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PROCEEDINGS

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RADIO CLUB OF AMERICA

Transformer-Coupled Audio Amplifiers

A Paper Delivered Before the Radio Club of America on April 15, 1926

By Alfred W. Saunders

Engineer, F. A. D. Andrea Company

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SPECIAL RESOLUTION

Radio Club Stands for Broadcast Regulation

At a special meeting of its Board of Directors, the Radio Club of America—the oldest radio club extant—drew up a resolution backing the regulations heretofore rigidly observed in broadcast practice. While the Club has no authority other than over its extensive membership, the action at this time is significant in the sense that this Club has always stood for the rights of radio amateurs and radio listeners just as it is doing to-day.

The resolution drawn up by the Board of Directors of the Radio Club of America reads as follows:

> *"RESOLVED that until the present limitation on the powers of the Department of Commerce shall have been removed or other provision made by legislation, no broadcaster should change his wave length or hours on the air or increase his power without first receiving the approval of a committee representative of the art, organized for the purpose, and be it further*
>
> *"RESOLVED that the Radio Club of America, organized for the object, among others, of developing the radio art, hereby declares that the present condition in the radio field, caused by the temporary removal of legal restraints, is a new occasion for the exercise of that capacity for self-government and respect for the interest of the public, in which the radio art has led, until it further declares that it will hold its members responsible in the opinion of the Club for their conduct in the observance of the principles underlying these Resolutions."*

Originally founded in 1909, under the name of The Junior Wireless Club, Ltd., the name of the organization was changed in 1911 to the Radio Club of America. The main purpose of this organization has been since its inception to facilitate an interchange of ideas among those interested in radio communication. However, the Club has always taken an active interest in all legislation outlined to the rights of radio amateurs and broadcast listeners. For this reason, the Club can be expected to follow the present broadcast developments with more than ordinary interest.

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Transformer-Coupled Audio Amplifiers

A Paper Delivered Before the Radio Club of America, Which Considers the Proper Design of Audio Transformers, How Their Characteristics May Be Measured and Evaluated—A Comparison Between Resistance-, Impedance-, and Transformer-Coupling

By ALFRED W. SAUNDERS

Engineer, F. A. D. Andrea Company

RADIO broadcasting of musical programs, speeches, and other matter of general interest has made tremendous advances during the last few years. Probably the only reason for public interest in the art, during its early stages, was the novelty of using the ether as a medium of transmitting programs. In the early stages of the art, the quality of a program was secondary in importance to "reaching out." Developments during recent years, however, have served to make radio as much a necessity as a novelty or luxury, with the result that quality is of prime importance to-day. Radio reception is no longer a novelty in the eyes of the public, but it is, instead, a firmly grounded institution, and like other public utilities it must meet the demands of its customers both in regard to the quality and form of entertainment to be broadcast. As one writer has aptly put it, "Radio is in every sense a public institution and should therefore be controlled by the public for the public good."

It is well known that in general the quality of the transmitted programs is far more satisfactory than the quality of those received. The economics of the situation would lead us to expect the existence of this state of affairs, since any radio receiver must be relatively cheap compared to a transmitter which serves a large number of listeners. While it is true that the quality of reception depends on a number of circuit elements, probably none is more important than the audio amplifier. However, the fact must not be overlooked that quality is also affected by the tuning characteristic of the radio-frequency amplifiers, the time constant of the grid leak and condenser combination of the detector, the loud speaker, and by overloadin any portion of this circuit. It is the purpose of this paper to outline some of the fundamental considerations involved in the design of a specific type of audio amplifier and to show how some of the desirable amplifier characteristics may be obtained in practice.

Since the performance of a transformer-coupled amplifier depends primarily upon the transformer characteristics it seems logical to start with the transformer itself. The perfect transformer has been defined by K. S. Johnson—*Transmission Circuits for Telephone Communication,* D. Van Nostrand Company as one which neither stores nor dissipates energy. That is to say, an ideal transformer has no dead resistance,

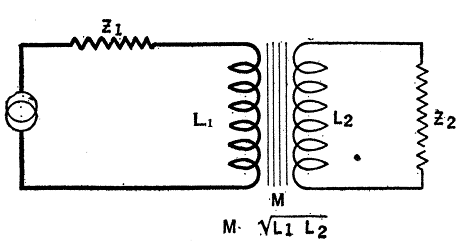

FIG. I

no losses, and a perfect flux linkage between windings. This amounts to saying that the primary and secondary self impedances must be infinitely high with respect to the sending and terminating impedances and that each must be purely imaginary in character. Moreover, for this definition to hold, the mutual impedance must be an imaginary quantity equal to the geometric mean of the primary and secondary self impedances. The reasons for these limitations are evident from Fig. 1.

