon the judgment of the expert listener but analytical methods are of service in establishing reference points by measurements which can be duplicated without reference to any particular person. The purpose of this paper is to describe some work undertaken for this purpose.

Departure from the ideal straight line relationship between input and output results in the production of harmonic overtones of all the frequencies present in the input and in the production of beat notes between frequencies if there is more than a single frequency in the input. It follows from this that if a complex wave is passed through a device having a characteristic of this nature the output will differ from the input in the proportion of the different frequencies and may contain frequencies that were not present in the input at all. A change in the proportion of the different frequencies may be partly due to cause (a) but the introduction of new frequencies can only be due to cause (b). As is now known (BELL SYSTEM TECHNICAL JOURNAL October, 1923) the response of the ear itself is non-linear so that subjective harmonics and sum and difference tones are heard by every listener. Under good conditions, therefore, the distortion produced by the non-linear transmission of the amplifier will be so small compared to that produced in the ear itself that it will not be noticed. On the other hand, it may be so great as to render unrecognizable the speech or music being transmitted. This condition will be familiar to everyone who has been compelled by an enthusiastic friend to listen to a heavily overloaded radio receiver.

The principal parts of a vacuum tube amplifier where one might expect to find the non-linear response under consideration are in the magnetic circuits of the transformers and retard coils and in the vacuum tubes. Generally, in the amplifiers considered in this paper, the design of the transformers is such that the magnetic flux density is small so that the magnetization curve is practically a straight line and very little distortion is to be expected from this cause. On the other hand the $E_c - I_b$ characteristic of the vacuum tube is approximately straight for only a small portion of its length and has a pronounced curvature in the usual working range. This is the case even for well designed circuits where under proper operation there is no possibility of the grid of the tube drawing current. It is therefore, in the characteristics of the vacuum tubes that the principal source of trouble of this nature is to be looked for. That this anticipation is justified will be shown by the results described in this paper.

The relationship between output and input of a vacuum tube has been studied from a mathematical viewpoint and formulae have been established by which the resultant output for a given input may be calculated provided the tube parameters and circuit impedances are precisely known. For any commercial amplifier having several stages the measurement of these quantities and the necessary calculations would be a slow procedure. By experimental methods it is possible to determine directly and quantitatively the distortion that occurs in any particular case. This has been done for a number of amplifiers under various load conditions with a view to establishing convenient criteria by which it is possible to determine quickly and easily how much energy any amplifier will transmit without serious distortion. The amplifiers dealt with were all audio-frequency amplifiers so that no questions of radio frequency amplification or of intentional rectification or modulation are considered and the measurements were all made with single frequency inputs as this naturally forms the basis for a more complete analysis of the problem. Three kinds of measurements were made.

1. The gain of the amplifier was measured under load conditions which varied from a point well below its carrying capacity to a point where it was obviously overloaded. The results from tests of this kind show that the gain is uniform at low outputs, begins to fall off when the output reaches a certain level and falls off more and more rapidly as the load is further increased. The point at which the gain begins to fall off has sometimes been taken as a criterion of the load carrying capacity of the amplifier.
2. With a single frequency (1,000 c.p.s.) input to the amplifier the output was analyzed at a number of points along the load-gain curve and the percentage of harmonic to fundamental in the output plotted against the same scale of energy output as for the load-gain curve.
3. The input voltage was made to produce a horizontal deflection in a cathode ray oscillograph while the output voltage or current was made to produce a vertical deflection. In effect this is a convenient means of drawing the input-output characteristic of the amplifier so that its general curvature and the loads at which any sudden changes of curvature occur may be easily observed. For an amplifier that produced no distortion or phase shift, the resultant figure would be a straight line whatever the wave shape of the input. If there were phase shift but no distortion the result would be an ellipse or circle depending on the phase and amplitude relationships of the input and output provided the input were a pure frequency. In general for the practical case the result is a distorted ellipse showing that the wave undergoes both distortion and change of phase in passing through the amplifier. With increasing load the distortion becomes more and more pronounced.

The gain measurements were made by methods in principle the same as those embodied in standard gain measuring sets of the Bell System, and while it is not the intention of this paper to give a detailed description it may be desirable to give a brief statement of the principles involved. For the purposes of this paper the gain of an amplifier is defined as the logarithm of the ratio of the power delivered into its load impedance to the power that would be delivered if the amplifier were removed and replaced by the best possible passive network.

Thus

$$N_{TU}=10\ \mathrm{Log}_{10}\left(\frac{W_o}{W_i}\right).$$

In practice an amplifier is almost always measured between impedances that are pure resistances. These impedances are set up by variable resistance networks so designed that when the current in one mesh of the input network is equal to the current in a mesh of the output network the gain of the amplifier may be read from the settings of the dials and switches controlling the networks. An indicating device which may be switched from the input network to the output network indicates when the currents in the two meshes mentioned are equal. Where sufficient energy is available a thermocouple is used as the indicating device. It follows that measurements are then always in terms of r.m.s. values of the currents employed. So long as these currents are approximately single frequency the r.m.s. value of the whole wave is very nearly equal to the r.m.s. value of the fundamental. In all the experiments described here gain measurements were made by thermocouple and as will be seen later the proportions of harmonics were such that unless the amplifier was overloaded the discrepancy between the r.m.s. measurements made and those that might be made by methods taking account of the fundamental only was usually less than 1%, and in the cases of extreme overload less than 5%.

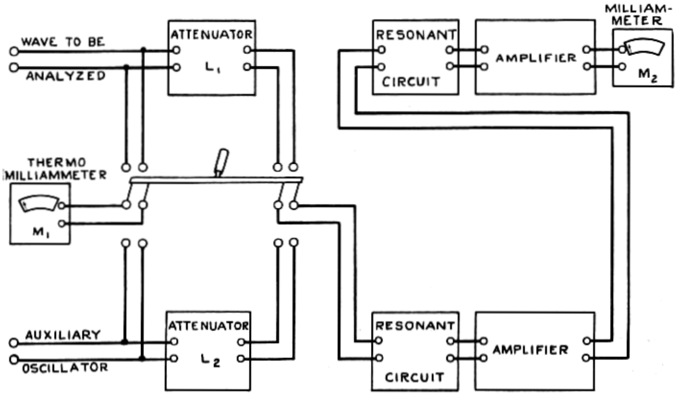

Fig. 1—Circuit for harmonic analysis

The harmonic analyses were made by an electrical analyzer whose principles of operation are indicated in Fig. 1.[1] In operating this

