Transformer-Coupled Amplifiers

An Analysis of the Operation of a Transformer

By SYLVAN HARRIS

BEFORE we go ahead with this article let us recapitulate what has gone before. This series of articles began with a general discussion of the nature of music, analyzing the relations between pitch and frequency, fundamentals and overtones and the effect of the overtones or harmonics on the quality or "timbre" of the musical sounds emitted from the various musical instruments. It was shown how the introduction of spurious frequencies into these sounds or the loss of any of the overtones affects the timbre of the sound, when reproduced by an audio amplifier.

Other articles pointed out some of the difficulties that are met in the design and operation of audio amplifiers, and from the practical viewpoint, what is required of an amplifier in order that it may reproduce faithfully the sounds, musical or otherwise, which go into it. After that we studied some of the effects of overloading the amplifier upon the reproduction, and some of the inherent characteristics of electron-tube circuits which influence this overloading. The preceding article took up the structural study of the amplifier, showing how the various arrangements of amplifiers closely resemble each other, both in structure and operating characteristics; this will be devoted to the analysis of the several types of amplifiers separately.

We shall begin with the type of amplifier that is in most general use at the present time—the transformer-coupled amplifier. Its structure in schematic diagram form is shown in Fig. 1, while Fig. 2 pictures a "bread-board layout" of this type of amplifier. The operation of the amplifier is well understood; the electrical impulses to be amplified are impressed upon the amplifier at the *input* terminals, while those which are to actuate the loud-speaker emanate from the *output* terminals. Between the input and output terminals of the amplifier we desire to have the various components of the electrical impulses—whether they arise from music or otherwise, whether they be pleasant to the ear or not—amplified *in the same ratio, regardless of frequency or amplitude.* This has been brought out in the previous articles.

THEORY OF THE COUPLING

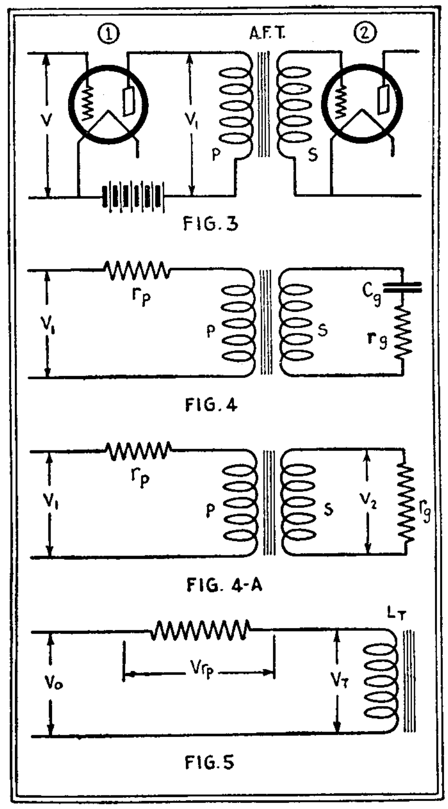
For our present purpose, let us consider Fig. 3, which represents a portion of an audio amplifier utilizing transformer coupling. We will consider mainly the transformer itself, in connection with its *terminal impedances,* by which we mean the impedances, resistances, or what-not, which are connected to the primary and secondary windings of the transformer. An alternating voltage V, due to the impulses to be amplified, is impressed on the grid or input circuit of the first tube. This voltage V is amplified in the tube, giving rise to an alternating voltage V_1 in the plate circuit of the first tube, having the same wave-form and frequency. We will assume that the alternating voltage established in the plate circuit of the first tube is an exact reproduction of the alternating voltage, V, put into it, but *magnified.* This is not exactly true, for the tube may contribute a little toward distorting the signals; but since we are not primarily studying tubes we will omit this source of distortion for the present.

We, therefore, are starting out with an alternating voltage in the plate circuit of the first tube, which is represented by V_1 in Fig. 4. Now, the path which the electrons take in the first tube, in their course from the filament to the plate, has a certain resistance, known as the plate resistance of the tube; and this resistance, which is considered as in series with the load external to the tube, is represented as r_p in Fig. 4. Connected in series with this is the primary of the transformer.