If the transformer is to cause no loss in the circuit it must evidently draw zero current from the source when Z_2 is infinite. Moreover, it is evident that L_1 must be imaginary as well as infinite if it is to have zero loss when it draws current. The same criteria of course hold for the secondary self impedance. If all these conditions hold for a given transformer, the impedance looking into the primary will be Z_2 divided

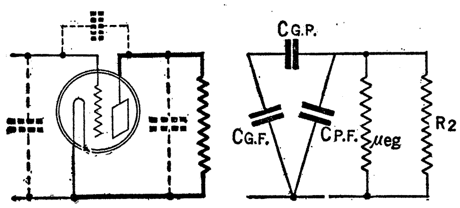

FIG. 2

by the square root of the turns ratio, where the turns ratio is given as the secondary turns divided by the number of primary turns.

THE IDEAL TRANSFORMER

EVIDENTLY then, an ideal transformer will absorb only sufficient power from the source to supply the load being drawn. Construction difficulties, however, permit us only to approach rather than realize ideal transformers in practice. That is to say, the coupling in any physical transformer is never perfect, nor are either of the self impedances infinite. The physical transformer, however, can, for all practical purposes, be considered as made up of an ideal transformer with series resistance and inductance added to take care of the dead resistance of the windings and the so-called leakage reactance. The dead resistance of the windings can usually be neglected for all except the lowest frequencies. While losses are always present in any physical transformer, proper design generally makes them negligible at all except the extremes of the transmitted frequency band. It is well known that the input impedance of a vacuum tube introduces a highly capacitative load. Fig. 2 shows the capacity and resistance network of a vacuum tube. It has been shown by J. M. Miller, *Bulletin United States Bureau of Standards,* No. 351, November, 1919, and others, that the input capacity of a vacuum tube is:

$$C = C_{G.F.} + \left\{ \frac{\mu R_2}{R_0 + R_2} + 1 \right\} C_{G.P.}$$

Since input transformers operate into the highly reactive input impedance of a vacuum tube, it is evident that the impedance reflected into the primary can match the tube impedance in magnitude at only one frequency. This is of little importance since it is only necessary to deliver a constant voltage rather than constant power to the tube input to produce a flat amplifier characteristic. It is therefore unnecessary to match impedances at all transmitted frequencies to limit distortion. See W. L. Casper, *Journal A. I. E. E.,* March, 1924.

The capacities of the transformer windings under conditions met in practice become of considerable importance at the upper extreme of the transmitted frequency band, just as the resistance of the windings in many cases plays an important rôle at the lower extreme. Fig. 3 shows diagrammatically some of these capacities. For simplicity these capacities have been shown lumped at certain points, although in reality they are distributed capacities in every case. In this diagram C_1 is the interwinding capacity, C_2 and C_3 the distributed capacities of the primary and secondary respectively, C_4 the capacity of the inner winding to core, and Lx the leakage reactance. It is obvious that the leakage reactance can be kept small by winding the secondary next to the core with the primary over the secondary. In general, each of the above capacities are of the order of 20 to 60 micro-microfarads, depending, of course, on the construction of the transformer. The tube input impedance is represented by C_5 and R_5. These values are, of course, dependent on the load in the plate circuit of the tube.

ACTION OF THE TRANSFORMER IN CIRCUIT

LET us consider the action of the transformer when it is used to couple two amplifier tubes. This is illustrated schematically in Fig. 4. It is customary to represent the gain or voltage amplification of input transformers as such, rather than to rate them in terms of a perfect transformer. In this diagram, μeg represents the voltage generated in the plate circuit of the first tube, R_0 its plate impedance, and E the voltage applied to the grid of the second amplifier tube. Now it is well known that maximum power is absorbed by a given load when the impedance of the load is equal to that of the generator, and further, for a complex impedance load, the magnitude of both com-