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[1] The principles of this analyzer are fully described in a paper by Mr. A. G. Landeen to be published in the *B. S. T. J.*

analyzer the resonant circuits of the amplifier detector and the auxiliary oscillator were tuned to the harmonic to be measured. The input currents and the attenuators $L_1$ and $L_2$ were adjusted so that the readings of meters $M_1$ and $M_2$ did not change when the four-pole, double-throw switch was thrown from one position to the other. It will be seen that the difference between the settings $L_1$ and $L_2$ then gives the proportion of harmonic to total r.m.s. value of the output wave of the amplifier. The proportion of harmonic necessary to cause a 1% change in the r.m.s. value of a wave is approximately 14% and for the values obtained in the experiment the r.m.s. value of the output could be taken as equal to the fundamental in the output. The difference between $L_1$ and $L_2$ therefore gives the proportion of harmonic to fundamental. In the present work the difference between the frequencies to be separated was large enough to avoid any difficulty in obtaining sufficient resolution by the use of simple resonant circuits.

It is, of course, necessary that for measurements of this kind the current supplied to the amplifier under test should be a single frequency. A vacuum tube oscillator which was known to give a very pure wave was used as the source of current. To obtain sufficient energy for all the measurements made it was necessary to amplify the output current from this oscillator and subsequently filter it to remove the harmonics introduced by the amplifier. Final analysis of the wave applied to the amplifier under test showed in most cases less than 0.2% and in all cases less than 0.5% of third harmonic and less than .1% of all other harmonics. Greater purity could have been obtained at the expense of more time and trouble but this was considered sufficient for the purposes in view. Where necessary a small correction for the harmonic content of the input wave has been applied to the results.

The voltages to operate the cathode ray oscillograph were obtained by a step-up transformer for the input and directly off a resistance potentiometer for the output. The use of a step-up transformer for the output wave is in general undesirable because it introduces phase and amplitude changes which differ for the component frequencies of the wave and thus the transformer itself introduces a distortion which renders the interpretation of the figure as applied to the amplifier distortion more difficult. This limits the method to cases where a minimum of 10 volts is available in the output. For the amplifiers dealt with here this voltage was available and the limitation was not felt. On the input side the step-up transformer has to transmit one frequency only so that the same difficulty does not occur. Pictures of the figures obtained on the fluorescent screen were taken with an ordinary camera with from one to three-minute exposures. On most of the pictures the horizontal and vertical axes were also recorded on the screen.

The circuits of the amplifiers dealt with and the results of the analyses are graphically presented in the following figures. Amplifier

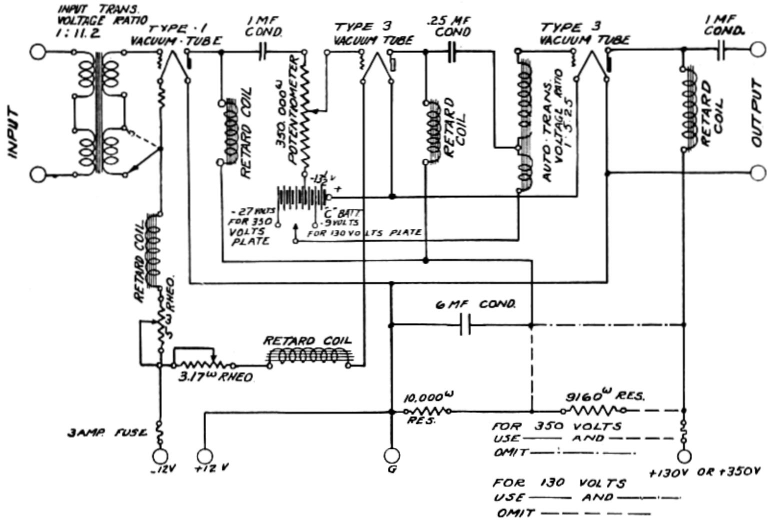

Fig. 2—Amplifier No. 1

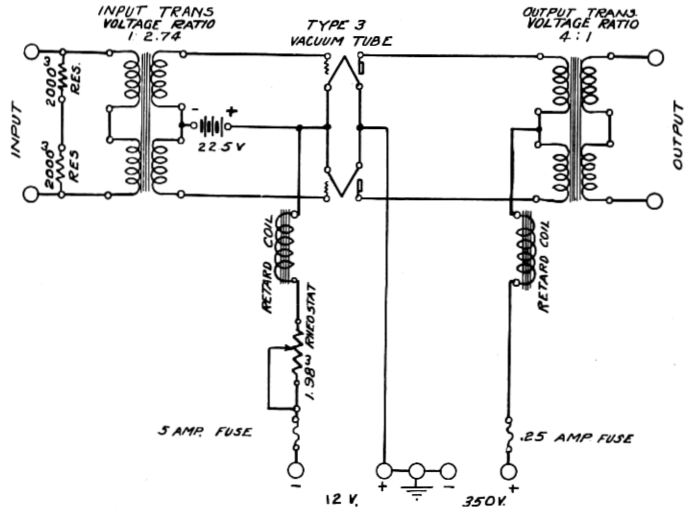

Fig. 3—Amplifier No. 2

No. 1 shown in Fig. 2 is used for amplification from very low up to medium powers in Public Address, Radio Broadcasting and similar systems. Provision is made for operating this amplifier on either 130 or 350 volt anode potential and tests were made under both these conditions. This amplifier is designed to work from an impedance of 200 ohms into one of 4,000 ohms. Amplifier No. 2 shown in Fig. 3

