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2. Illustrations should invariably be in black ink on white paper or tracing cloth. Blueprints are inacceptable.

3. Corrected galley proofs should be returned within 12 hours to the office of publication. Additions or major corrections cannot be made in an article at this time.

4. A brief summary of the paper, embodying the major conclusions, is desirable.

5. The Club reserves the right of decision on the publication of any paper which may be read before the Club.

*For 1929 the Chairman of the Papers Committee is Mr. L. G. Pacent, 91 Seventh Avenue, New York City

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CHARACTERISTICS OF AUDIO TRANSFORMERS

By PROF. H. M. TURNER

Sheffield Scientific School, Yale University

Delivered Before the Club, April 10, 1929

AS A result of the keen competition among manufacturers stimulated by the demand of the radio public for better and better quality there has been marked improvement in the performance of audio-frequency transformers during the past few years. The subject has been extensively investigated by competent research engineers and designers but the results of their studies come to us in the form of the finished product with little information as to the exact changes that have brought about improved performance. There is in no sense a criticism of the manufacturer for such information is his stock in trade. However, one of an inquiring mind desires to know in what way and to what extent the characteristics are modified by a change in a design or operating condition.

What constitutes a good transformer? This, of course, depends upon the use that is made of it. For broadcast reception of music, the primary consideration is quality or faithful reproduction which requires, assuming an ideal loud speaker, that the amplification be essentially independent of frequency over some predetermined band, say from 30 to 8000 cycles. However, with commercial loud speakers, considerable departure from a flat characteristic is permissible and in some cases even desirable in order to compensate deficiencies in the reproducing unit. For telegraph purposes the primary consideration is intensity or large amplification. The band may be much narrower, say from 800 to 1200 cycles, for a peaked characteristic is quite desirable in that it may be made to give a louder response to the desired signal and at the same time greatly reduce interference from neighboring channels.

Unfortunately it is not always possible to obtain excellent quality and high amplification from the same transformer. The response characteristic of transformers, however, may be materially modified by design and operating conditions as follows: the amount of iron in the core; the ratio of turns; the actual number of turns in the windings and their position with respect to each other and to the core, that is, whether the windings are interwoven or the primary or secondary is placed next to the core; the total resistance of the plate circuit; the plate voltage and grid bias of the amplifying tube associated with the primary of the transformer; and to some extent, the capacity in parallel with the primary and secondary.

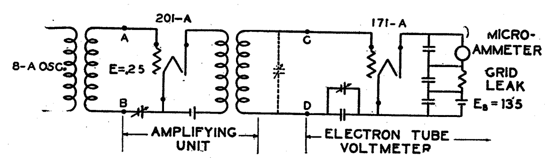


Fig. 1

OBJECT OF INVESTIGATION

THE object of this paper is to report on some experiments with audio-frequency transformers of different design that operated under widely different conditions with the hope of at least partially answering some of the questions that occur to one but which in some cases remain unanswered due to lack of time or adequate facilities for conducting the necessary experiments. No attempt is made to define or to determine an ideal transformer but rather to show the effect produced upon the amplification characteristic by certain changes many of which are far removed from those encountered in practice.

Faithful reproduction is dependent not only on the transformer but also on the associated amplifier, loud speaker, and the response characteristics of the receiving ear. But since the imperfection of the latter are present whether one hears the original program or a loud speaker reproduction it may be left out of consideration here. Although the ear must be the final judge of both quality and intensity it is not a satisfactory instrument for laboratory determinations. In the first place the ear, although sensitive to changes in pitch, is quite tolerant of changes in intensity and variations of 10 to 20 per cent. or more may take place without being perceived. This is fortunate for if the response were directly pro-