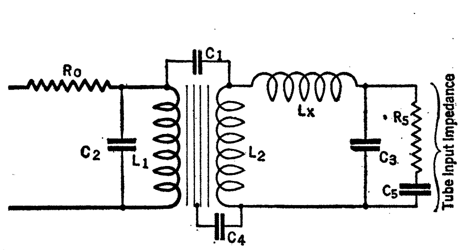

FIG. 3

ponents of the load impedance should be equal to the generator impedance, and the imaginary components of the two should be in phase opposition for maximum power transfer. As previously stated, the impedance reflected into the primary circuit can match the output impedance of the tube at only one frequency. It is obvious that if the transformer were ideal and of the proper ratio to match impedances, a flat transmission characteristic would not be obtained due to the losses on either side of the frequencies at which the impedances were matched. It has been found that it is practical to use a much lower ratio transformer than one having the ratio for optimum power transfer. It is quite common practice, too, to design transformers in which the secondary resonates with its own distributed capacity plus that of the load at frequencies less than 500 cycles. This has a tendency, of course, to increase the efficiency at these lower frequencies and in most cases it serves to further flatten the characteristic. The expression, secondary resonance, is not rigorously correct but amounts to resonance of the secondary self impedance plus the impedance reflected into the secondary by virtue of the mutual impedance of this transformer. See Pierce, *Electric Oscillations and Electric Waves*, also Casper, *Journal A. I. E. E.*, March, 1924. The ratio of the transformer is, however, determined to a certain extent by the ratio of the input and output impedances of the amplifier tubes. For this reason it is customary to use lower ratio transformers between detector and amplifier than between two amplifiers, since the output impedance of a tube functioning as a detector is in general greater than when it functions as an amplifier.

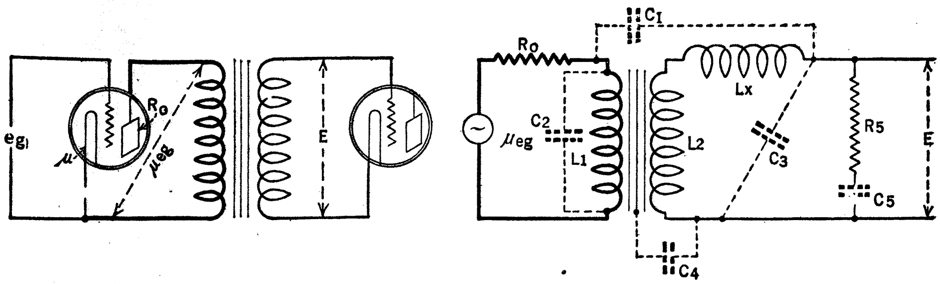

FIG. 4

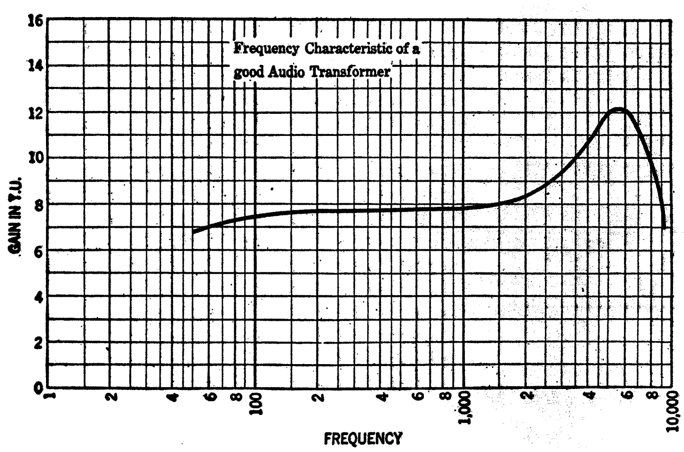

FIG. 5

The characteristic of a good audio transformer is shown in Fig. 5. The peak at the upper end of the frequency spectrum is due to resonance between the transformer leakage reactance and the tube input capacity combined with the secondary distributed capacity. The falling characteristic at the lower end of the frequency spectrum is largely influenced by the resistance and inductance of the primary winding. This would be expected because the primary self impedance increases with frequency while the winding resistance is practically a constant value. It is obvious then, that at low frequencies, the effect of the primary resistance will become more and more apparent in that it absorbs relatively much more power than at the higher frequencies.

