Removing the Mystery from Matching

How does tube or transistor impedance affect speaker performance?

By NORMAN H. CROWHURST

PRECEDING ARTICLES (SEE REFERENCES) dealt with the difference that three governing values—maximum power, minimum distortion and maximum gain —can make in the choice of optimum load for a triode, pentode or transistor. All these are concerned with the effect the load value has on these parameters of the tube or transistor operation. The fourth parameter, which we take up here, reverses the viewpoint; it is concerned with how the resistance or impedance of the tube or transistor affects the load—usually a speaker.

The previous articles explained what damping does to the performance of a speaker. By feeding it with a voltage derived from a source with very little internal resistance, any tendency of the speaker to overshoot or behave erratically is damped by the short-circuiting effect of the low internal resistance.

Because a low internal resistance provides better speaker damping than a high one, the ratio between load and source resistance has been called *damping factor*. If a 16-ohm speaker is fed from a source of 2 ohms, the damping factor is 16 divided by 2, or 8.

Hence, this aspect of matching has to provide good damping. While arranging that the load of a 16-ohm loudspeaker provides the optimum load (assume 4,000 ohms) required in the plate circuit of a tube, the circuit must also see to it that the 16-ohm loudspeaker is fed from a source impedance, or resistance, of 1 ohm.

A transformer transforms impedances both ways (Fig. 1). If 16 ohms reflects through the transformer to look like 4,000 ohms (250 times the actual value), the plate resistance of the tube must also be transformed down by 250:1. If it is to look like 1 ohm, its value at the primary must be 250 ohms.

Even a triode tube does not have *that* low a plate resistance, if its optimum load is 4,000 ohms. So the *effective* plate resistance is adjusted to the desired value by *feedback*. Now we've got feedback, as well as simple matching ratio, into the matching picture.

Let's take the example of a typical output pentode, feeding its normal "optimum load." Assume that, without feedback, the plate resistance at the operating point is 10 times the required load impedance. At one extremity—the "knee" of the pentode curves (Fig. 2)—the plate resistance drops to twice load impedance. At the other extremity of the load line, the plate resistance (represented by the slope of the plate current/voltage curves) rises to 100 times load impedance. The average is about 10 times.

Gain, as well as resistance, changes. Notice the spacing between points where the load line crosses the curves. They are fairly uniform, except for the lowest space, which is only about half the width of the others. This means the gain of the tube drops to about half the value throughout the rest of the waveform, when the grid swing drives it down to that end.

Because the average plate resistance is 10 times load impedance, removing the load would cause a rise in output voltage of 11 times (assuming the input level is low enough to allow that much rise without saturating the tube).

Now let's assume feedback is applied, enough to reduce gain by 6 dB with the load connected. To find what this does to impedances, we have to consider the *circuit* impedance at different points on the waveform.

At the operating point, the total shunt impedance is $^{10}/_{11}$ (about 0.91) of the load impedance; 6 dB feedback will reduce this to half—$^{5}/_{11}$ of the load impedance. This means the source impedance part of this will be $^{5}/_{6}$ of load impedance; hence the damping factor at the operating point is 1.2.

At the limit of positive grid excursion, the total shunt impedance is $^{2}/_{3}$ of load impedance; 6 dB feedback will reduce this to $^{1}/_{3}$, which means the source impedance part will be half the load impedance. The damping factor at this point is therefore 2.

At the other limit of output waveform excursion, the total shunt impedance is $\frac{100}{100+1} = 100/101$ of the load impedance. But the gain is reduced to half. This results in a damping factor of 0.515.

So, throughout a high-amplitude output waveform, the damping factor of a pentode loaded with the correct optimum load resistance changes from 2 to 0.515.

Apart from the fact that such fluctuation of damping factor could cause serious IM distortion when higher frequencies are present at the same time, we have looked at things from the viewpoint of the load, which we have been regarding as fixed.

Assuming a resistor (dummy load), rather than a speaker, the load *is* a *fixed* value. Even so, from the tube's viewpoint, waveform changes modify grid drive, due to resultant changes in feedback. This is equivalent to changing a voltage, or making the loading vary at different points on the waveform. If it's that complicated with a dummy load, think (but don't imagine too hard) what speaker impedance can do!

Multiple operation

Multiple output matching can best be understood by referring to a matching transformer. (The principle, of course, is not by any means restricted to matching transformers.) Some examples will illustrate typical possibilities.

First, assume we have a transformer designed to work from an 8,000-ohm plate-to-plate load, with 4-, 8- and 16-ohm taps on the secondary (Fig. 3). This means that connecting any one load of 4, 8 or 16 ohms to its appropriate tap will reflect an impedance of 8,000 ohms plate to plate (Figs. 3-a and b).

