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How an Output Transformer Causes Distortion

NORMAN H. CROWHURST*

The operation of audio transformers has long been surrounded with an aura of mystery. This article distinguishes the different forms of distortion an output transformer can produce, and gives some simple measurement methods.

In Two Parts — Part 1

The use of audio transformers has long been deprecated on the grounds that they cause distortion. In fact the output transformer seems to be almost the sole survivor of the species and many attempts have been made to do without even this. A few amplifiers have been designed to dispense with the output transformer, apparently in the belief that the output transformer is the principal remaining cause of distortion.

Careful analysis will usually show that the tubes introduce more distortion than the output transformer would have and that a well-designed amplifier using the conventional output transformer can achieve a much lower order of distortion than is possible without one.

A few simple facts about transformers seem to get overlooked: when tube curvature causes distortion it distorts all frequencies; but the distortion a transformer causes due to nonlinearity of its magnetizing current is concentrated at the low-frequency end. The worst transformer made will not distort the middle frequencies and the way it distorts at both lower and higher frequencies is one of the things we shall clarify in this article.

But, surely, someone will say, a transformer *can* cause distortion at middle frequencies? "I remember replacing a transformer, and the replacement would not give so much power without distortion as the original did." Doesn't this prove that the transformer distorts at the middle frequency? To understand the cause of this experience, let's consider the effect of transformer efficiency on amplifier performance.

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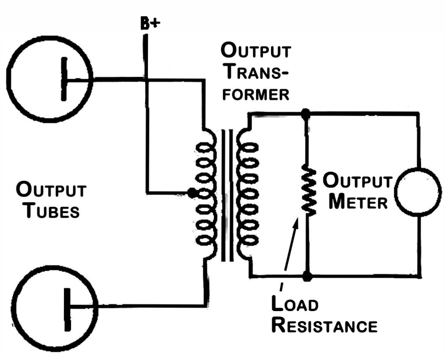


Fig. 1. Usual method of measuring output power consists of calculating the watts dissipated in a load resistor connected to the **secondary** of the output transformer. While this is the available power output, the output tubes actually deliver a little more than this.

The Importance of Efficiency

Amplifiers are rated to give a certain maximum output, determined by the performance of the output tubes. However, the output power is always measured on the secondary side of the output transformer, as shown at *Fig.* 1.

A good output transformer is probably about 95 per cent efficient. This means that, if the amplifier gives 50 watts output, measured on the secondary side of the transformer, there must be nearly 53 watts output *delivered to the primary side* from the output tubes. The output tubes are having to give nearly 53 watts output for us to measure a good 50 watts.

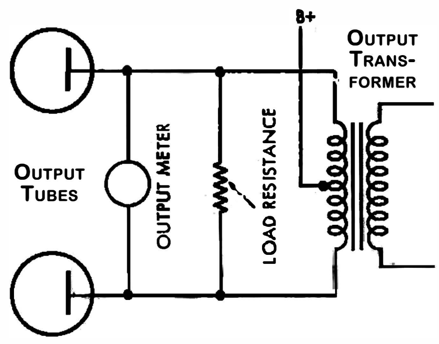


Fig. 2. Connecting a suitable load resistor on the primary of the output transformer to measure power avoids some of the loss in the output transformer, but the tubes still have to supply the core loss.

This is a little difficult to verify by actual measurement. The simplest step towards it is to remove the secondary resistance load and apply a plate-to-plate load on the primary, as at *Fig.* 2. If the secondary load was 16 ohms and the transformer refers this back to be, say, 6000 ohms plate-to-plate resistance, then a 6000 ohm resistor, of at least 50 watts dissipation, should be connected across the primary. The power is now delivered by the output tubes directly to the load, without passing through the output transformer, and can now be measured in the 6000-ohm resistor.

But all of the losses in the output transformer have not been removed by transferring the load from the secondary to the primary. The transformer core loss is still present. If, of the 3 watts lost in the transformer, 1 watt is due to core losses and 2 watts to losses in the winding resistances, we shall only measure 52 watts in the load connected to the primary, because the odd 1 watt will still be lost in the core.

This discussion is based on a transformer having an efficiency of 95 per cent. A 50-watt output transformer with an efficiency of 95 per cent, and a really good frequency response from 20 to 20,000 cps, is going to be fairly large and expensive. A 5 per cent power loss is only 0.2 db, so some will argue that we can accept a transformer of 90 per cent efficiency, which still represents a loss of less than 0.5 db, in order to achieve better quality in terms of frequency response, at a size and cost that is more reasonable. From some aspects the second transformer could be regarded as a better-quality job than the first, but . . .

Supposing we have made a substitution of a 90 per cent efficiency transformer into an amplifier that originally used a 95 per cent transformer: the tubes will still be capable of giving the same output—slightly less than 53 watts, which, with a 95 per cent efficient transformer *will* deliver 50 watts on the secondary: but with a 90 per cent efficient transformer, the same tubes will only deliver a little over 47 watts on the secondary.