Moreover, the primary self impedance being of the same order of magnitude as the output impedance of the tube at the lower frequencies, relatively more of the voltage drop will be across the tube output impedance and winding resistance (which for practical purposes can be lumped since both represent a dead loss) and less across the primary winding. It is for this reason that it is necessary that the primary self impedance be high in value. The sudden drop at the higher frequencies is due to the effect of the leakage reactance and shunt capacities which together act to suppress high frequency notes. The frequency at which the peak occurs can be readily changed by properly poling the secondary winding so as to utilize the secondary distributed capacity. This is illustrated in Fig. 6. Curve A is for the transformer connected so that only the secondary distributed capacity and the tube capacity are effective. Curve B represents the condition in which the secondary is poled so that the interwinding capacity or the capacity of winding to core or both are effectively added to the tube and secondary distributed capacities. It is at once obvious that the transformer characteristic can be materially altered by the simple expedient of grounding the core or reversing the secondary. The curves of Fig. 6 are almost identical with some characteristics of good commercial transformers recently measured, having a voltage amplification of about 2.5 to 1. It might be mentioned in this connection that it is difficult with ordinary core materials to obtain a good transmission characteristic with a transformer having a voltage step-up of more than 3 to 1.

DETERMINING THESE CHARACTERISTICS

THE method used in obtaining these characteristics is that in general use for this purpose. It consists essentially in the application of a constant amplitude voltage to the primary through a series impedance equal to the output impedance of the tube. The secondary is terminated in a calibrated C-battery detector. A biased d.c. micro-ammeter in the plate circuit of the tube serves to indicate changes in rectified current. Curves obtained by this method are, of course, not illustrative of the action of the transformer when it is terminated in an amplifier.

This is entirely due to the change in transformer terminations. The essential difference in the two cases is a matter of the load impedance supplied to the tube. In the case of the detector, the load impedance in the plate circuit of the tube is practically zero. Reference to the equation for input capacity will show that for the case of the detector the input capacity is relatively small while for the case of the amplifier the input capacity is relatively large, which means in the latter case we have a lower impedance. As a matter of fact, in the case of the amplifier, the input impedance consists of a resistance as well as a capacity. From this it is obvious that the transformer characteristic as taken by the detector will be changed in two respects when the transformer is terminated in the amplifier. First, the resonant peak will be at a lower frequency due to the larger capacity, and second, it will not be as sharp due to the resistance effectively added by the amplifier. This is illustrated in Fig. 7. Curve 1 is that of a characteristic measured with a detector. Curve 2 shows the characteristic of the same transformer terminated in an amplifier.

Two stages of transformer-coupled amplification might or might not give a desirable characteristic. If the tubes and the transformers are identical, it is at once apparent that the peak will be relatively very much higher for two stages than for one. This will in general result in an undesirable characteristic and may even cause singing at a frequency corresponding to the tip of the resonance peak. The most obvious way to avoid this is to stagger the transformer characteristics. This is easily accomplished by reversing one of the transformer primaries or secondaries. It is at once apparent that there are a number of combinations, each giving a different characteristic, not all of which are desirable however.