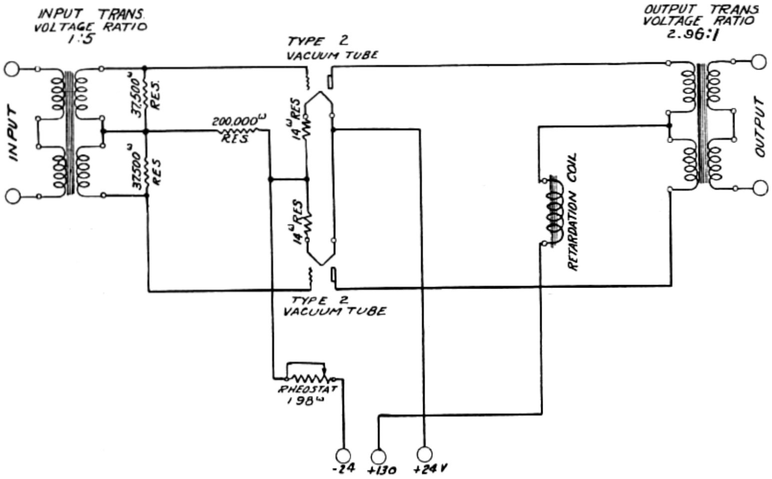

Fig. 4—Amplifier No. 3

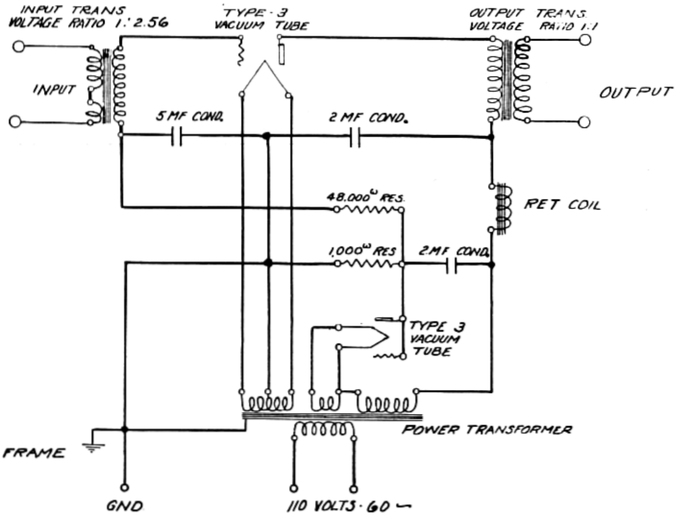

Fig. 5—Amplifier No. 4

follows amplifier No. 1 as the final output stage of a Public Address System and as shown consists of one stage with tubes in the push-pull arrangement. To match amplifier No. 1 its input circuit is designed for 4,000 ohms and its output is stepped down by a transformer to 500 ohms. Amplifier No. 3 shown in Fig. 4, also a push-pull amplifier, is designed as the output stage of an oscillator used in field measurements in the telephone plant. Its input and output impedances are 2,000 ohms and 600 ohms, respectively. Amplifier No. 4 is intended for use in radio reception, amplifying the signals to loud speaker volume and operating from 110 volt, 60 cycle A.C. supply. As shown there is one rectifying tube for converting the 60 cycle a.c. to d.c. for supplying the anode of the amplifying tube. Its rated input and output impedances are 20,000 ohms and 4,000 ohms, respectively.

As will be noted from the diagrams there are employed in these amplifiers three types of vacuum tubes. The normal operating voltages and average characteristics of these tubes are shown in Table I.

TABLE I

| | Filament Current | Anode Volts | Grid Biasing Volts | Anode Current Milli-amps. | Amplification Factor $\mu$ | Anode-Filament Impedance Ohms. |
|---|---|---|---|---|---|---|
| Vacuum Tube Type 1 | 1.00 | 130 | − 1.6 | 0.7 | 30 | 60,000 |
| Vacuum Tube Type 2 | 1.00 | 130 | −20 | 25.0 | 2.5 | 2,000 |
| Vacuum Tube Type 3 | 1.6 | 350 | −27 | 25.0 | 6.5 | 4,000 |
| Vacuum Tube Type 3 | 1.6 | 130 | − 9 | 5.0 | 6.5 | 8,000 |

The harmonic analyses and load-gain curves of the amplifiers under the conditions noted are shown in Figs. 6, 7, 8, 9 and 10. The gain in transmission units and percentage of each harmonic up to the 5th together with the root of the sum of the squares of these percentages being plotted against watts output on a logarithmic scale. The oscillograph pictures taken at various points along these curves are shown in Figs. 11, 12, 13, 14 and 15.

As stated above, the oscillograph figure presents the input-output curve of the amplifier. Furthermore, if there is no distortion in the transformers, the horizontal deflection will be proportional to the alternating grid voltage applied to the first stage while the vertical deflection will be proportional to the alternating component of the plate current in the last stage. The figure drawn is then the dynamic $E_c - I_b$ charactertistic of all the tubes combined. That this is substantially the case may be seen by inspection of the figures. In the first oscillogram of Fig. 11 there is shown the characteristic for amplifier No. 1 under 130 volts plate supply and .047 watts output where the amplitude of grid voltage is such that no grid becomes positive with respect to the filament nor is the plate current reduced to zero at any part of the cycle. Under these conditions the tube characteristic as shown in the oscillogram has the same nearly parabolic shape as is found by other methods. The analysis made at this point showed 7.3% second harmonic, .8% third and less than .1% fourth and fifth harmonics. The mathematical analysis of the problem expresses the $E_c - I_b$ characteristic of the tube by a power series and shows that the coefficient of the second power term in the series is the principal factor in producing second harmonic. The percentages of harmonic given therefore are such as would be obtained from a tube having a nearly parabolic characteristic.

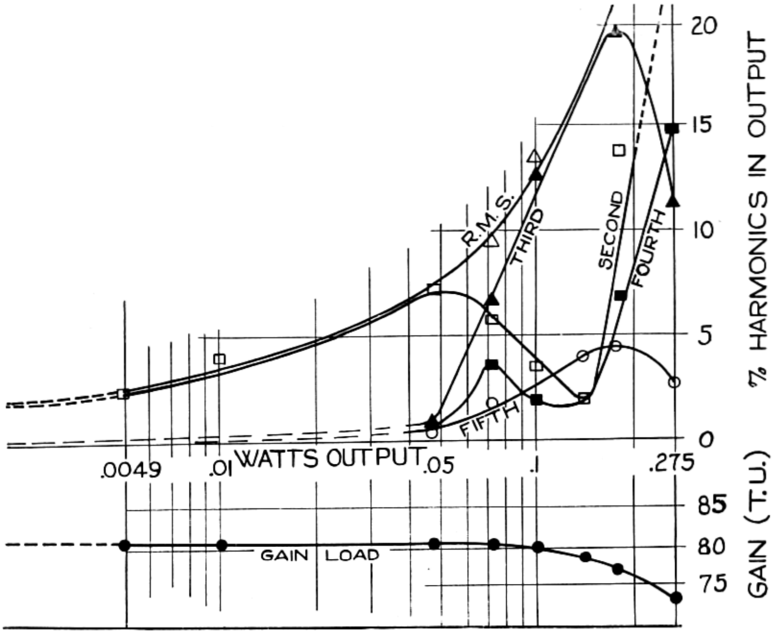

Fig. 6—Amplifier No. 1—Plate voltage 130-V, 1,000 c.p.s. input. Variation of gain and distortion with output