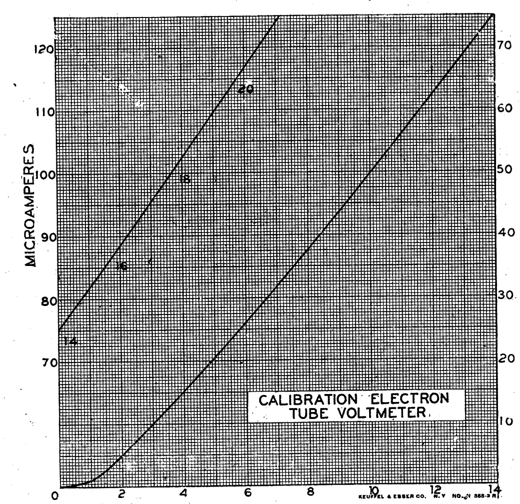


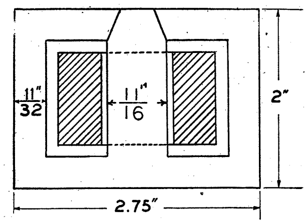
Fig. 2

portional to the stimulus an organ of hearing sufficiently sensitive to catch the slightest whisper would be destroyed by sound waves of great intensity or at least they would be a source of great pain. In the second place there would be disagreement among observers. Differences that would be apparent to a trained ear would be entirely overlooked by one less discriminating. Even the results obtained by a given observer vary from day to day. Thus for measurement purposes the ear cannot be considered an instrument of precision and for this reason an electron tube voltmeter was used to measure the amplification as determined by the output voltage of the transformer and its associated amplifying tube.

THE ELECTRIC CIRCUIT

THE circuit arrangement that was used is shown in Fig. 1. A variable frequency is obtained from an 8-A oscillator whose output transformer at the left supplies a voltage which is maintained at a constant value, usually 0.25 volts to the grid of a 201-A amplifying tube

Fig. 3



CORE LAMINATION

in the plate circuit of which is connected the primary of the transformer. The secondary or output voltage is measured by an electron tube voltmeter of the type developed by E. T. Dickey of the Radio Corporation. The condenser across the secondary of the transformer, shown dotted, is introduced in some of the experiments to be referred to later.

THE MAGNETIC CIRCUIT

WHERE the transformers were assembled in the laboratory, a core of 15 mil hipernik was used, the other dimensions being given in Fig. 3. In all cases,

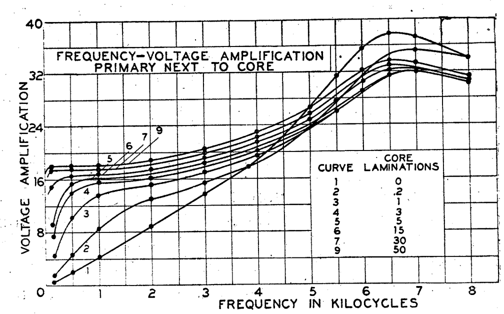


Fig. 4

unless otherwise indicated, the core consisted of 50 laminations, the exception being Fig. 4 and 7 where the amount of iron was varied.

Series I. This transformer consisted of a primary of 7000 turns of No. 40 enameled wire having a resistance of the order of 2400 ohms and a secondary of 15,000 turns of No. 40 of 7100-ohms resistance wound over the primary. The over-all voltage amplification of the 201-A tube and the transformer was measured for frequencies