Fortunately, it so happens that the leakage

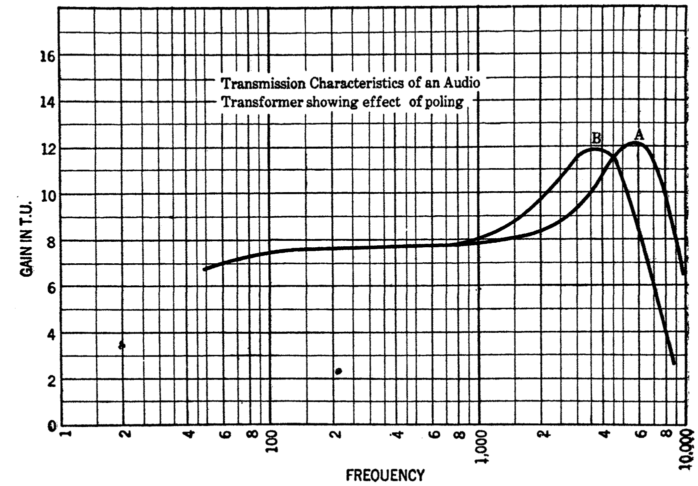

FIG. 6

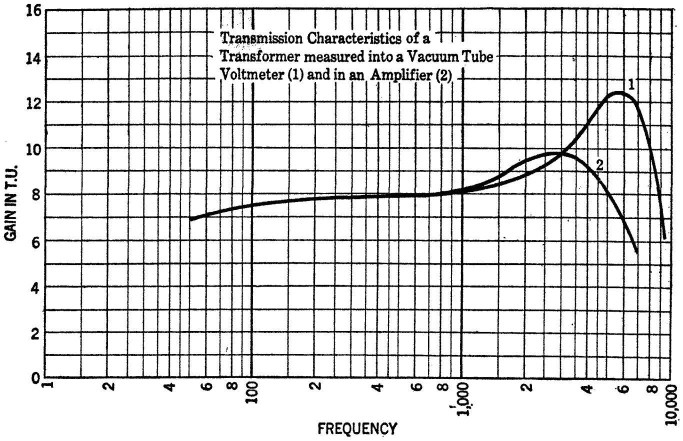

FIG. 7

reactance of the transformer can be turned to a practical use. For example, tube noises and other undesirable noises and crackles, with which all radio fans are familiar, can be very effectively eliminated without undue distortion to the transmitted signal frequency band by arranging for the leakage reactance to resonate at a frequency of about 5 kilocycles. That is to say that the amplifier characteristic will fall much more rapidly and drop much more sharply with the two stages than with either one alone. This is clearly illustrated in Fig. 8, in which Curve A is a characteristic of a two-stage amplifier arranged to obtain a flat gain characteristic. Curve B depicts the squared characteristic of one stage, while Curve C represents the squared characteristic of the other stage.

TWO TYPES OF AMPLIFIER CHARACTERISTICS

THERE are in general two types of amplifier characteristics of interest. The first is a gain-frequency characteristic, some examples of which are shown in Fig. 9 and the second is the load characteristic of Fig. 10.

Fig. 9 also illustrates what results may be expected from the simple expedient of altering transformer connections. Here the second transformer connections were left unchanged while the connections of the first transformer were varied. Curve 1 we will call normal. Curve 2 indicates the change caused by reversing the primary of the first transformer. Curve 3 shows the results of reversing both the primary and secondary of the first transformer. Curve 4 indicates the change caused by grounding the transformer cores.

The load characteristic of an amplifier, while not in such common use, is equally as important as the frequency characteristic. Overloading of tubes is the cause of serious distortion in the audio-amplifier and must be avoided if good quality is to be insured. Everyone is familiar with the grid voltage-plate current characteristics of a vacuum tube. These tube characteristics show that distortion is introduced when insufficient or too much C potential is used for a given plate potential. It is also evident that too much or too little plate potential for a given C battery introduces distortion. In general the tube functions as a grid rectifier if insufficient C battery is used, or as a plate rectifier if too much C battery is employed. (Plate circuit rectification may also occur when insufficient C battery is used, the criterion usually being the impedance of the transformer secondary.) As is often the case, the volume desired is beyond the capabilities of the last audio tube. Overloading is of course accompanied by amplitude distortion. Overloading can easily be detected by observing the plate current of the amplifier tubes. Any change in the plate current of an amplifier tube indicates that overloading and distortion are taking place. Grid rectification predominates when the plate current decreases. This can easily be remedied by increasing the C potential employed or by decreasing the plate potential. If the plate current increases, plate rectification is taking place. This may be remedied by decreasing the C potential or increasing the plate voltage. Overloading tends to cut down the gain of an amplifier because of the presence of the generated harmonics. The energy which is used to supply the overtones might just as well be used to supply the fundamental. It is true that more volume may be obtained in some cases when the amplifier is overloaded, but the desired fundamental is usually materially decreased.

Considerable information is obtained from the load characteristic of an amplifier. It expresses the relation between transmission gain and output power. It clearly indicates the overload point of an amplifier and also the maximum output level possible without serious overloading.

A common definition of transmission gain follows:

The transmission gain caused by the insertion of an amplifier in any circuit is measured directly by the ratio of the power delivered to the load when the amplifier is in the circuit and when it is removed. Having decided upon a definition of transmission gain, measurements may be made to conform with this definition, which is similar to that commonly employed in telephone practice. An input voltage is applied to the amplifier input through a resistance corresponding to the output impedance of a detector tube, and the output of the amplifier is terminated in a resistance which matches the a.c. output impedance of the last tube. This is the condition under which maximum power is delivered to the load. Gain is measured in terms of the ratio of the power delivered by the amplifier to the power which would be delivered without the amplifier. When gain characteristics of the amplifier are measured, the input frequency is varied and the input voltage maintained constant. The load characteristic was measured by maintaining a constant frequency and varying the amplitude of the input voltage.