Analyses made at lower outputs showed that the amount of second harmonic present varies with the power output in a manner described by a slightly curved line on the logarithmic scale used (Fig. 6). The third and higher harmonics are negligible at low outputs but at

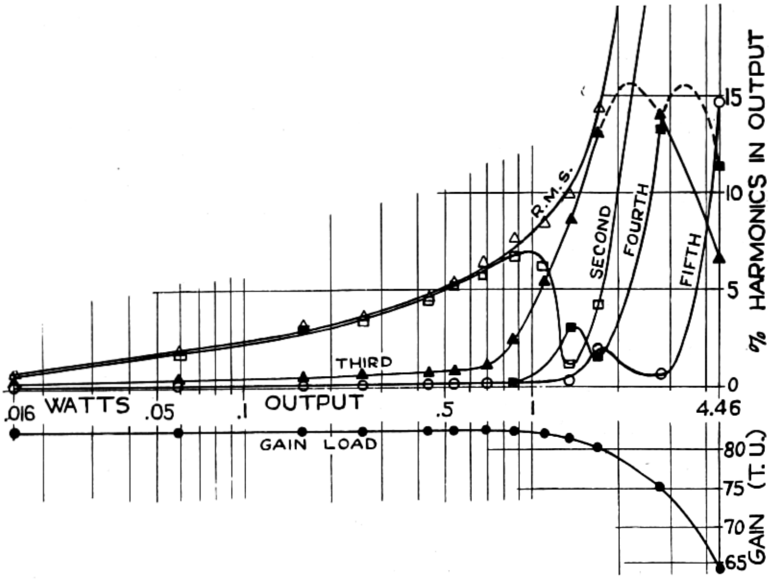

Fig. 7—Amplifier No. 1—Plate voltage 350-V, 1,000 c.p.s. input. Variation of gain and distortion with output

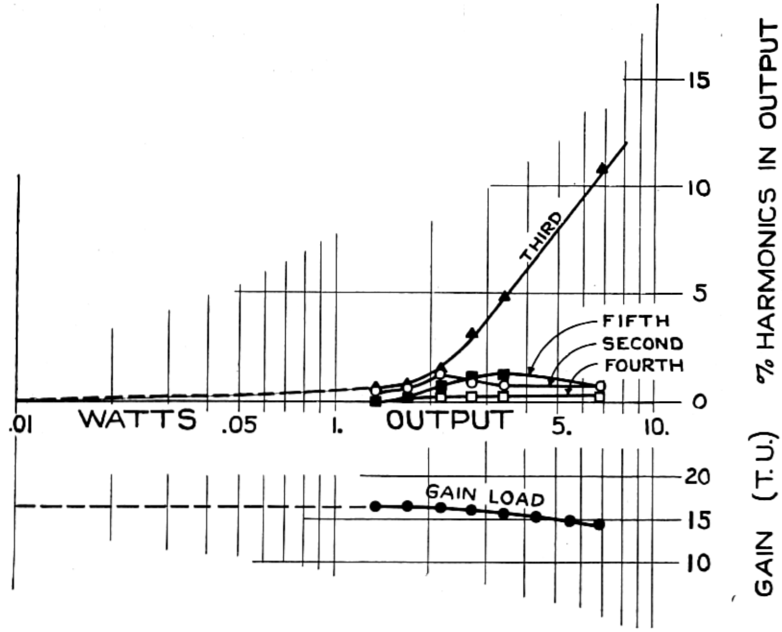

Fig. 8—Amplifier No. 2, 1,000 c.p.s. input. Variation of gain and distortion with output

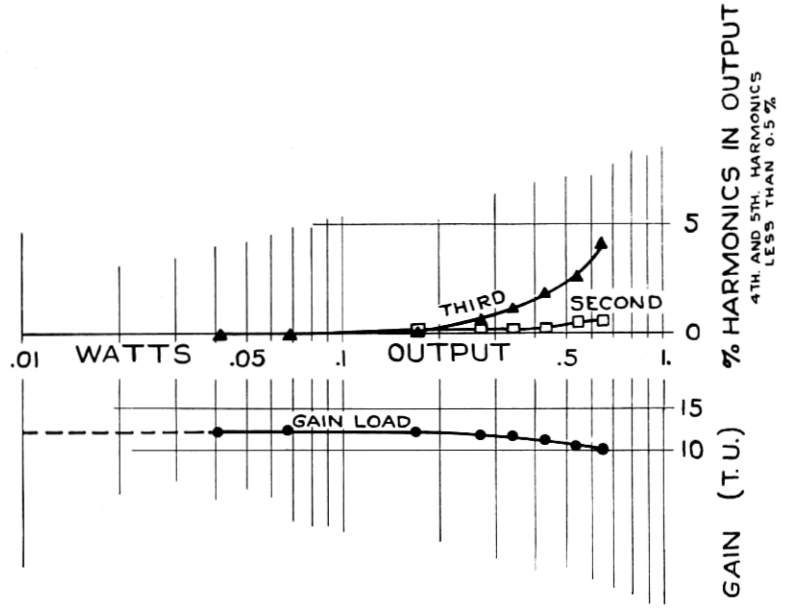

Fig. 9—Amplifier No. 3, 1,000 c.p.s. input. Variation of gain and distortion with output