In Fig. 3 the secondary of the transformer is shown connected to the input or grid circuit of the second tube. It was shown in the previous article that the input of an electron tube represents a certain load on the transformer. This load is *a resistance in series with a capacity,* as indicated in Fig. 4, by C_g and r_g. In the ideal amplifier, the input of the electron tube should have infinite impedance; that is, the resistance r_g would be infinite, or the capacity C_g be zero, or both. Actually, this is not the case, as shown in the preceding articles; and for our purpose we shall represent the input of the second tube as a resistance load on the secondary of the transformer, designated by r_g in Fig. 4A, and having impressed upon it the secondary voltage V_2.

For a given input voltage V_1 we wish this secondary terminal voltage V_2 to be as high as possible, without introducing distortion. In other words, we wish the ratio of V_2 to V_1, which is the voltage ratio of the system, to be as high as possible. This is the circuit of the transformer which we are to study.

(*Continued on page* 594)



These four figures illustrate the theory of the operation of transformers in audio-frequency amplifiers. See the accompanying text for explanation.

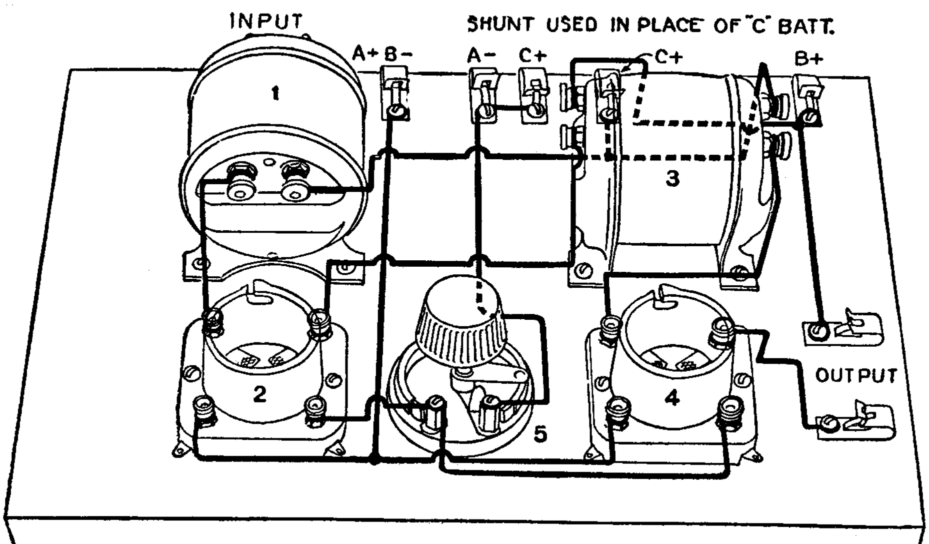


Fig. 2 (above) shows an excellent arrangement for the apparatus in an audio amplifier of the transformer-coupled type.

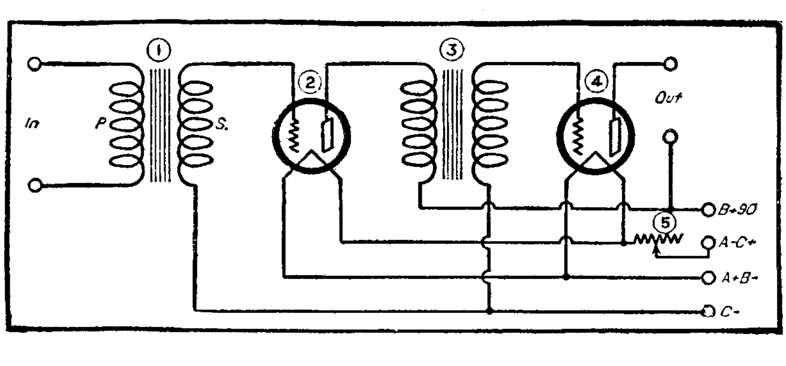


Fig. 1 (at the right) is the circuit diagram of the transformer-coupled A.F. amplifier, showing schematically the various battery connections illustrated in Fig. 2.