At first glance, this may not seem to be a very serious loss. If you make the measurement at 47 watts on the secondary, you may correctly assess its true value. But unfortunately, output tubes to give 50 watts quickly run into distortion when they are pushed to a higher

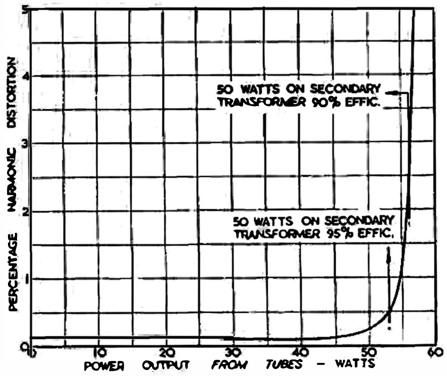


Fig. 3. Typical distortion characteristic of amplifier, plotted in terms of the power given by the tubes, to illustrate how use of transformers of differing efficiency can change the distortion at rated maximum output quite drastically, because the tubes also have to supply the transformer losses.

level. The distortion characteristic is similar to that shown at *Fig.* 3: the distortion at the 53 watts required to give 50 watts from a 95 per cent efficient transformer may be only 0.5 per cent; but to get the almost 56 watts needed for a 90 per cent efficient transformer, the distortion may rise to 2½ per cent, or even more. So, if the measurement is made only at the 50 watt level *measured on the secondary,* the impression can easily be obtained that the second output transformer is considerably increasing the distortion, as compared with the first one.

Unfortunately also, many people place considerable stress on getting the full value of wattage stated, within the rated distortion limit. If the output is stated to be 50 watts at 0.5 per cent distortion, then an amplifier is considered to be seriously lacking if it only delivers 48 watts with 0.5 per cent distortion, and runs up to 2 or 3 per cent distortion when the output is pushed to 50 watts. This viewpoint can be seriously detrimental to an assessment of transformer quality, when the only deficiency in the transformer is that it is slightly less efficient: it introduces a loss of 0.5 db, or maybe even less, instead of the original 0.2 db.

Low-Frequency Distortion

At the low-frequency end of the response, an output transformer causes distortion due to saturation of the core, which causes a nonlinear magnetizing current. This at one time was always true. But in recent years, with modern magnetic materials, and with some methods of operating tubes, the statement needs modifying, as we shall see. First let us see how we measure the low-frequency waveform of the transformer itself, and what kind of results we get.

Transformer Waveforms

In *Fig.* 4, (A) shows the arrangement for measuring the magnetizing current in a sample transformer by means of an oscilloscope pattern. Resistor R should be chosen so its voltage drop is a small fraction of that across the transformer winding, so the voltage on the winding is also close to sinusoidal. As full line voltage will probably be not enough to produce saturation in the primary of an output transformer the secondary winding should be used for the test, leaving the primary open-circuited and taking care not to get too near the open ends, which will produce a prohibitively large a.c. voltage.

It is important to take care which way round the Variac is connected to the line and also to see that the ground side of the scope does not return to the line ground, because, in these measurements, the scope ground is returned to a floating point between the resistor *R* and one side of the transformer winding. So take care to avoid having more than one ground point and also avoid metal-to-metal contact between the scope case and other grounded chassis.

The type of trace that the arrangement of (A) *Fig.* 4 gives when the core begins to go into saturation is shown at (A) in *Fig.* 5. The voltage applied to the vertical plates is approximately sinusoidal while the horizontal voltage follows the magnetizing current wave-

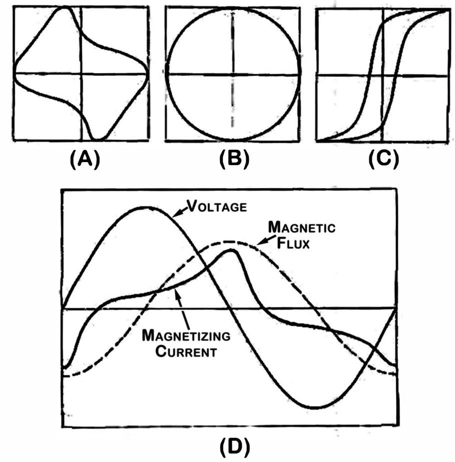


Fig. 5. Traces associated with core analysis: (A) magnetizing current horizontal with voltage vertical, using nearly sinusoidal voltage waveform; (B) circular pattern to check for 90-deg. phase shift in voltage display; (C) hysteresis loop obtained by 90-deg. shift on vertical plates; (D) waveforms displayed by normal time base, corresponding to the patterns of (A) and (C). Magnetic flux is shown dotted, because this cannot be displayed directly.

form, shown separately against a conventional time base at (D) in *Fig.* 5.