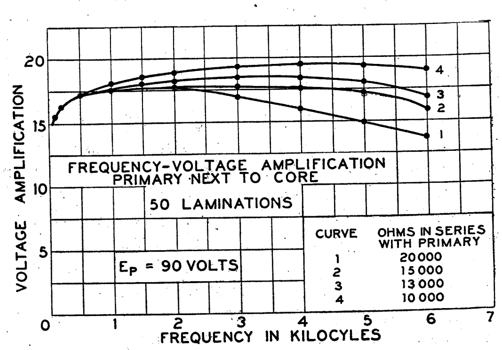


Fig. 5

from 200 up to 8000 cycles first with a core of 50 laminations and then with 30, 15, 5, 3, 1, 0.2 and 0 laminations. It will be observed that the removal of most of the iron has a relatively small effect upon the amplification over the greater portion of the frequency range, however, the effect of the core is rather pronounced at the low frequencies so in order to retain the low notes a considerable amount of iron is required in this particular transformer. By 0.2 of a lamination is meant that portion of a single lamination which passes through the opening in the coil and having a length equal to that of the coil or approximately one inch. The increased amplification due to this small amount of iron over that with no iron at all is pronounced below 200 cycles. Above 4500 cycles, regardless of the number of laminations, the core has practically no effect on the amplification other than to prevent an over exaggeration of the higher frequencies. Regardless of the amount of iron the maximum amplification occurs at 6500

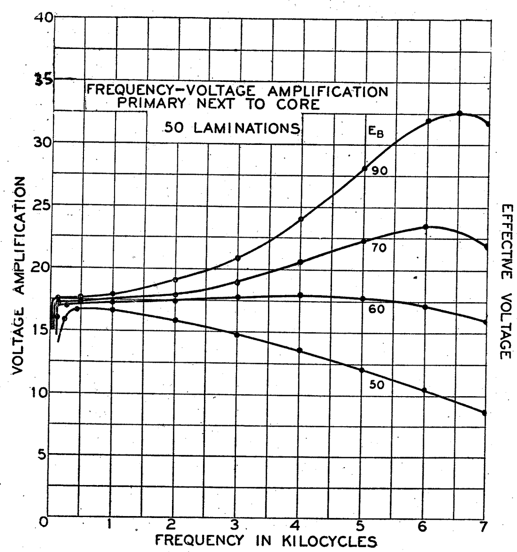


Fig. 6

cycles which is rather surprising and indicates that the introduction of iron does more than merely increase the induction. The maximum amplification is approximately twice that of the lower frequencies which is determined by the amplification of the electron tube and the turn ratio of the transformer.

The form of the curve suggests a resonance effect which is due to the distributed capacity of the secondary and the capacity of the grid-filament of the tube to which it is connected. It is evident that the introduction of resistance in the primary circuit would tend to flatten out this curve and make the amplification much more uniform throughout the frequency range which is confirmed by Fig. 5.

A change of plate voltage would have something of the same effect as shown in Fig. 6 as this will change the internal resistance of the tube. A decrease in plate voltage from 90 to 67.5 for a 201-A with normal grid bias causes an increase in plate resistance from approxi-

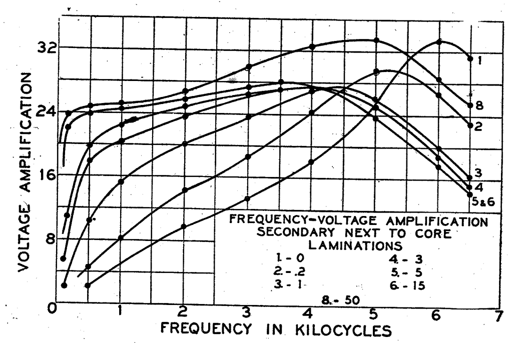


Fig. 7

mately 10,000 to 14,000 ohms and at the same time decreases slightly the amplification factor. A decrease of plate voltage from 67.5 to 45 would increase the resistance from 14,000 to 18,000 ohms. There are certain other factors that will have a secondary effect.