Radio News for November, 1926

Transformer-Coupled Amplifiers

(*Continued from page* 511)

THE FLUXES

Now, in every transformer, it is the *magnetic flux,* which is established by the current flowing in the primary and which threads the secondary winding, that induces the electromotive force in the secondary. But not all of this flux is utilized in thus producing the secondary e.m.f. Part of the flux set up by the primary current does not thread the secondary winding; this is known as the "primary leakage flux." Likewise, since the secondary winding derives its energy from the energy in the primary, it is the reaction of the secondary, which determines how much energy the primary draws from the source V_1 in Fig. 4A.

In other words, the induced secondary e.m.f. establishes a secondary current, which sets up a flux threading back through the primary windings. As with the primary leakage flux, all of this secondary reacting flux does not thread the primary winding; and this part of the secondary flux is known as the secondary leakage flux. To sum up then, that part of the primary flux which threads both windings is the useful part of the flux and is known as the "mutual flux"; it is reacted upon by part of the secondary flux. That part of either the primary or secondary fluxes, which does not link both windings, but threads only that winding in which it is generated, is the leakage flux. It is the relation between the mutual flux and the total fluxes which determines the *degree of coupling* in the transformer. (This principle applies to radio-frequency transformers as well).

It is well to know that these leakage fluxes exist, although it is difficult to apply this knowledge analytically in the design of transformers. The leakage flux, in every case, will lower the voltage ratio of the transformer and make it act less efficiently.

To simplify the explanation, we will assume that our transformer has no leakage flux; in other words, that it is a perfect transformer, and that all the energy fed into the primary goes into the secondary via the mutual flux. In that case when the transformer works into an *open circuit* (that is, when the resistance load connected to the secondary has infinite impedance so that there is no *current* in the secondary circuit) the voltage ratio is equal to the turns ratio of the transformer. This is the simplest case.

THE PRIMARY IMPEDANCE

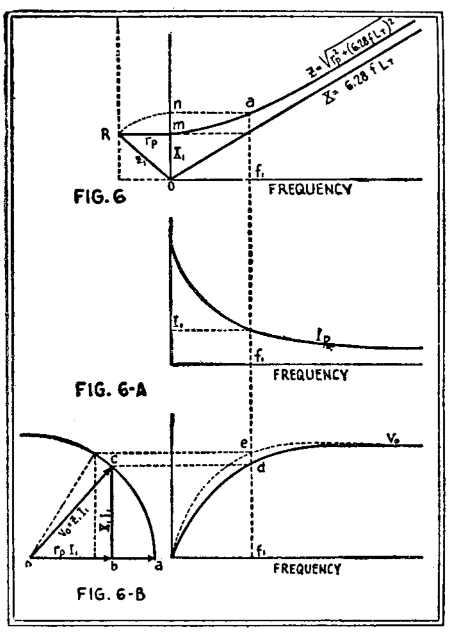
Another thing which interests us considerably is the *primary impedance* of the transformer; that is, the impedance which it presents to the impressed alternating voltage V_1 in Fig. 4A. In voltage amplifiers, which are generally used in radio receivers, it is required that this be as high as possible; in order that the greatest part of the total voltage V_1 be expended *in the transformer* and not in the resistance r_p. On the other hand there are limitations to the application of this principle which are determined by size of transformer, cost, etc. The question of faithful reproduction also depends upon the magnitude of the primary impedance; the greater the inductance of the primary the better will be the amplification of the low frequencies. More of this later.

In the theoretical perfect transformer the primary impedance is entirely due to the mutual inductance and is equivalent in ohms to $6.28nf$M, in which n is the ratio of the primary turns to the secondary turns, f is the frequency, and M is the mutual inductance in henries. Thus, in a 3-to-1 transformer, having a mutual inductance of 20 henries, the primary impedance at 1,000 cycles is 6.28x1,000x20x⅓, or about 42,000 ohms. When the transformer windings have resistance, as must be true in practice, the impedance is increased somewhat; although generally this change of impedance due to the resistance is negligible in amplifier transformers.