With a little adaptation, the circuit can be made to display the well-known hysteresis loop for the transformer core. The necessary changes are illustrated at

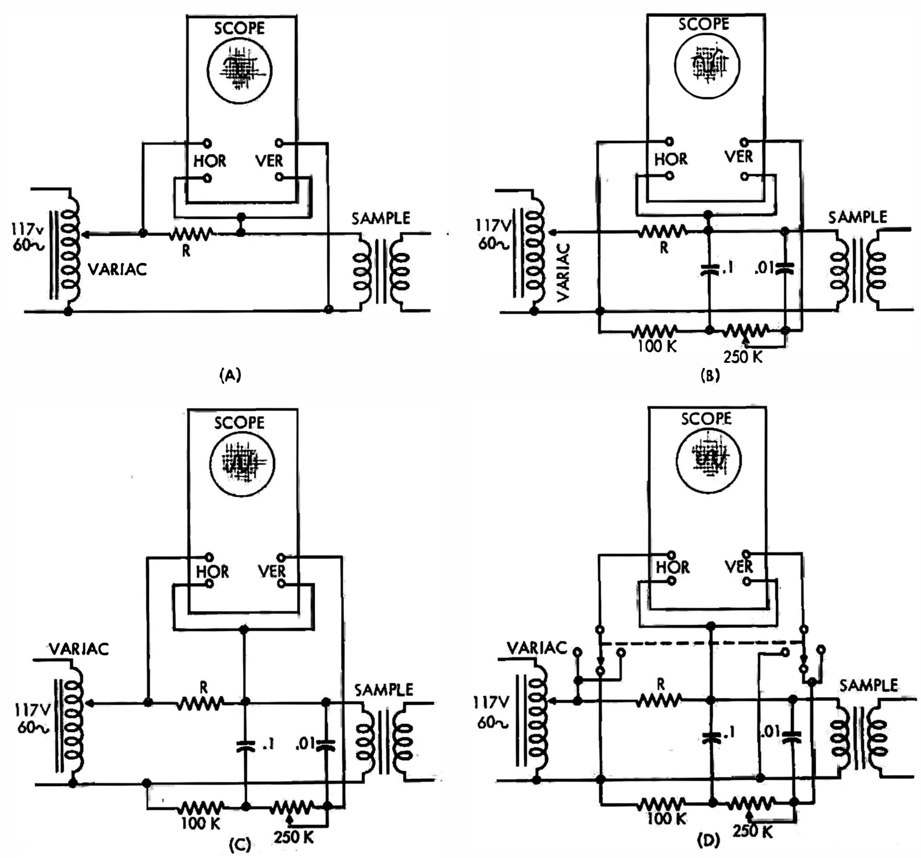


Fig. 4. Circuit arrangements for producing the oscilloscope traces: (A) the arrangement for the trace of (A) in Fig. 5; (B) connections for setting 90-deg. phase shift, by adjusting to get circle of (B) in Fig. 5; (C) connections to use with 90-deg. phase shift to give hysteresis loop at (C) in Fig. 5; (D) circuit with switching so that each display can be presented in quick sequence.

(B) and (C) in *Fig.* 4. When a sinusoidal voltage is used the magnetic flux in the core is also sinusoidal, but displaced 90 deg. from the voltage it induces. So, by introducing a 90 deg. phase shift in the vertical deflection, we can produce a hysteresis loop.

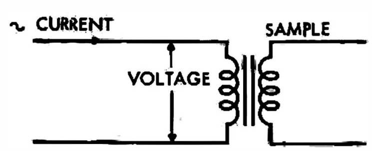
First we have to set up the 90-deg. phase shift. To do this, the components shown at (B) in *Fig.* 4 are added and the 0.25-megohm variable resistor and the scope gain controls are adjusted to obtain the circular trace of *Fig.* 5. Then, without altering the setting of the 0.25-meg. resistor, change the circuit to the arrangement of C in *Fig.* 4, when the hysteresis loop shown at (C) in *Fig.* 5 will be displayed.

This setting will give the hysteresis loop at 60 cps, and its behavior at different levels can be observed by turning the Variac up and down. However, to arrange the setup so that this procedure can be repeated at different frequencies, the switching arrangement of (D) in *Fig.* 1 can be included, which provides for making the connections shown at (A), (B), and (C) of *Fig.* 4 in quick succession. The Variac should then be fed from a high-power amplifier that will deliver the necessary voltage without waveform distortion at the frequencies required.

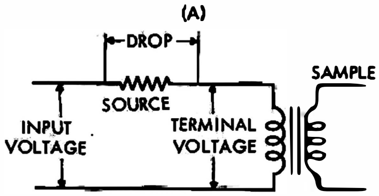
If you switch the scope back to regular time base, which means the horizontal input is then disconnected and the vertical is displayed against time, the waveforms shown at (D) in *Fig.* 5 can be obtained (except the magnetic flux waveform, because there is no means of measuring this). Although these waveforms can be displayed there is no simple means of identifying the relative phase. This is the advantage of using the loop kind of display shown in *Fig.* 5 at (A), (B), and (C).