Now, if we want to feed two 16-ohm speakers in parallel we'll connect them to the 8-ohm tap (Fig. 3-c), because that's what their parallel value is. Correspondingly, but slightly less obviously, to share power equally between a 16-ohm and an 8-ohm speaker, we would connect the 16-ohm to the 8-ohm tap and the 8-ohm to the 4-ohm tap (Fig. 3-d).

From this example, you see that the reflected load impedance is the combined effect of all the secondary loadings in parallel. One doesn't just connect all 16-ohm speakers directly to the 16-ohm tap. That would be right only for one 16-ohm speaker, working by itself. When the 16-ohm speaker is connected to the 8-ohm tap and the 8-ohm speaker to the 4-ohm tap, both receive power and are thus in parallel for the transformer.

If we connect a 16- and an 8-ohm speaker in parallel (Fig. 4-a), the 8-ohm unit receives twice as much power as the 16-ohm unit, because it takes twice the current at the same voltage. Now suppose we want one of two 12-

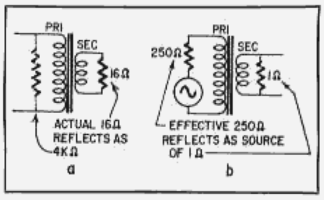

Fig. 1—An output transformer transforms impedances two ways. a—It makes 16-ohm load look like 4,000 ohms to tube plate. b—It makes plate resistance of 250 ohms look like 1 ohm to the loudspeaker.

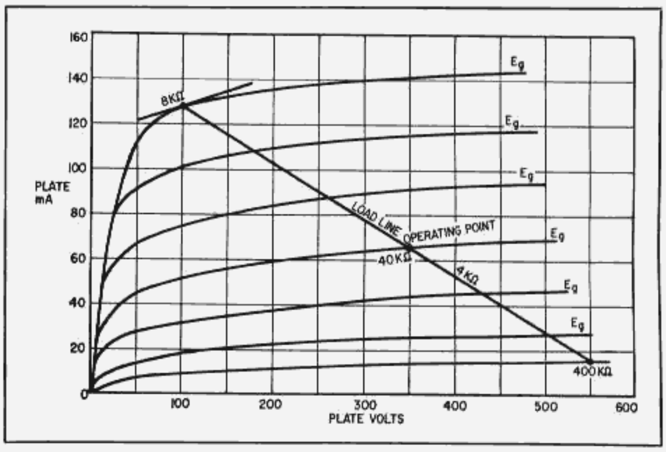

Fig. 2—Operating plate voltage and current curves taken from a single-ended pentode, used to illustrate effects of impedance and gain relations at different points along the load line. A feedback signal, when used, will drastically alter the effect of the damping factor under the conditions described above, as explained in text.

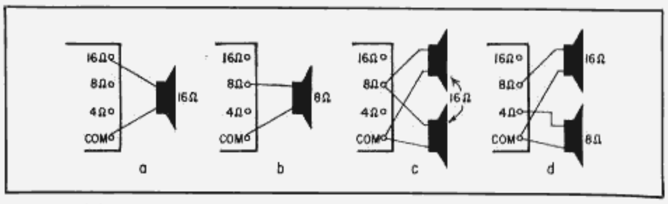

Fig. 3—Division of power between multiple loads: a, b—A single 16- or 8-ohm loudspeaker connects directly to its appropriate output tap. c—Two 16-ohm units are in parallel on the 8-ohm tap. d—A 16-ohm and an 8-ohm unit each connect to a tap with half of their respective impedance ratings. Although it seems incorrect, such connections are necessary in order for both speakers to share the power equally.

ohm loudspeakers to receive twice the power the other does.

This is readily accomplished by connecting one to the 8-ohm and one to the 4-ohm tap (Fig. 4). The 12-ohm unit connected to the 4-ohm tap gets ⅓ the power a 4-ohm unit would, while the 12-ohm unit connected to the 8-ohm tap gets ⅔ the power an 8-ohm unit would. Each connected only to its nominally correct tap would get all the power. But with this connection, the unit connected to the 8-ohm tap gets ⅔ and the one connected to the 4-ohm gets ⅓ of the total power, which is what we wanted.

This is not an article on speaker power distribution, so we won't get into any more complicated instances. The next example of multiple matching concerns the class of operation of the tubes or transistors.

First, assume we have a transformer output-loaded as before. If two tubes require a plate load of 4,000 ohms each, working in class A, the total load is 8,000 ohms plate to plate. Actually the impedance at each plate is 2,000 ohms, ¼ the total winding, because the impedance ratio equals the turns ratio squared. But in class A, both tubes deliver power together, so they each feed half the power to the output load, which we'll take as 16 ohms.

Half the power, with a common voltage, means half the current, so each tube actually drives the equivalent of 32 ohms on the 16-ohm tap. Each plate "sees" twice the "nominal" impedance of 2,000 ohms for the half primary, or 4,000 ohms. Working it out either way, the matching is right.