Series II. The primary of this transformer has 5000 turns of No. 40 wire with a resistance of 2500 ohms and a secondary of 15,000 turns of No. 40 wire with a resistance of 6100 ohms. The amount of iron was varied as in

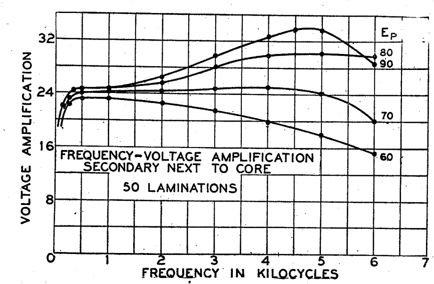


Fig. 8

Series I but the general appearance of the curves is quite different. There is a more pronounced spreading of the curves, see Fig. 7, and the maximum points occur at different frequencies, the maximum amplification for the air core occurring at 6000 cycles. Introducing iron has

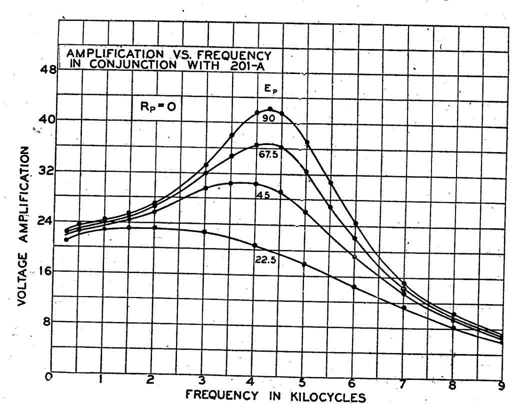


Fig. 9

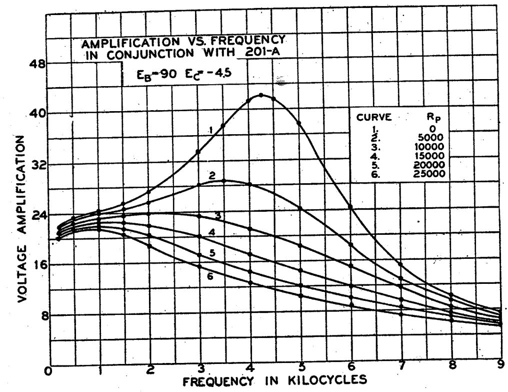


Fig. 10

the general effect of lowering the frequency; as the amount of iron was increased the maximum came at 5200, 4500, 4000, 3500 and then increased to 4800. The difference between this series and the last was largely due to the increased capacity of the secondary winding which was placed next to the core and possibly to a change in leakage reactance. There is also a greater spreading of the curves for the different values of plate voltage, see Fig. 8, than for the corresponding case where the primary was wound over the secondary.

Series III. This is a commercial transformer for which there is no information regarding the number of turns or the turn ratio but the ratio is probably between 2.5 and 3 as indicated by the amplification at the lower frequencies. The primary resistance is approximately 2000 ohms and the secondary 7500. It is considered a high-quality transformer. Fig. 9 to 13 shows the effect of changing the plate voltage, adding resistance in the plate circuit and varying the capacity across the secondary of the transformer for three different values of plate voltage with normal bias in each case. It should be noted that the effect of added capacity is to decrease materially the amplification at the higher frequencies. The fact that the amplification varies considerably with frequency does not necessarily indicate that the quality will be poor. The maximum amplification for normal plate voltage and grid bias occurs at 4200 cycles and is approximately twice that at low frequency.

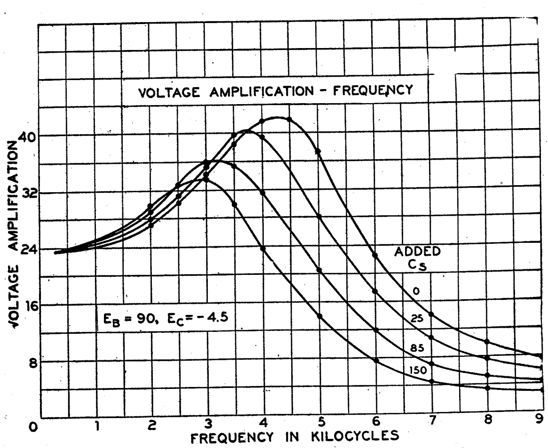


Fig. 11

Series IV. This is a commercial transformer having a 6:1 ratio giving an amplification of approximately twice that of the last transformer at low frequencies. The increase of amplification with frequency is less pronounced than for the last transformer the maximum, being about 30 per cent. greater in this case although due to the larger distributed capacity it occurs at 3200 cycles and decreases quite rapidly for frequencies above this value. The primary resistance was 1300 ohms and the secondary 12,000.