Transformers in Tube Circuits

All of these displays use at least an approximately sinusoidal voltage waveform. Distortion occurs because the *voltage* departs from the true sine wave. This happens because the distorted current waveform is drawn from a source resistance that produces a volt drop. In the arrangement of *Fig.* 4 we used the Variac and the low value of resistor *R* to maintain an approximate sinusoidal voltage by avoiding this voltage drop. But in practical amplifier circuits the plate resistance of the output tubes does not allow this condition.



(A)

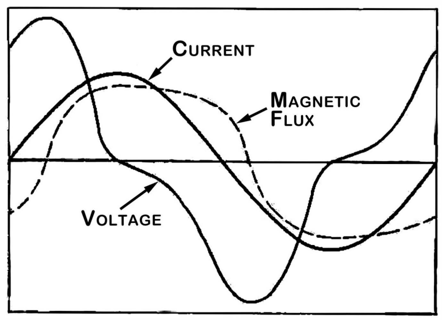


(B)

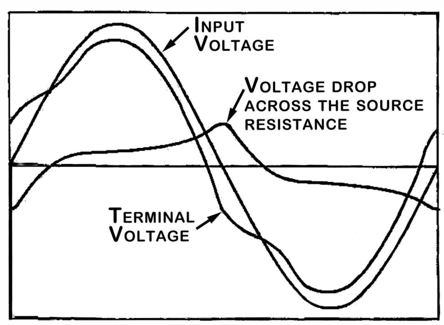
Fig. 6. Showing the quantities displayed in Fig. 7: (A) fed from a pentode, or high resistance source, the current is sinusoidal; (B) with a lower source resistance, neither the voltage or current is sinusoidal.

Pentode Outputs

A pentode is virtually a "current" source, so swinging to the other extreme for a moment, we could assume that the current is sinusoidal, as represented at (A) in *Fig.* 6. In this case the magnetic flux will be determined from the hysteresis loop and the voltage, in turn, is produced by the rate at which the flux varies at any instant. The waveforms produced are shown at (A) in *Fig.* 7. Current and voltage can of course be displayed on the scope, but the magnetic flux we can only deduce.



(A)



(B)

Fig. 7. Waveforms in different practical circuits: (A) with a pentode or high resistance source, the current is sinusoidal; (B) with a lower source resistance, these waveforms are typical.

These waveforms apply approximately to a pentode output stage without feedback. When feedback is used, the voltage waveform gets fed back over the whole amplifier so as to "correct" the current waveform, which then is no longer sinusoidal.

Triode Outputs

(B) in *Fig.* 6 shows how we can simulate the condition for triode amplifiers. The input voltage, which is sinusoidal, can be regarded as the open-circuit voltage at the plate. This input voltage is that applied to the grid multiplied by the amplification factor of the tube. The source resistance corresponds with the tube plate resistance and because of the drop in this source resistance, due to the current drawn by the transformer winding, the terminal voltage will differ from the output voltage, as shown at (B) in *Fig.* 7.

Notice that the terminal voltage comes much nearer to being in phase with the input voltage than the phase relationship between voltage and current at (A) in *Fig.* 7.

From this brief discussion it becomes evident that the magnetizing current and terminal voltage of a transformer cannot *both* be sinusoidal. In practice both of them depart from a true sine wave in shape and a certain amount of distortion results.

Another Kind of Low-Frequency Distortion

However, if the magnetizing current is a relatively small proportion of the total current in the transformer windings, the distortion may be a very small percentage. These curves were displayed with the transformer unloaded so that the magnetizing current is the only current in the windings. Had the transformer been terminated by its normal load resistance, the waveforms would probably have been indistinguishable from pure sine waves and distortion could only be detected by means of an analyzer.

Magnetizing current [or, excitation current] is invariably related to effective primary inductance, and the way a transformer distorts at low frequencies depends upon the precise relationship between primary inductance [open circuit inductance, OCL] and magnetizing current. Two numerical cases will illustrate this distinction.

First, suppose that the magnetizing current is 10 per cent of the load current. This means that the reactance due to primary inductance would be ten times the primary load resistance. This would cause an attenuation of less than .05 db. But if this magnetizing current was running into saturation so the magnetizing current waveform is as shown at (B) in *Fig.* 7, containing 20 per cent harmonic, this magnetizing current, being 1/10th of the total load current, could produce 1/10th this amount of distortion in the output waveform, or 2 per cent.

The second kind of distortion that can occur at low frequencies is not directly due to the waveform of the magnetizing current at all. The transformer may operate well within the saturation limit, but inductance only represents a reactance of, say, twice that of the load resistance. This will result in an about 1dB loss at this frequency and will also cause the load line on the tube characteristics to open out into an ellipse. In this case the distortion present will due to the elliptical load line rather than the non-linearity of the transformer magnetizing current.