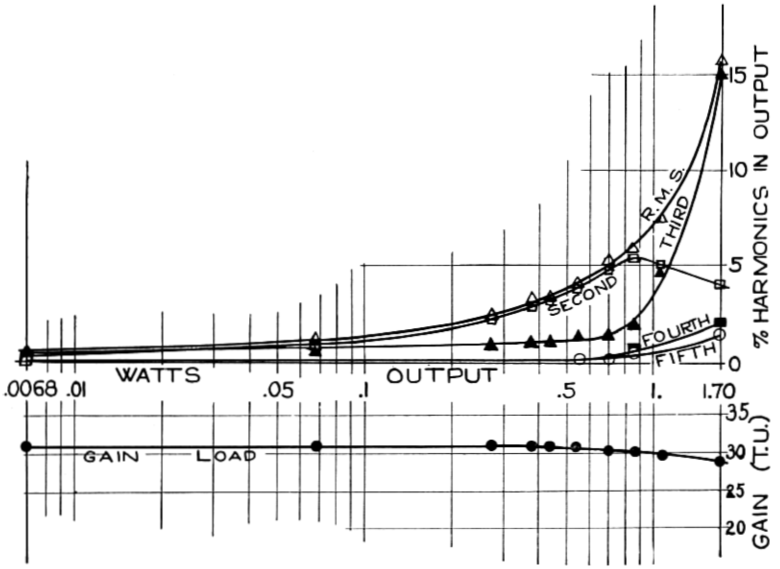

Fig. 10—Amplifier No. 4, 1,000 c.ps. input. Variation of gain and distortion with output

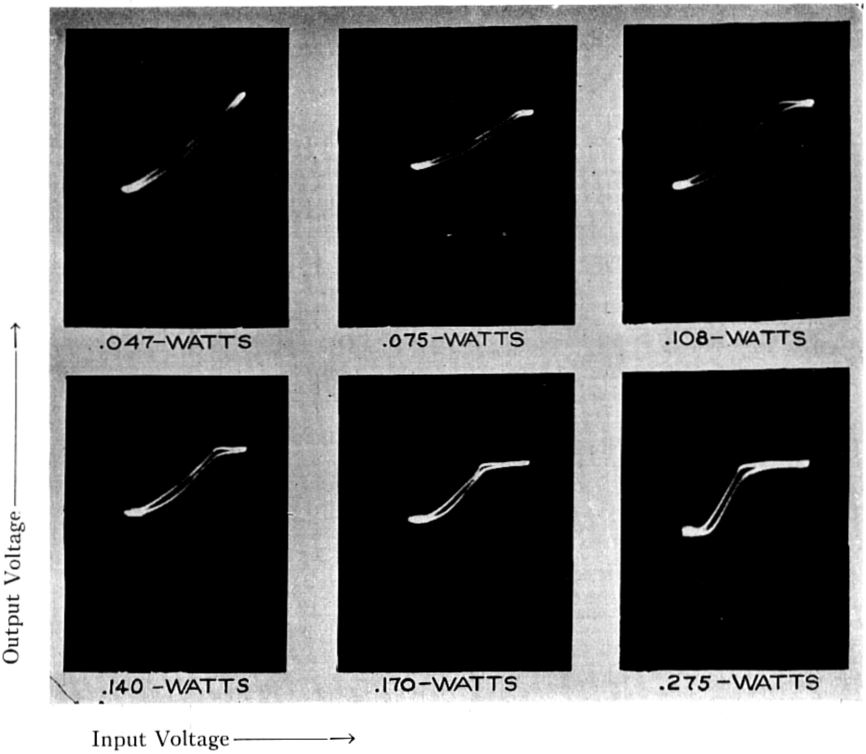

Fig. 11—Amplifier No. 1; 1,000 c.p.s.; load 4,000 ohm resistance, 130 volt plate supply

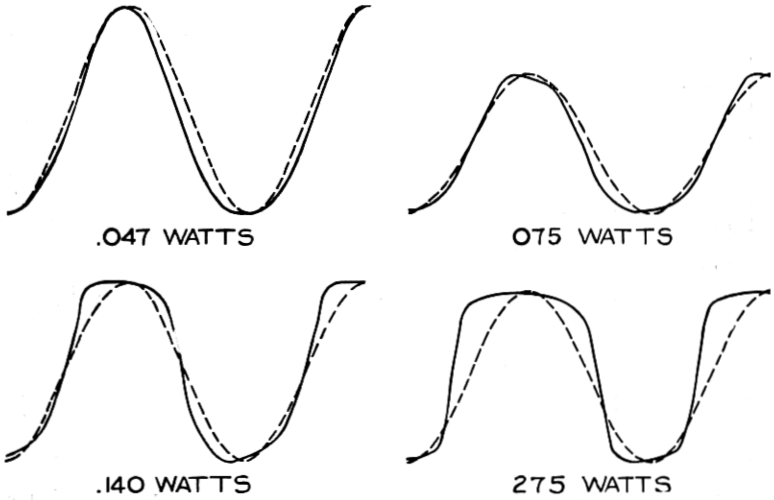

Fig. 11-A—Projection of output wave from oscillograms of Fig. 11

outputs above .05 watts the third harmonic increases rapidly and then falls somewhat while the second harmonic falls to a minimum of about 2% at .14 watt output and then increases rapidly. The fourth and fifth harmonics follow similar cycles of increase and decrease, the fourth following the second and the fifth the third.

To assist in interpreting the stages in the tube overloading at which these changes in the percentages of the different harmonics take place the waves corresponding to the vertical deflections of some of the oscillograms have been projected against a time axis by an appropriate geometrical construction, assuming the horizontal deflection a sine wave as it very nearly was.