It is advantageous to have the primary impedance of the transformer as high as possible for two reasons; first, this prevents the voltage applied to the transformer primary terminals from dropping too low and thus impairing the amplification at low frequencies; and, secondly, the high impedance tends also to straighten out the *characteristic* of the tube to which the transformer is connected. This effect is negligible in comparison with the former, so we will defer discussing it, and consider the former in detail.

FORMULAE OF THE INTERACTIONS

Let us look at Fig. 5. The primary circuit of the transformer is essentially an e.m.f. V_o in series with a resistance r_p and an inductance L_t. We will neglect, as before, the resistance of the transformer, as its effect is generally negligible. The primary impedance of the transformer will then be the *reactance;* which is equal to $6.28fL_t$, in which L_t is in henries.



These theoretical curves give an excellent graphical representation of the theory of transformer coupling.

Now, the total voltage generated in the plate circuit is V_o, which is the same as μe_g (μ is the voltage-amplification constant of the tube and e_g the input on the grid). This voltage is divided into two parts: viz., that part which appears as a voltage drop in the plate resistance, r_p, and the remainder, which is the *useful* part, and which is impressed on the primary terminals of the transformer. The former is designated as V_{rp} and the latter as V_t in Fig. 5.

The voltage drop in either the resistance or the reactance is equal to the resistance or reactance multiplied by the current. Thus, if I_p is the current, the voltage drop in the resistance is r_pI_p and that in the reactance is $6.28fL_tI_p$. (I_p is in amperes). Since r_p and L_t are in series, both carry the same current; and it follows that the voltage drops in the two are proportional to their impedances.

This is not important at the present, but it indicates that in order to have a large part of the total voltage drop appear across the terminals of the transformer, L_t must be large.

A GRAPHICAL SOLUTION

This whole discussion may seem complicated at first, just as the figure which we are about to describe, but once understood, the simplicity of it all will be apparent. In connection with Fig. 6, the following ideas must be borne in mind:

(1) The *reactance of the transformer is dependent upon the frequency* and is equal to $6.28fL_t$.

(2) The impedance of a series circuit, such as we are studying, is the square root of the sum of the squares of the resistance and the reactance, or, $\sqrt{r_p^2 + (6.28fL)^2}$. This is the same formula which gives the hypotenuse of a right triangle whose sides are respectively equal in length to the values of the resistance and the reactance. For this reason in Fig. 6, instead of computing the total impedance of the plate circuit, we obtain it graphically by constructing right-angled triangles.

(3) Assuming the alternating voltage applied to the grid of the tube preceding the transformer to be constant, then the voltage V_o developed in the plate circuit will be constant, and the current in the plate circuit, or I_p, will be this voltage divided by the total impedance of the circuit.

(4) The voltage drop in the resistance is r_pI_p, and that across the terminals of the transformer is X_tI_t; where X represents the reactance of the transformer (and is equal to $6.28fL_t$).

Now to study Fig. 6: at the upper right we have a diagram showing the frequency f on the horizontal axis, and the reactance, X_t on the vertical axis. (The straight line drawn on the graph shows the manner in which the reactance varies with the frequency; it is straight for the reason that the reactance is proportional to the frequency, that is, if the frequency is double the reactance is double, etc.)

Now, at any given frequency, as at f_1, the reactance is X_1. Using this value as the line Om in the figure, the altitude of a right triangle, we can lay off at right angles to it the line mR, the length of which represents the resistance r_p. The length of the hypotenuse of this triangle, or the line OR, represents the total impedance of the plate circuit, and is marked Z_1. Then, taking a pair of compasses, from the center O, measure OR on the axis of X_t, as indicated by the broken arc, giving the line On. Then (moving horizontally over the dotted line, from the point n to the vertical line drawn through f_1) we obtain the point a, the height of which above the axis of frequency Of_1 is the total impedance Z_1 at the particular frequency. If this sounds complicated, go back and read this paragraph again. It will very soon become clear enough.

If we follow this procedure for many points on the axis of frequency, we shall obtain the curve marked Z, which shows how the total impedance of the plate circuit varies with the frequency. It will be noted that at very low frequencies, the total impedance differs considerably from the transformer reactance, but as the frequency increases they become more and more nearly equal.