Another variation of this condition occurs in amplifiers with large amounts of feedback. This produces a low effective source resistance, so the distortion component of the magnetizing *current* does not appreciably distort *voltage*. With a damping factor of 30, a magnetizing current 25% of the load current, and containing 30% harmonic, will cause only 0.25% distortion in the output. But 25% reactive magnetizing current may cause the tubes to clip, producing a much bigger distortion than this.

(To be concluded)

How an Output Transformer Causes Distortion

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In Two Parts — Part 2

As this distortion due to reactive loading is quite similar to the varieties that a transformer causes at high frequencies we will consider both together. (A) in *Fig.* 8 shows the practical circuit of an output transformer while (B), *Fig.* 8 shows the load seen by the output tubes.

Directly shunting from plate to plate is the primary capacitance of the transformer. The load resistance gets stepped up by the ratio N^2 but, due to leakage flux that gets between the primary and secondary windings, there is an effective inductance between this load and the tubes, shown in the equivalent circuit of (B), *Fig.* 8 as leakage inductance.

The winding capacitance has the same properties as any other capacitance in a circuit. A leakage inductance is precisely similar to any air-cored inductance: it cannot introduce distortion of itself.

However, if the leakage inductance is the dominant reactance at the high-frequency end, then the load resistance, referred back to the primary will look like a resistance with an inductance *in series.* If the output tubes cause distortion with series reactance added to the load resistance, then this kind of transformer will appear to cause distortion.

In other amplifiers, distortion may appear more rapidly when a reactance is added *in parallel* with the load resistance. In this case a transformer, in which the winding capacitance is the dominant reactance at the high frequency end, will show distortion more rapidly.

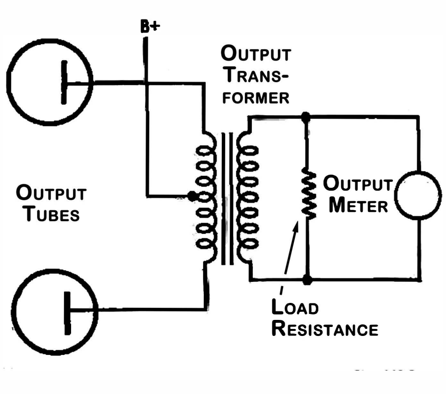

Fig. 8. Practical and equivalent circuit of output transformer for high frequency response: (A) actual circuit: (B) equivalent plate load for output tubes.

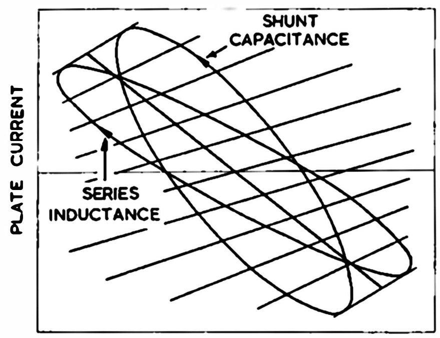

Fig. 9. A succession of elliptical load lines representing progressively larger values of reactance in series with a constant value of resistance, represented by the straight line. The parallel sloping lines at top and bottom represent the ideal tube characteristics for the extremes of grid voltage excursion.

These facts can be more readily appreciated by looking at the effect on the resultant load line of reactances applied in series and parallel with the resistance load. The kinds of ellipse produced are shown at *Figs.* 9 and 10. When these kinds of elliptical digression are applied to tube characteristics, distortion may appear more rapidly when the ellipse departs from the straight line on one side than on the other.

The two ways in which the reactances of (B), *Fig.* 8, can cause the load line to open out to an ellipse are illustrated against composite tube characteristics at *Fig.* 11. The series leakage inductance causes a voltage drop additional to that in the load and increases the effective plate-voltage swing while cutting down the current. The shunt capacitance takes additional current from the output tubes and tends to drop the plate-voltage swing. The resultant ellipse depends on which of these two effects is the greater. As we shall see presently, the transformer can present one of two kinds of impedance response to the output tubes. From the viewpoint of potential high frequency distortion this is the most important difference between different output transformers that may appear to give the same frequency response.

How Reactance Causes Distortion

In *Fig.* 11 the almost parallel lines are not a carelessly drawn attempt—they represent typical composite curves for a pair of pentode or tetrode type tubes operating in pushpull. In practice these lines would not be straight, but slightly curved. To make the drawing easier, straight lines have been shown, but the angle of the lines is representative of typical tubes. The middle line, passing through the operating point, is at the shallowest slope, while the extreme lines, representing zero grid voltage on alternate tubes, have the steepest slopes. This fact is generally true, whether pentodes or triodes are used—it is a little more prominent with tetrode or pentode type tubes than with triodes but the trend is the same.

