# How an Output Transformer Causes Distortion

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**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 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'*** 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 ease a transformer, in which the winding capacitance is the dominant reactance at the high frequency end, will show distortion more rapidly.

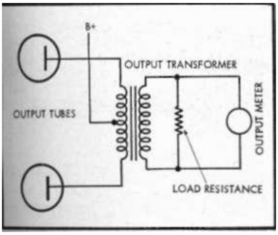

Fig. 8. Practical and equivalent circuit of output transformer for high frequency response: (A) actual circuit: (B) equivalent plate load for output tubes.

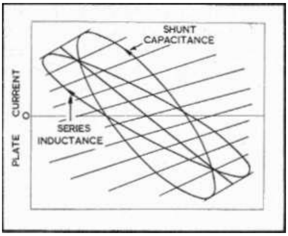

Fig. 9. A succession of elliptical load lines representing progressively larger values of reactance in series with a constant value of resistance, represented by the straight line. The parallel sloping lines at top and bottom represent the ideal tube characteristics for the extremes of grid voltage excursion.

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-

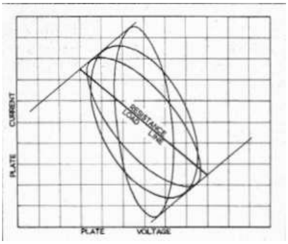

Fig. 10. A succession of elliptical load lines representing a reactance in shunt with a constant value of resistance.

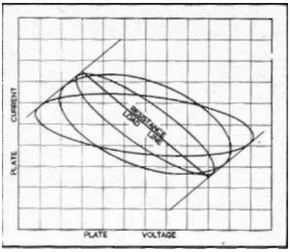

Fig. 11, Load lines on composite characteristics relevant to different possibilities in high-frequency response: the straight line across the characteristics represents the resistive load value at middle frequencies.

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 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.

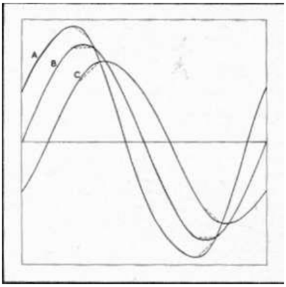

Fig. 12. Possible output waveforms, corresponding with the varieties of load line shown in Fig. 11: (A) for series inductance component; (B) for pure resistance (the only curve that is a sine wave;) (C) for shunt-capacitance component. The dotted portions illustrate the additional effect when clipping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

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

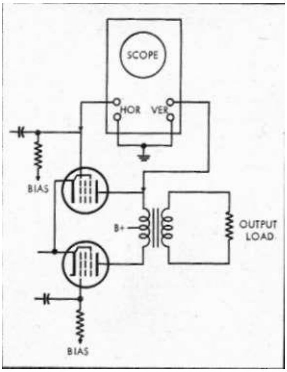

Fig. 13. Method of applying oscilloscope to amplifier circuit to check performance of output transformer at low and high frequencies. Before applying this method the waveforms on both grids and plates should be checked for symmetry.

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.

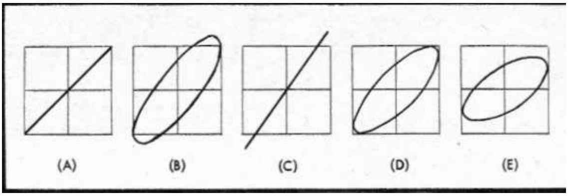

**Fig. 15. Sequence of patterns at progressively higher frequencies when inductive and capacitive reactances resonate: (A) mid-frequency—totally resistive: (B) series inductance has predominant effect; (C) both combine to produce resistive dynamic impedance higher than (A); (D) and (E) successive shapes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

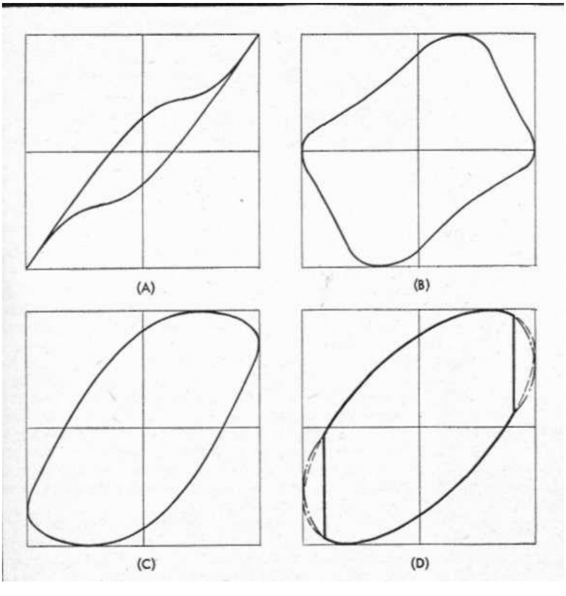

**Fig. 14. Kinds of trace associated with different sources of distortion: (A) due to magnetizing current waveform only; (B) due to magnetizing current where this is highly inductive, producing considerable phase-shift; (C) due to tube curvature and any kind of reactance component; (D) due to clipping 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.**

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 primany, 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.