The effect of a change in either plate voltage or grid bias materially modified the shape of the characteristic, as shown by Fig. 14, the amplification increases with an increase of plate voltage and a decrease of negative grid bias. For a plate voltage of 45 and a grid bias of three volts the curve rises rapidly to a maximum and

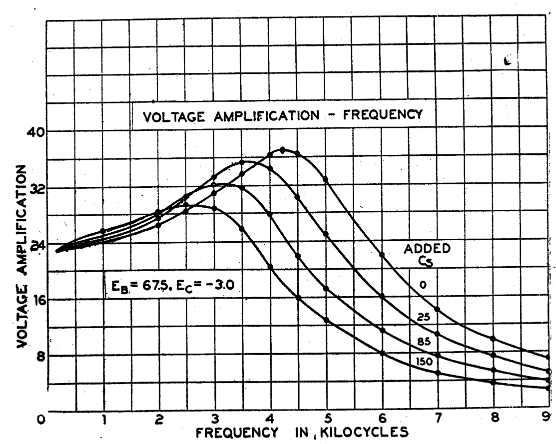


Fig. 12

then decreases rapidly to a very low value as the frequency is increased.

Series V. The five transformers here compared have the following constants:

	T_1	T_2	T_3	T_4	T_5
Ratio	3:1	4:1	5:1	3:1	5:1
Primary turns	5,000	5,000	5,000	7,500	7,500
Secondary turns	15,000	20,000	25,000	22,500	7,500
Primary resistance	1,750	1,750	1,750	6,200	6,200
Secondary resistance	7,300	13,500	27,000	25,000	46,000
Size of wire	40–40	40–41	40–44	44–44	44–44

A comparison of the three transformers having 5000 turns in the primary and 15,000, 20,000 and 25,000 in the secondaries respectively is given in Fig. 15. There are two curves for each transformer but for the present consider only the higher one which is for normal conditions of operation. At low frequencies the amplification is almost exactly proportional to the number of turns in the secondaries but as the frequency is increased the amplification gradually increases to a maximum of approximately 175, 150 and 115 per cent. of the low frequency values and then decreases quite rapidly.

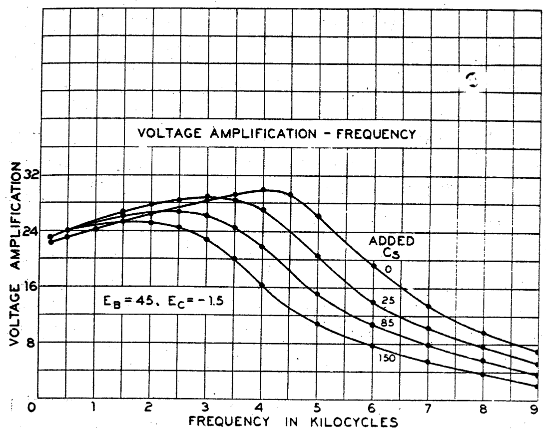


Fig. 13

These transformers reach their maximum amplification at 6000, 4000 and 3000 respectively. It happens that the first and last transformers have almost exactly the same average amplification over the nine-kilocycle band while the intermediate one has a somewhat higher average and on the whole is probably the best. Although the average amplification is not necessarily the best measure of a transformer, especially if taken over a wide band of frequencies, for frequencies below five thousand may be far more important in some cases than those above. An added capacity of 50 mmfd. across the secondary has a slight tendency to increase the amplification at certain frequencies which is greatest in the case of the low ratio transformer, is negligible for the intermediate and vanishes for the high ratio. Above a certain frequency, depending on the transformer, there is a marked decrease in the amplification due to the added capacity indicating the desirability of keeping the distributed capacity of the secondary and the capacity of the leads as small as possible.