The arrowheads marked on the two ellipses show the way the operating point travels around the ellipse in the course of a cycle. Notice that, for shunt capacitance, the spacing between intersections on consecutive grid voltage lines is wider going out from zero than coming back, while for series inductance it is narrower going out from zero than coming back. This introduces a form of distortion illustrated on the normal waveform display at *Fig.* 12.

In curve A the slope from each peak back to the zero line is steeper than that from the zero line up to the following peak. Curve B is a sine wave represent-

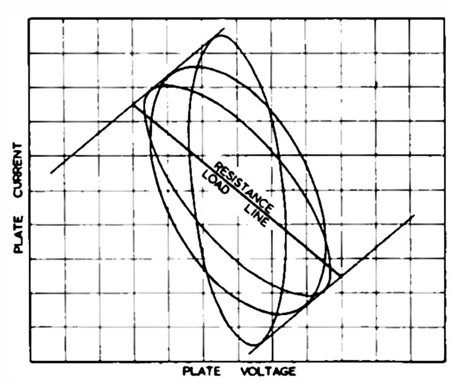

Fig. 10. A succession of elliptical load lines representing a reactance in shunt with a constant value of resistance.

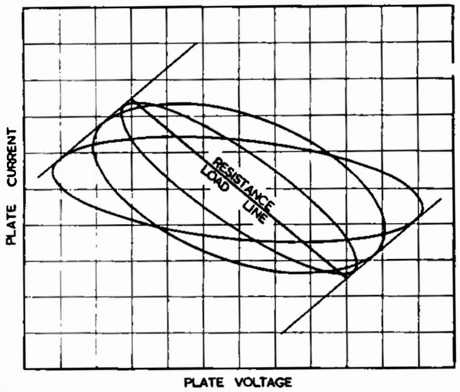

Fig. 11. Load lines on composite characteristics relevant to different possibilities in high-frequency response: the straight line across the characteristics represents the resistive load value at middle frequencies.

ing the output with the resistive load line, while curve C shows the reverse condition to that of curve A, the upward slope from zero to the peak is steeper than the return from the peak to zero.

If the grid voltage swing is increased a little more than that shown in *Fig.* 11, clipping occurs at both ends of the load line. The dotted sections in *Fig.* 12 show how the clipping shows up on each of the output waveforms.

Reverting now to the case of the shunt primary inductance causing distortion. This will produce an ellipse in a similar position to that shown for shunt capacitance in *Fig.* 11, because it will draw more plate current for a lower voltage swing than the resistance load line, but the direction of rotation will be reversed because it is the opposite kind of reactance. This means that the kind of wave shape will be similar to that produced by series inductance as shown at A in *Fig.* 12. If clipping occurs due to this shunting effect (maybe aided by feedback) then the flattening will also be in a position similar to that shown on curve A.

All the foregoing discussion is based on symmetrical forms of distortion. Some kinds of distortion, especially at the high frequencies, occur due to asymmetrical loading by the output transformer. If the leakage inductance and winding capacitance are not uniformly distributed between the two halves of the primary, each may have its own pattern of resonant frequencies. This will give rise to phase differences at the two plate's circuits (other than the normal 180 deg.). And these differences, especially in (a) pentode output circuits. and (b) with over-all feedback, can produce the most erratic forms of asymmetrical waveform distortion. In a sense the output transformer is responsible for this kind of distortion, but it is not due to non-linearity in the accepted sense. All the reactances in the transformer that cause it are linear circuit elements.

Identifying the Distortion

The curves shown in *Fig.* 7 and *Fig.* 12 show how the waveforms depart from sinusoidal when there is a relatively large amount of distortion. It would be difficult to determine the cause of distortion from the waveform when it is considerably less than 5 per cent. So we need a more precise method of observation. In some instances the distortion would be more than 5 per cent without the over-all feedback applied. In these cases the method of testing just to be described is a great help, because it shows up the original amount of distortion even with the feedback connected.

This very simple method employs loop traces on the oscilloscope, using the setup shown in *Fig.* 13. If over-all feedback is applied, the waveform at the plate

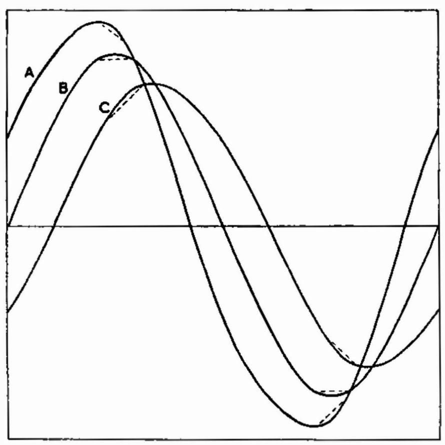

Fig. 12. Possible output waveforms, corresponding with the varieties of load line shown in Fig. 11: (A) for series inductance component; (B) for pure resistance (the only curve that is a sine wave;) (C) for shunt-capacitance component. The dotted portions illustrate the additional effect when clipping begins.

may be practically sinusoidal but, to achieve this, the waveform at the grid may need to depart considerably from a true sine wave. However, both waveforms, observed separately, may be so close to a sine wave that it is difficult to determine what kind of distortion is occurring, but by using the loop trace method of observation the two waveforms are compared and the kind of distortion is much more easily identified.