EFFECT OF CHANGE IN FREQUENCY

This means that at low frequencies the resistance of the plate, r_p, has a predominating influence on the impedance of the circuit; whereas at higher frequencies its influence is less, the reactance contributing the greater part of the total impedance.

Now we will go a step farther. We have assumed that the voltage developed in the plate circuit, V_o in Fig. 5, is constant. Therefore, if we divide this voltage by the total impedance for various frequencies we will obtain a curve which shows how the plate current I_p varies with the frequency. For instance, divide the voltage, V_o, by the impedance, Z_1, at the frequency f_1 and we obtain the plate current, I_1, at that frequency. By doing this for various points on the Z curve, we obtain the curve shown at 6A, marked I_p.

This curve tells us something interesting, which it is probable may not have occurred to the reader before. If we have an alternating voltage applied to the grid of a tube, and increase its frequency from a very low to a high value, keeping the voltage the same, the current in the plate circuit will decrease from a definite value at zero frequency (direct current) as the frequency is increased.

Now we will look at Fig. 6B, and in interpreting it will make use of some of these things we learned from Fig. 6. Suppose we take the plate current at zero frequency and multiply it by the resistance r_p. We will then obtain the voltage drop in r_p, which may be represented by the length of the line Oa. If we multiply the current at zero frequency by the reactance at zero frequency (which is 0), we will get zero, so that at zero frequency there is no voltage drop in the transformer. Now do the same thing at the frequency f_1; multiply the current I_1 by the resistance r_p and obtain the voltage drop Ob. Again multiply the current I_1 by the reactance X_1 and obtain the voltage drop bc. Note that we have again formed a right triangle; for the same law applies to the voltage drops across the resistance and reactance as to the resistance and reactance themselves, provided of course, the current is the same in each, as it is in this case.

THE PERFECT CHARACTERISTIC

If we now project the point c horizontally to the vertical line corresponding to the frequency f_1, we have the point d representing the voltage across the transformer primary at that frequency. By doing this successively for several values of the frequency we get a complete curve, showing how the voltage impressed at the transformer terminals varies with frequency. Note the similarity between the appearance of this curve and the usual *amplification characteristic.*

If we had a perfect transformer, without resonance peaks, we could simply multiply every point on this curve by the turns ratio of the transformer and the amplification constant of the tube, and obtain the true amplification characteristic of the complete stage. This would also require that the load to which the secondary is attached have infinite impedance so that the secondary winding would carry no current. Of course, such a condition does not occur in practice; but this method of analysis can be applied to determine approximately the operating conditions.

Now, to discuss the curves. When the frequency is low the reactance is low; the total impedance is therefore low and is determined mainly by the plate resistance. As the frequency increases the reactance increases. This increases the circuit impedance and decreases the current. The decrease of current causes the drop in r_p to lessen. But the reactance increases at a greater rate than the current decreases, so that *the voltage drop in the transformer increases with the frequency.* With the resistance drop decreasing and the transformer voltage increasing, it is seen that as the frequency increases the transformer assumes a greater and greater proportion of the total voltage.

As the frequency becomes very high the transformer voltage approaches a maximum constant value. This must be so; as it is not possible to get a voltage on the primary terminals higher than that which is available at the plate. This is shown at the left of Fig. 6B. In the first place the arc ac is part of a circle, because the developed voltage V_o, which is the same as Z_1I_1, remains constant; and the radius of the arc is of course constant. The largest value that the voltage drop in the reactance can have is obtained by swinging Z_1I_1 into a vertical position. Then the reactive drop will be represented by the radius of the circle, which is the total available voltage in the plate circuit. This is the limiting case, and is not quite realized in practice.

This diagram can be used also to show why a high transformer reactance is desirable. Suppose at the frequency f_1 the reactance was greater than X_1. Then the reactive drop X_1I_1 would be drawn in the position of the dotted line in the circle diagram; the resistance drop would be smaller, and the voltage on the transformer primary would be indicated by the point e instead of d. The characteristic would then be higher at the low frequencies, although the limiting voltage would be the same.

In this article we have considered qualitatively the operation of the transformer; the next will deal with some points of practical design, such as the best turn-ratio to use, the required impedances, and the factors which influence the selection of these.