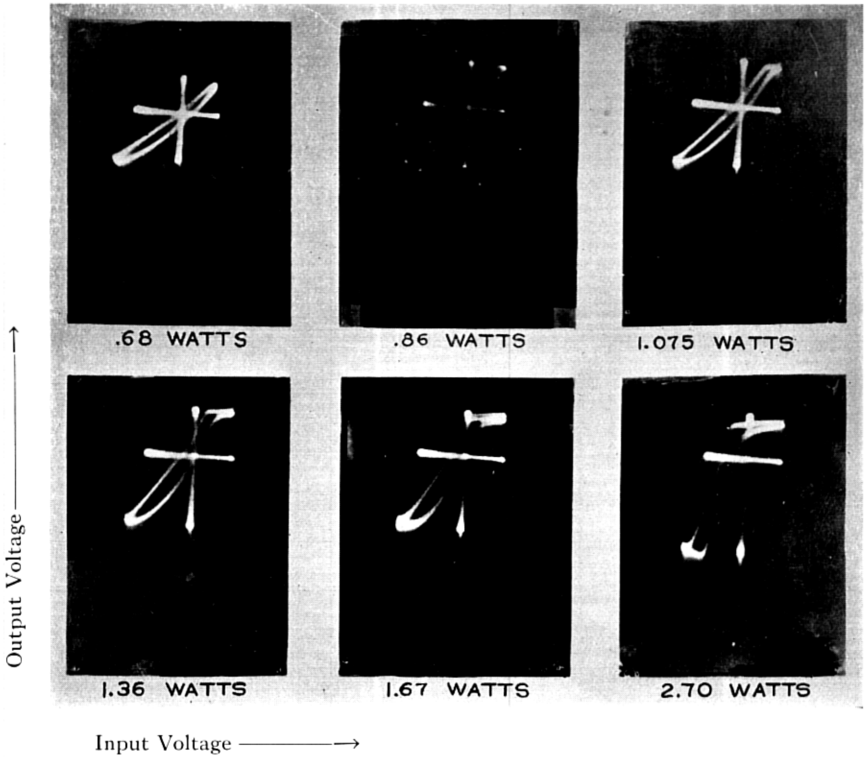

Fig. 12—Amplifier No. 1; 1,000 c.p.s.; load 4,000 ohm resistance, 350 volt plate supply

These projections for four of the oscillograms of Fig. 11 are shown in Fig. 11-A, a pure sine wave being drawn against each figure for purposes of comparison. Up to an output of .047 watt the curved characteristic of the tube results in the asymmetrical wave shown with a predominant second harmonic. At a point slightly above .047 watt one or more of the grids becomes positive to the filament for part of a cycle and draws current. On account of the high impedance of the circuits supplying the grids this immediately results in a flattening of the top of the wave which is well developed at .075 watt output. This flattening of the top of the wave compensates to some extent for the curvature of the lower part of the tube characteristic so that the curve becomes more symmetrical with regard to the zero axis although more distorted. This corresponds to the fall of the second harmonic and increase of the third. At an output of .140 watt this compensation is more nearly complete than at any other output. At still higher outputs the top of the wave is still more flattened and the plate current is reduced to zero for a considerable part of the cycle so that the output wave becomes nearly rectangular as shown. This corresponds to large amounts of all harmonics.

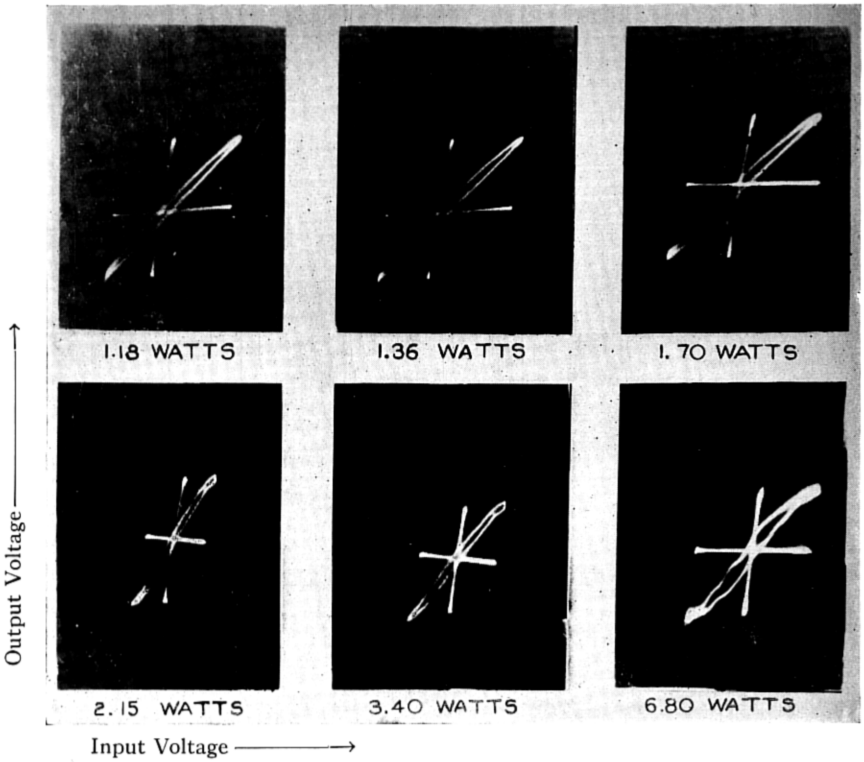

Fig. 13—Amplifier No. 2; 1,000 c.p.s., load 500 ohm resistance

In selecting from these results some point to be taken as the maximum carrying capacity of this amplifier, the question arises as to how much the second harmonic which is present at practically all loads will be noticeable. This, of course, depends on the training of the ear of the observer and on the quality of the music being transmitted. Comparing the note obtained from a cone type loud speaker when the wave corresponding to an output of .043 watts was applied with that obtained when the 1,000 cycle input was applied so as to produce a note of equal volume, it was found that it required a fairly sensitive ear to note the change in quality. On the other hand when a wave corresponding to the output wave obtained at a level of .068 watt was used for comparison the difference in quality between the pure tone and the distorted output was very easily noticed. From these data it may be assumed that when this amplifier is used in a system for the transmission and reproduction of speech or music it