Before applying this method it is advisable to make sure that the amplifier is balanced to see that the waveform on both grids is identical and also that on both plates. A difference between the waveforms on each side indicates there is lack of proper balance somewhere in the amplifier, which should be attended to before further investigation. This procedure has been adequately described elsewhere, so we will assume that the amplifier is operating under a condition of good balance.

Figure 14 shows the kinds of trace that will be obtained with each of the varieties of distortion we have discussed except the asymmetrical one, which can cause such a variety of forms that no trace can be regarded as representative. These are somewhat exaggerated so the differences in shape can be clearly seen. Observation of a scope trace, even where the distortion is small, will quickly identify which of these varieties (or a combination of two or more) is occurring.

In *Fig.* 14, (A) is the kind of trace produced by saturation rather than reactance loading. The reason for this shape will be seen by reference to (B) of *Fig.* 7, where the input and terminal voltages are practically in phase but the latter has considerable distortion.

(B) shows the kind of trace produced by the relationship represented at (A) in *Fig.* 7 where the principal effect is due to the inductive reactance. The magnetizing current approaches 90 deg. phase lag behind the terminal voltage. In (A) of *Fig.* 7 the current is sinusoidal and the voltage waveform is distorted. If over-all feedback is used to "correct" the input waveform so that the output voltage waveform is almost sinusoidal, the sequence of relations will be similar, so the spot will travel round a similar trace but its traverse speed will vary. Either way a loop similar to (B) in *Fig.* 14 is displayed.

(C) shows the kind of trace produced by the reactive ellipse on pushpull characteristics. If the ellipse departs from its true shape by a straightening along alternate quadrants and a bending along the others as shown here, the cause of distortion is the reactive loading on the output tubes.

(D) shows what clipping does to reactance loading. If the horizontal deflection is taken from the grid circuit, as

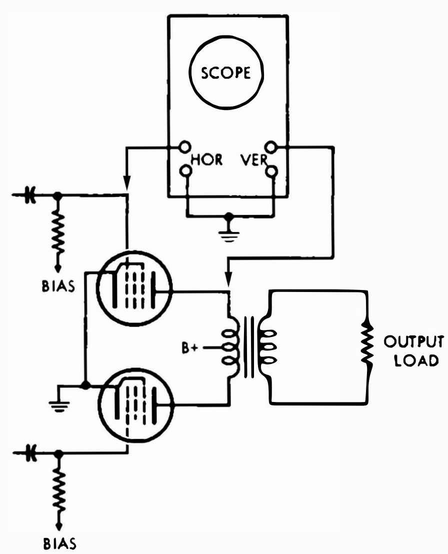

Fig. 13. Method of applying oscilloscope to amplifier circuit to check performance of output transformer at low and high frequencies. Before applying this method the waveforms on both grids and plates should be checked for symmetry.

shown in *Fig.* 13, the excursion will be abruptly limited by the grid current, producing the "lopped-off" end shown in solid line. The dashed line shows the true elliptical form in the absence of clipping. If the horizontal deflection is taken from some point earlier in the amplifier, the grid clipping will not show on the horizontal, but its result on the output waveform will produce distortion represented by the dot and dash curve in (D) *Fig.* 14.

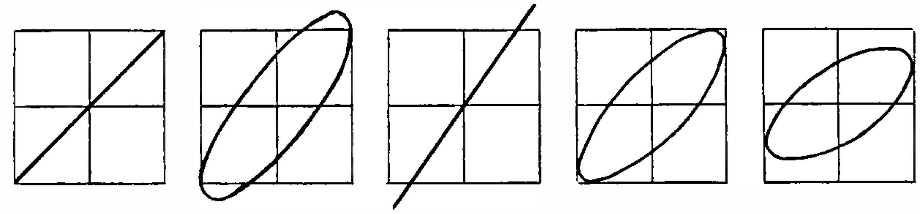
(A) (B) (C) (D) (E)

Fig. 15. Sequence of patterns at progressively higher frequencies when inductive and capacitive reactances resonate: (A) mid-frequency—totally resistive; (B) series inductance has predominant effect; (C) both combine to produce resistive dynamic impedance higher than (A); (D) and (E) successive shapes when capacitive reactance takes over.

Impedance Characteristic

By sweeping the audio generator over these higher frequencies we can see what kind of load-line response the transformer produces for the output tubes. One variety is illustrated at *Fig.* 15, which represents the display presented at successively higher frequencies: starting at a mid-frequency where the load is resistive; first the leakage inductance increases the output voltage producing an ellipse with a slightly increased slope, shown at (B); continuing to higher frequencies, the capacitive reactance begins to take effect: a point is reached where the two reactive components produce a dynamically resistive load line, as at (C); because the effective resistance is now higher than the original value, the *slope* of the line trace will be steeper than at (A).