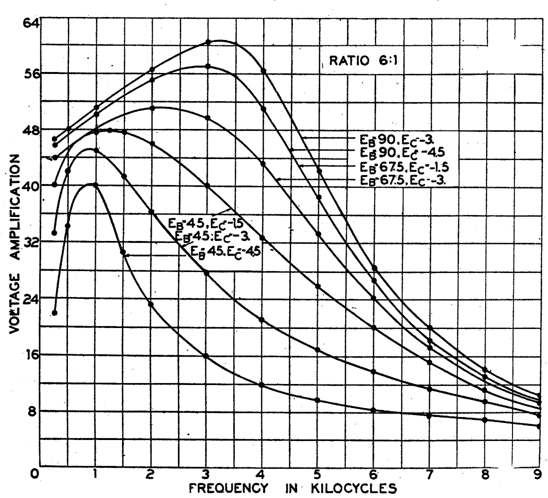


Fig. 14

DIFFERENT TURNS RATIOS COMPARED

In Fig. 16 are compared transformers having a ratio of 3:1 with primaries of 5000 and 7500 turns and transformers having a ratio of 5:1 also with primaries of 5000 and 7500 turns. It will be observed that the cut-off is much more marked in the case of the high ratio transformers. This is largely due to the increased distributed capacity of the secondaries as indicated in Fig. 15. In the case of the 5:1 transformer with 7500 in the primary the cut-off is at 2000 cycles and is quite sharp. In Fig. 17, the same comparison is made but with 45 volts on the plate which shows that there is considerable difference between the characteristics for the two plate voltages.

In analyzing these curves in greater detail than time will here permit it will be helpful to recall the equations for the equivalent transformer constants. Where the primary of a transformer has resistance and inductance

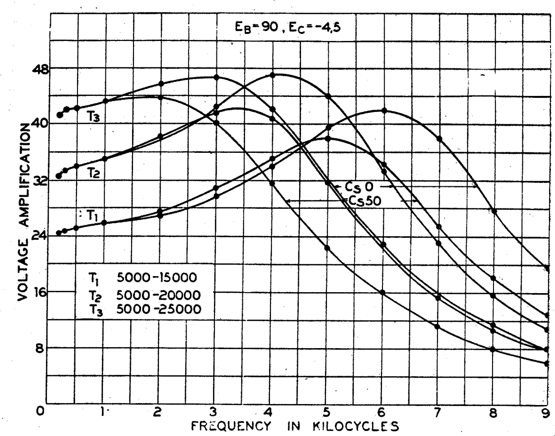


Fig. 15

but negligible distributed capacity and the secondary has resistance, inductance and capacity which includes the distributed capacity of the secondary and that of the leads and grid-filament of the associated tube, for the sake of simplicity, taken as a fixed value across the secondary and further that the mutual capacity between the two windings be neglected, one may replace the transformer with an equivalent resistance and reactance in so far as the plate circuit of the amplifying tube associated with the primary is concerned. The equivalent constants then have the following values:

$$R_{eq.} = R_1 + \frac{W^2M^2}{Z^2_2} R_2 \text{ and}$$

$$X_{eq.} = wL_1 - \frac{w^2M^2}{Z^2_2}\left(wL_2 - \frac{1}{wC_2}\right)$$

For low values of frequency and the capacity usually associated with the secondary the total reactance of the secondary is capacitive and when transferred to the primary has the effect of increasing the equivalent inductive reactance and therefore tends to cause a larger portion of the total amplified voltage in the