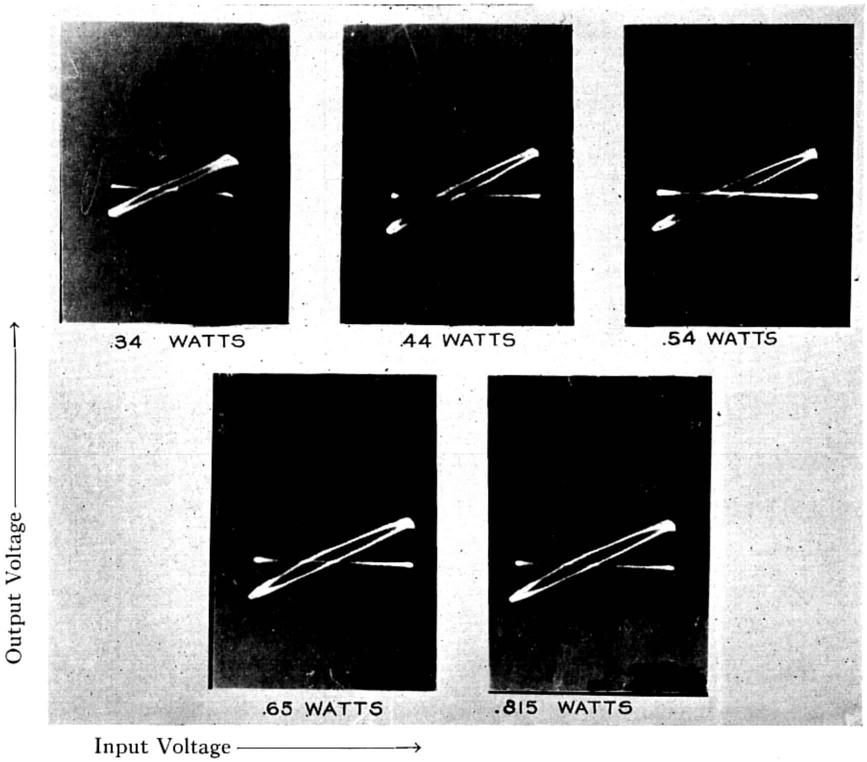

Fig. 14—Amplifier No. 3; 1,000 c.p.s.; load 600 ohm resistance

is fully loaded at an output of .04–.05 watt, representing the point where the grid of a tube begins to draw current and the third harmonic increases rapidly. It will be noted from the gain-load curve that the output has to increase to .1 watt before there is a noticeable falling off in the gain of the amplifier.

For the amplifier No. 1 under the condition of 350 volt plate supply the curves and oscillograms shown in Figs. 7 and 12 are of the same general nature. On account of the higher plate and grid biasing potentials an output of 0.7 watts is reached before the increase of third harmonic due to grid modulation occurs. This point is very definitely marked in the oscillograms for, of the pictures taken at outputs of 0.68 and 0.86 watts, the first is entirely free from this distortion, while the second where the current output is only 12.5% higher shows it clearly in the flattening at the top of the curve. On

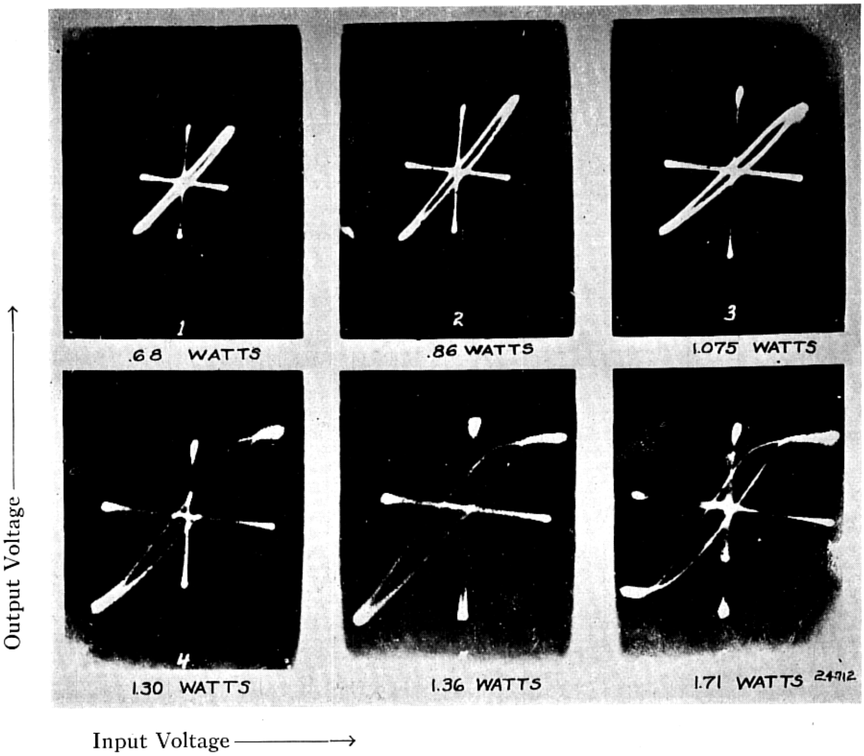

Fig. 15—Amplifier No. 4; 1,000 c.p.s.; load 4,000 ohms resistance

the other hand the gain-load curve does not show any appreciable decrease of gain until the amplifier is considerably overloaded.

For high power amplifiers and those amplifiers in which it is desired to reduce distortion to a minimum the push-pull arrangement of tubes has been used because with this arrangement the even harmonics generated in the tubes are suppressed in the output circuit. That the suppression is quite effective is shown by the curves and oscillograms of Figs. 8, 9, 13 and 14 which were taken on the No. 2 and No. 3 amplifiers. These show that the even harmonics are very small at all loads and that the third harmonic increases suddenly at a point which in view of the plate and grid biasing potentials employed may be taken as the point at which grid modulation commences. On the oscillograms this point is not so clearly marked as in the previous cases but on those for No. 2 there is a slight flattening of the ends of the curve which is noticeable at 1.7 watts but not at 1.36 watts. On No. 3 amplifier where the impedance of the circuit

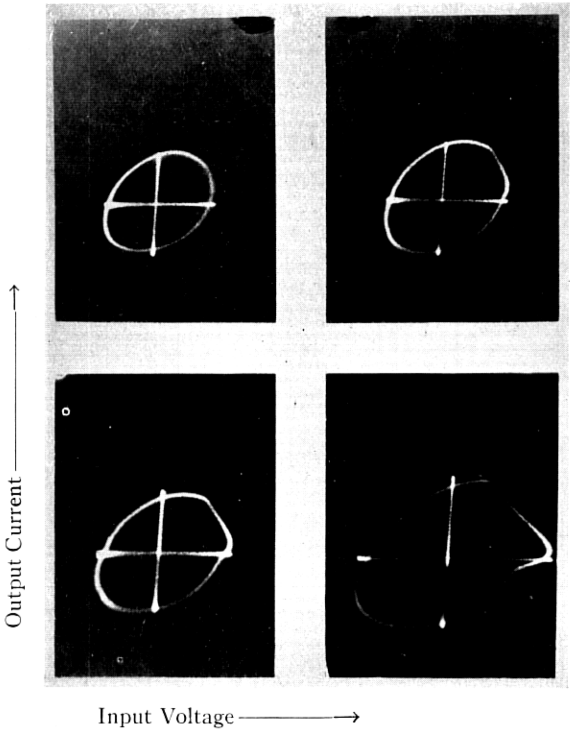

Fig. 16—Amplifier No. 4; 200 c.p.s. input; load 7,000 ohm negative reactance

supplying the grids is lower than in No. 2 the effect of grid modulation is still less marked on the oscillograph and the rise of third harmonic in the analysis is less rapid. This amplifier was designed for an output of .365 watts. The results show that this is obtained at the expense of the introduction of about 2% third harmonic.