Do not confuse *slope* with *length*. If the amplifier has a non-uniform frequency response the length of the line or size of the trace may increase or decrease but the slope indicates the relative magnitude over the output stage only.

At (D) a further increase in frequency turns the reactance over to the capacitive side and the output amplitude is falling off relative to the input amplitude; finally, at (E), the capacitive reactance is well on the way to a high-frequency roll-off.

The alternative kind of load-impedance characteristic a transformer can present to the output stage has the capacitive reactance predominating all the way. This happens because the leakage inductance is made so low that the load resistance is tightly coupled to the primary, and primary capacitance produces considerable roll-off before leakage inductance has appreciable effect.

In this case the intermediate patterns represented by (B), (C), and (D) of *Fig.* 15 will not appear, but the transition will be directly from the straight line of A in *Fig.* 15 to an ellipse in the direction indicated at (E).

Conclusions

On the basis of the facts, the prevalent prejudice against output transformers would seem unfounded. This does not mean that we should turn around and get audio transformers at other places in the circuit in place of tubes once again. Maybe interstage transformers died a little prematurely because of prejudice, but the advent of over-all feedback would have signed their death warrant anyhow. The fact is, the tubes are still the principal cause of distortion.

This article has concentrated on giving a clear picture of how to make measurements on the performance of a transformer with a particular view to determining the cause of distortion. Sometimes two transformers may be equally good basically, but they will not operate equally well in the same amplifier circuit without certain circuit modifications. What we need to know is how to make the changes so the replacement transformer can produce best results. In a further article we shall go into the question of how to make measurements on different transformers operating in amplifiers and how to determine the changes necessary to produce the best operating conditions.

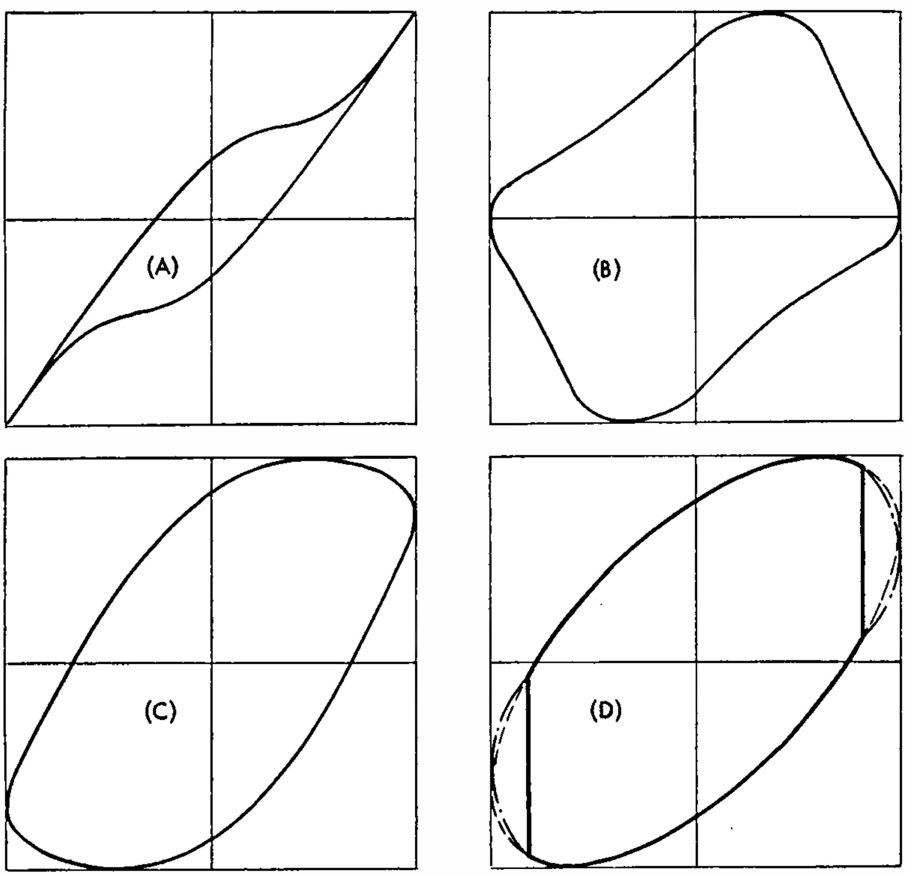

Fig. 14. Kinds of trace associated with different sources of distortion: (A) due to magnetizing current waveform only; (B) due to magnetizing current where this is highly inductive, producing considerable phase-shift; (C) due to tube curvature and any kind of reactance component; (D) due to clipping caused by reactive components: the solid line represents grid voltage horizontal, plate voltage vertical; the dashed line is a true ellipse, for comparison; the dot-and-dash line represents the shape where the input waveform is taken from a point before clipping occurs.