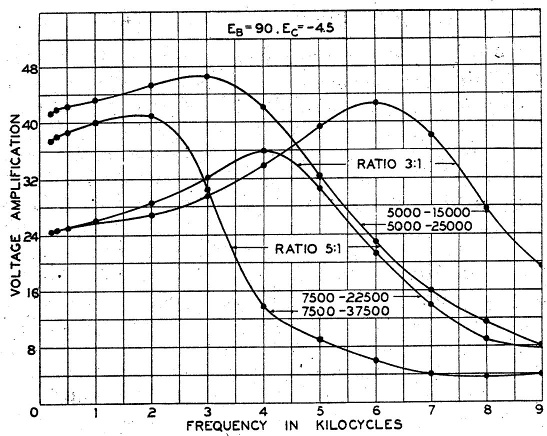


Fig. 16

plate circuit to be consumed by the induced electromotive force of the primary, and therefore a greater induced electromotive force in the secondary. The primary current may be found from the following equation:

$$I_1 = \frac{E_1}{\sqrt{\left[R_1 + \frac{w^2M^2R^2}{Z^2_2}\right]^2 + \left[wL_1 - \frac{w^2M^2}{Z^2_2}\left(wL_2 - \frac{1}{wC_2}\right)\right]^2}}$$

and the secondary current $I_2 = \frac{wMI_1}{Z_2}$ and what we are more concerned with is the voltage across the terminals of the secondary which is

$$E_2 = \frac{E_1M/C_2}{\sqrt{R^2_2 + \left(wL_2 - \frac{1}{wC_2}\right)^2}\ \sqrt{\left[R_1 + \frac{w^2\,M^2\,R_2}{R^2_2 + \left(wL_2 - \frac{1}{wC_2}\right)^2}\right]^2 + \left[wL_1 - \frac{w^2\,M^2\left(wL^2 - \frac{1}{wC_2}\right)^2}{R^2_2 + \left(wL_2 - \frac{1}{wC_2}\right)}\right]}}$$

For low frequencies wL_2 is less than $1/wC_2$ and as the frequency is increased these two factors approach equality until a condition of resonance is reached in the secondary and the first radical in the denominator decreases to a minimum value of R_2 as a result of which a large output voltage is obtained. As the frequency is further increased wL_2 is greater than $1/wC_2$ and the denominator increases thus reducing the output voltage.

An increase of secondary capacity due to the added condenser cause the condition of resonance to be reached at a lower frequency after which the output voltage decreases rapidly as may be seen from the equation. These results will be somewhat modified by the mutual capacity between the two windings of the transformer.

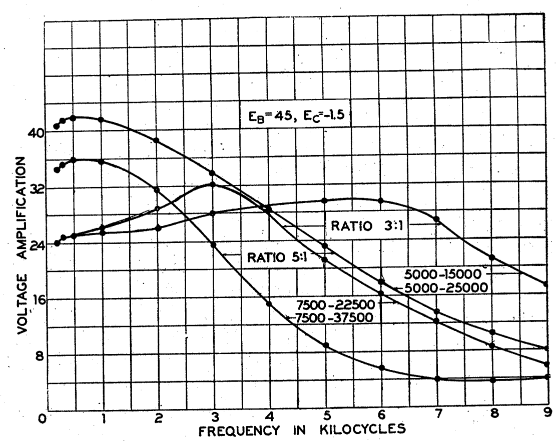


Fig. 17

Notes of the Club Membership

These notes add much, we feel, to the club for our membership is large and scattered and only through contact such as this can all the membership be informed of the activities of all. Send in a few words about what you are doing to the Club Notes Editor care Club Headquarters.

David Brown reports "nothing new whatever except a lot more high notes in my receiving set" and challenges George Burghard and Carl Dreher to come around "to hear what a broadcast receiver should sound like." As far as Dreher is concerned, seemingly he doesn't want to know what a broadcast receiver should sound like. It is reported that he has three receivers in his palace on West End Avenue, that they are rarely in working order, and that when he gets one running it sounds terrible. He blames everything on the talking movies.