Now assume we are working class B. Each tube feeds all the power for half the cycle. So now each plate gets a load of 2,000 ohms, *during its operating half-cycle.*

While this means that the same matching ratio can usually be used for different classes of operation with the same tubes, it does not mean the same transformer will do. The class-B transformer must be specially designed so it can perform this "switching" from one plate to the other between half-cycles without producing any spurious effects, like "notch distortion."

The third example of multiple matching concerns ultralinear operation and, more properly, bridging connections. In describing how ultralinear circuits work, the term *screen loading* is often used. Numbers are given, derived in a way similar to those for impedance taps on the transformer.

For example, the popular screen-tapping point for many tubes is at 43% of the primary turns, measured from the center tap toward each plate (Fig. 5). For convenience, we will take 40%, which is ⅖. If this tapping were used as the primary connection, instead of the plate tapping, the reflected impedance would be $\frac{4}{25}$ (⅖ squared) of the rating for the plate connections. The fraction $\frac{4}{25}$ represents 16%. Using a 43% *voltage* tap is equivalent to an 18½% *impedance* tap. This has sometimes been referred to as 18½% screen loading—meaning impedance.

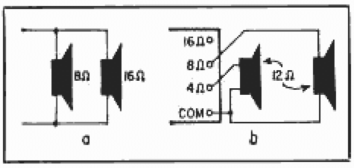

Fig. 4—Two ways of feeding unequal levels of power to loudspeakers: a—Speakers with unequal impedances are connected to taps with same impedance. b—Speakers of like impedance are connected to taps having unlike impedances, splitting power.

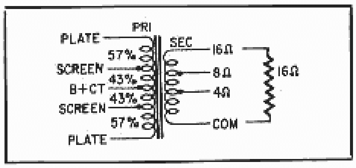

Fig. 5—Ultralinear output transformer discussed in text. Percentages marked on primary relate to turns, not impedance. Numbers by secondary taps indicate impedance load for which they are intended. Effect of screen voltage is key to operation.

Assuming the secondary is correctly loaded, the impedance measured at each plate would be, say, 2,000 ohms. That measured at the screen taps would be $\frac{4}{25}$ of this, or 320 ohms (370 ohms for 18½%). *But this does not mean the screens are loaded with 320 or 370 ohms.* The fluctuations in voltage and current to the screens may contribute a very small part of the output power from an ultralinear circuit—probably 1% or 2%. But this is not the basis of its operation.

The ultralinear circuit produces its particular effect because the *voltage* applied to the screen affects plate current to a much greater degree than does voltage applied to the plate. The small change in screen current, flowing through a small proportion of the transformer's turns, contributes very little to the output, and nothing to making it more linear.

Really, the screen connection in an ultralinear circuit is a form of *bridging* connection. A bridging input, for example, normally has an impedance of at least 10 times that of the circuit into which it is connected. Consider the broadcast and recording-studio practice of using a matched 600-ohm line between one amplifier's output and another's input (Fig. 6). (This is done particularly when the amplifiers are several hundred or more feet apart.) The line amplifier's output is designed to be loaded with 600 ohms, while the other amplifier's input is designed to provide that load of 600 ohms. Additionally, to monitor the transmission level, a VU meter is often connected, at either or both ends. Such a meter has an impedance of 6,000 ohms or more, to produce a minimum of extra loading on the line amplifier. The VU meter is "bridging" the line.

In ultralinear operation, the flow of audio power is in the opposite direction, *from* the screens *to* the transformer; but the operation of the circuit occurs in its particular manner because of the voltage applied *to* the screen by the transformer.

Thus, matching isn't as mysterious as is often thought. Like a window, a transformer works both ways. While a tube or transistor is looking at a speaker and seeing a certain impedance, that same speaker is looking back through the transformer and seeing the tube or transistor's impedance. Each affects the other. END

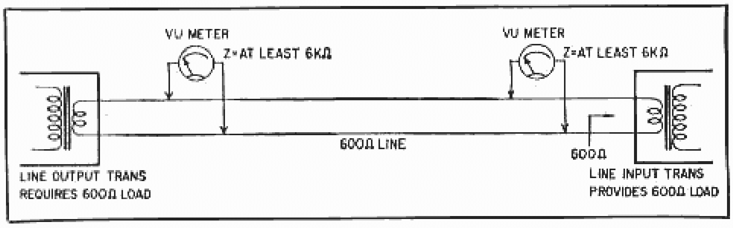

Fig. 6—Bridging connections applied to a line. Input to the line-terminating amplifier provides 600-ohm load required by the output of the amplifier feeding the line. The VU meters monitoring line level have an impedance of 6,000 ohms or more.

References (all by Norman H. Crowhurst in following issues of RADIO-ELECTRONICS)

1. "Applying Variable Damping," July 1957.
2. "Tube Data and Amplifier Design," November, December 1957.
3. "Is the Output Transformer Out?" January 1958.
4. "Using Audio Transformers," April 1960.