The No. 4 amplifier is equivalent to the last stage of the No. 1 amplifier both using about 350 volts anode potential and 27 volts grid bias which in the case of the No. 4 amplifier is obtained from a resistance drop in the anode circuit. The harmonic analysis curves shown in Fig. 10 indicate somewhat less second harmonic at low outputs which is probably due to the smaller number of stages. Third harmonic is approximately the same in the two cases. The oscillograph figure shows a somewhat larger output before grid modulation takes place but the difference is not great.

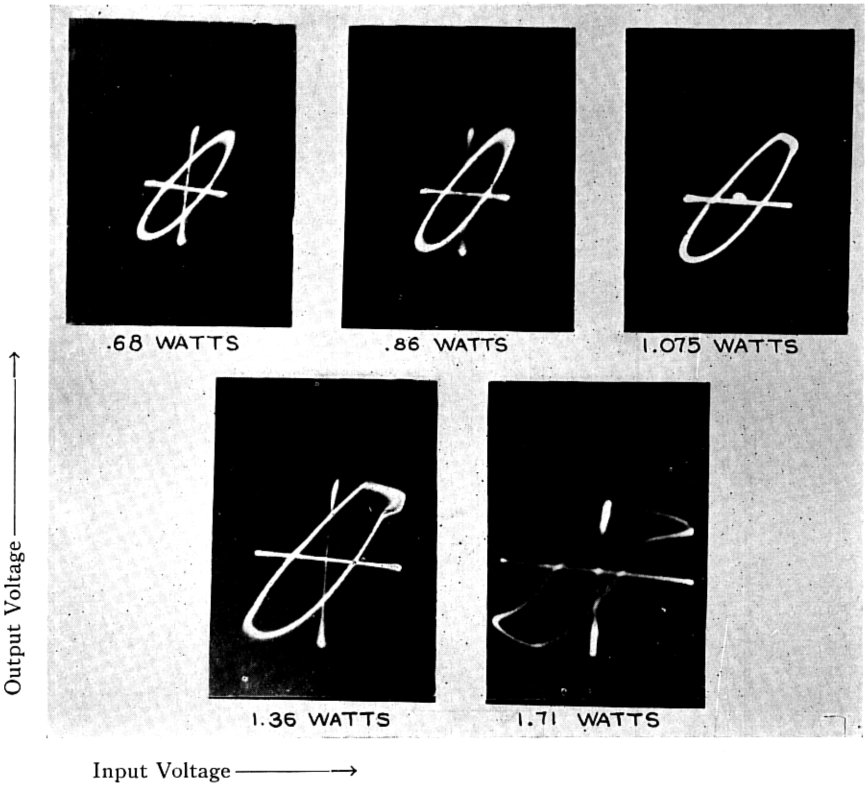

Fig. 17—Amplifier No. 4; 200 c.p.s. input; load 4,000 ohm resistance

To check whether similar results would be obtained at other frequencies and with reactive loads oscillograms were taken with output impedances having large positive and negative phase angles at frequencies of 200 c.p.s. and 1,000 c.p.s. While the width of the ellipse obtained varied greatly as was to be expected, it was found that the points where marked irregularities in the figures occurred were at the same grid excitations as in the case of the figures taken at 1,000 c.p.s. with resistance load. Figures were also taken using the output current to deflect the electron stream magnetically with the same results. Typical oscillograms for these varying conditions are reproduced in Figs. 16, 17 and 18.

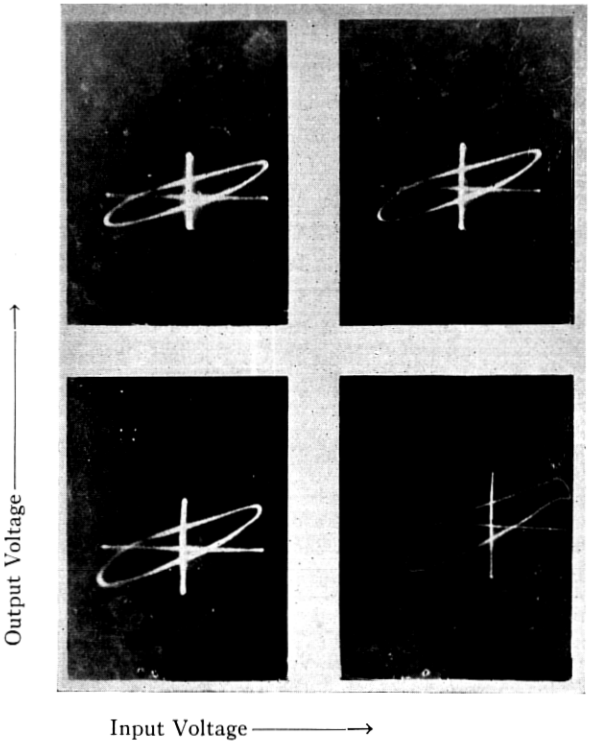

Fig. 18—Amplifier No. 4; 1000 c.p.s.; load 7,000 ohm positive reactance

In conclusion, the load carrying capacity of an amplifier may be determined by either method with approximately the same results. An harmonic analysis reveals in detail the amount of each harmonic that is introduced at any load and gives useful data for fundamental studies. It requires considerable apparatus and is slow in operation. The fall of gain method while it gives approximately the same results as the other methods is not so precise since the gain falls very slowly at the overload point and does not begin to fall rapidly till the amplifier is heavily overloaded. It is therefore, difficult to pick the exact point where overloading occurs. Moreover the method affords no indication of the kind of overloading that is occurring.

Determination by the use of the cathode ray oscillograph is more rapid and in most cases more precise although in the case of push-pull amplifiers with low grid-circuit impedances the overload point is not so clearly marked as in the other cases. The shape of the curves affords valuable information as to the place in the circuit where the overloading occurs and, by comparison with previously made analyses, a good indication of the amount of harmonic introduced. It therefore forms a very valuable tool for the design engineer.

By either method the result obtained shows the load carrying capacity of an amplifier for a single frequency. The complete answer as to how much volume in speech or music a particular amplifying system will handle depends upon an analysis of the power in the speech or music such as that given in C. F. Sacia's paper on Speech Power and Energy in the October, 1925, issue of this Journal.

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