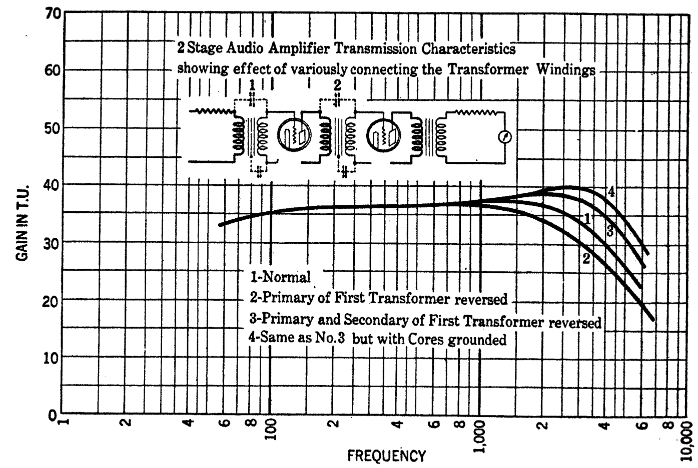

FIG. 9

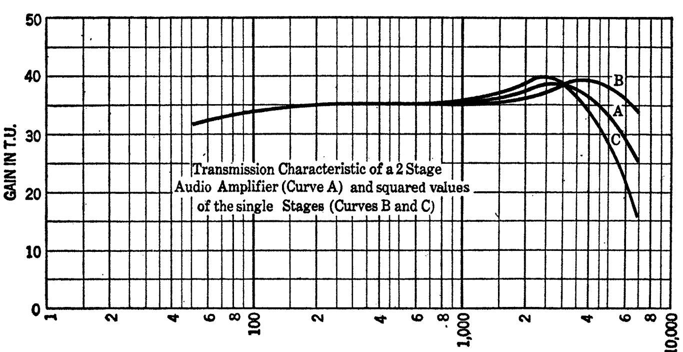

FIG. 8

COMPARING RESISTANCE-, IMPEDANCE-, AND TRANSFORMER-COUPLING

PRIOR to the development of high quality audio-frequency transformers, resistance- and impedance-coupled audio-frequency amplifiers led the field in quality. The advent of high quality input transformers and better

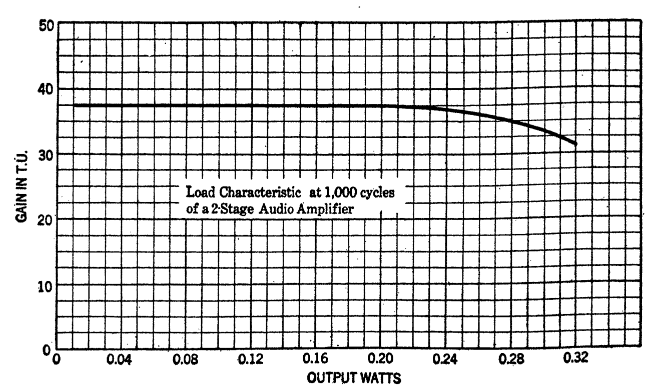

FIG. 10

acoustic translating devices, however, have all but made such devices obsolete. They represent one of the first steps toward better quality, and during the early stages of the art served their purpose. The limitations of both these types have been admirably pointed out by Mr. J. L. Schermerhorn, as follows: "An impedance- or resistance-coupled amplifier cannot be perfect. If the fixed condensers are not sufficiently large, the bass notes are missing. If they are large enough to pass the bass notes, they tend to introduce a time lag in the circuit. These conditions fix a definite limit for preventing the absolutely uniform amplification of all the audio frequencies." The time lag mentioned by Mr. Schermerhorn refers, of course, to the time constant of the condenser-resistance combination on the tube input. The minimum value of the series coupling-condenser is obviously fixed by its reactance to low notes. Now the time constant of the resistance-condenser combination must necessarily be low in order to prevent disagreeable hangovers which may either seriously alter the phase relations of independent notes or even cause some of the higher notes to disappear entirely, or be seriously masked by some of the higher amplitude low frequency notes. Inspection of the discharge curve of a condenser through a resistance would lead us to suspect this state of affairs. The product of the shunt resistance into the series capacity yields the length of time necessary for the condenser to lose about 63 per cent. of its charge. To prevent hangovers, it is necessary that the condenser discharge in less than a quarter cycle of that frequency which is the reciprocal of the time constant of the coupling combination. This of course imposes such a severe requirement on the amplifier that it would result in an overall transmission loss thereby defeating the purpose of the device. Hence it is necessary to affect a compromise between gain and distortion, and design the amplifier accordingly. The table in the next column shows a few values of time constant and their corresponding frequencies:

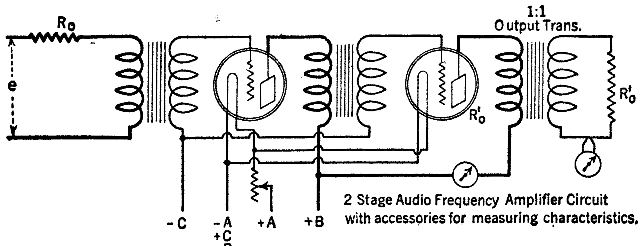

FIG. 11

C mfd.	At 50 cycles Xc ohms	R ohms	RC sec.	F c.p.s.	¼f. c.p.s.
1.0	3,180	10^6	.1	1	.25
		10^5	.1	10	2.5
		10^4	.01	100	25.0
0.1	31,800	10^6	.1	10	2.5
		10^5	.01	100	25.0
		10^4	.001	1,000	250.0
0.01	318,000	10^6	.01	100	25.0
		10^5	.001	1,000	250.0
		10^4	.0001	10,000	2,500.0
0.001	3,180,000	10^6	.001	1,000	250.0
		10^5	.0001	10,000	2,500.0
		10^4	.00001	100,000	25,000.0

In the above table, RC is the time constant of the resistance-condenser combination, in seconds, F the frequency having a period equal to the time constant, and ¼f, the highest frequency that will be unaffected by hangovers. It will be observed that an exceedingly low resistance must be used across the tube input if a reasonable time constant is to be maintained with a coupling condenser large enough to pass the low notes without undue attenuation. There are, of course, a number of other factors that enter, such as change in the gain frequency characteristic with the applied input voltage, etc. These facts are such general knowledge, however, that they merit no further discussion here. Two-stage transformer coupled amplifiers, on the other hand, can easily be designed to give an overall amplification varying less than 40 per cent. from the average value for all frequencies between 50 and 5000 cycles.

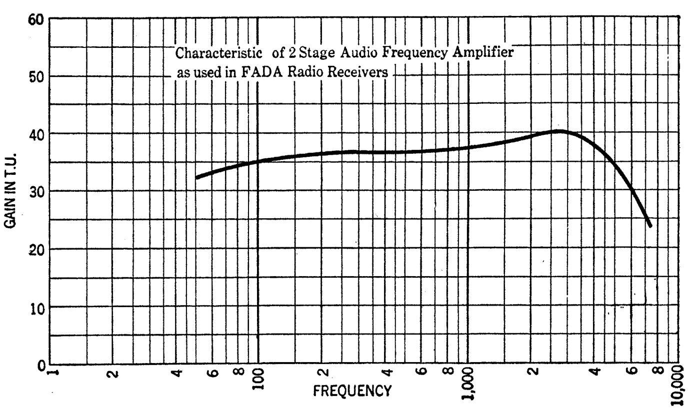

FIG. 12

To summarize: A perfect transformer has been defined as one which has perfect coupling and which neither stores nor dissipates energy. It has also been shown that it is desirable that a good input transformer depart from this definition since it is required that the input transformer deliver constant voltage rather than constant power. Furthermore, it is obvious that the leakage reactance can in some cases be used to advantage in eliminating high frequency noises by connecting the transformers in such sense that the inherent capacities resonate the leakage reactance at the proper frequency. A transformer characteristic as commonly measured by a C-battery detector does not give the true picture of its action in an amplifier, due mainly to the different input impedance of the amplifier tube. The general tendency of the amplifier tube is, of course, to decrease and broaden the resonance peak and to cause it to occur at a lower frequency. Transmission gain has been defined as the ratio of the power delivered to the load with the amplifier in the circuit to the power delivered with the amplifier removed. A method of measuring amplification conforming with this definition gives a truer picture of amplifier operation than the voltage amplification as ordinarily measured. There are, in general, two types of characteristics necessary to completely define amplifier operation. The first is the gain-frequency characteristic and the second the load characteristic. The former indicates the frequency distortion while the latter shows the load carrying capacity.

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