VAC Technical Monograph 90-9 - Output Impedance Matching

[printed copies available from VAC]

Introduction

VAC Technical Monographs are provided to help anyone interested in vacuum tube electronics to better understand the issues involved in the design of truly "high end" amplifiers. They are a direct response to the (unintentionally) inaccurate impressions created by the marketing arms of manufacturers and other writings, fraught with misunderstanding and outright inaccuracies regarding basic concepts of tube electronics, laws of physics, operation of circuits, measurement standards, and historical attribution. It is our intention to create an unambiguous and accurate reference for many of these issues. As such, these Monographs should prove valuable not only to individuals who are just becoming aware of these issues, but also to many experienced audiophiles who are awash in the competing claims.

To ensure accuracy and provide the reader with a source for even more information on these topics, extensive reference will be made to authoritative works in the electronics field. Thus, the thoughts presented herein are not merely the random musings and recollections of one individual, but a condensation of the accumulated wisdom of a great many authorities.

Naturally, no one work is ever exhaustive, so the reader may encounter an omission, or even spot an error (hopefully only typographical in nature). We are anxious to clarify any fuzzy points and correct any inaccuracies. As such, we encourage all interested readers to correspond with us on such points. After all, the goal here is to enlighten, not to confuse!

Readers with little electronics background will probably wish to check into some of the introductory sources contained in the "Recommended Readings" at the end of this Monograph.

Finally, remember that in audio electronics there is never one uniquely and absolutely correct way to design an amplifier. Design always entails compromise. The real question is which parameters are compromised and to what degree. The best way to judge audio equipment remains familiarity with live acoustic music. Listen, and let the sound be your guide.

OF TUBES AND IMPEDANCES

To start with, let's define resistance as the obstruction to the flow of electricity offered by a particular device or substance. What then is impedance? Technically experienced readers know that impedance is a complex quantity, with both a resistive and a reactive component. For the purposes of this Monograph, the non-engineer is invited to think of impedance as like resistance but specified for a particular frequency of alternating current.

The vacuum tube is often referred to as an inherently high impedance device because it performs best when presented with relatively high impedance loads, generally in the range of 1,000 ohms to 20,000 ohms. This makes it unsuitable for directly driving a modern loudspeaker, which has a rather low impedance, typically in the range from 1 ohm to 16 ohms.

The difference between a high impedance load and a low impedance load is in the relative proportions of voltage and current that make up a given power (wattage). These proportions are dictated by Ohm's law (see Appendix A). Figure 1 shows how the current and voltage required by a load to achieve 100 watts of power varies with changes in the load impedance.

As we can see, 100 watts at 5000 ohms (typical for a tube) requires 707 volts at .14 ampere, while the same power at 10 ohms (typical for a speaker) requires 28 volts at 3.5 amperes. Even a fairly large audio power tube such as the KT88 has a maximum current rating of only 230 milliamperes (.230 ampere). Obviously, it can deliver only a very small amount of power directly to a loudspeaker.

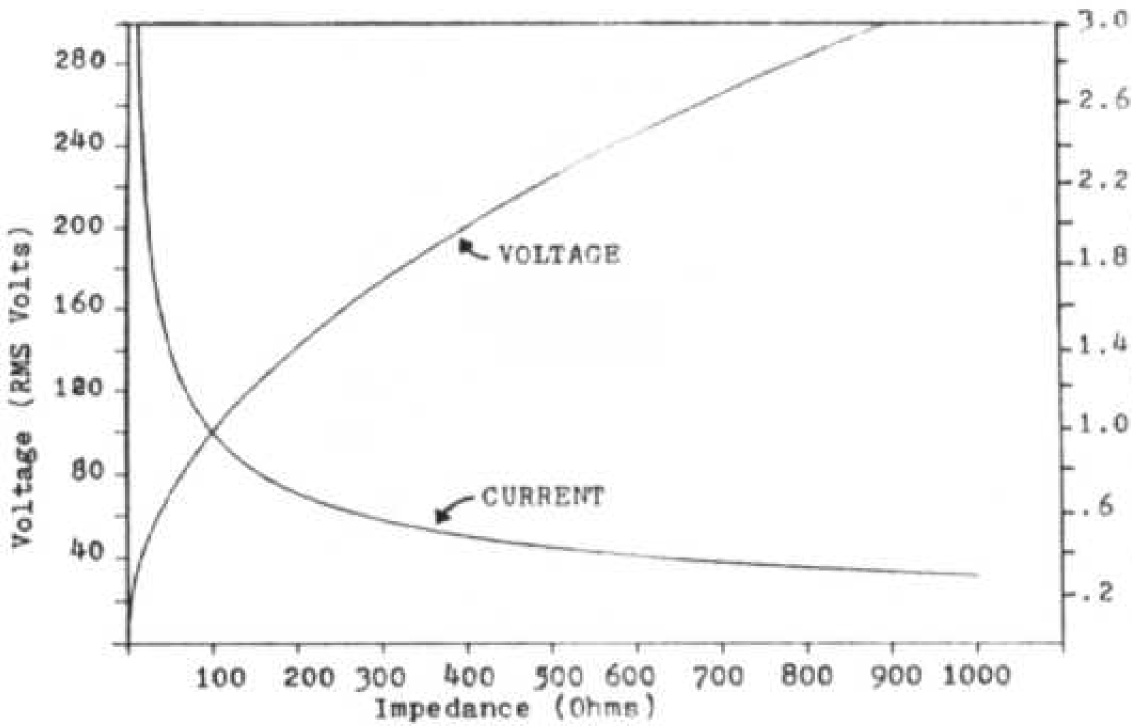

Figure 1: Current and voltage verses load for 100 watts.

ENTER THE OUTPUT TRANSFORMER

The need to trade the tube's high voltage/low current output for the speaker's high current/low voltage demand requires a translating device called a transformer. The transformer (simplistically) consists of two coils of wire wrapped around a magnetically permeable metal. The tube's output is connected to one coil (called the primary), while the load is connected to the other coil (the secondary).

In a sense, the transformer is the electronic equivalent of the lever, substituting voltage and current for weight and distance. When the primary and secondary coils consist of differing numbers of turns, the proportions of voltage and current in the two coils also differs. If the primary coil has more turns, there is less voltage in the secondary coil than in the primary. However, there is also more current in the secondary than in the primary. Thus, by having more turns in the primary coil than in the secondary coil we can reduce the voltage available to the load while simultaneously increasing the current available to the load. Appendix B shows the mathmatical relationships of this transformation.

This exchange of voltage for current implies a change in impedance. This is referred to as the impedance ratio, and it is a function of the square of the ratio of turns in the primary and secondary coils (the square of the turns ratio).

Thus, the impedance that the tube "sees" through a transformer is a function of the transformer's turns ratio and the impedance of the load attached to the secondary. We may refer to the impedance of the load presented to the tubes as the transformed or reflected load.

WHAT IMPEDANCE SHOULD BE REFLECTED TO THE TUBE?

Now that we know how to transform a given load impedance on the secondary into any arbitrary value on the primary, it would seem that our task of matching a tube to a speaker is simple. Unfortunately, two factors complicate matters: determining the optimum load for the tube, and coping with a loudspeaker whose impedance is not the same at all audio frequencies.

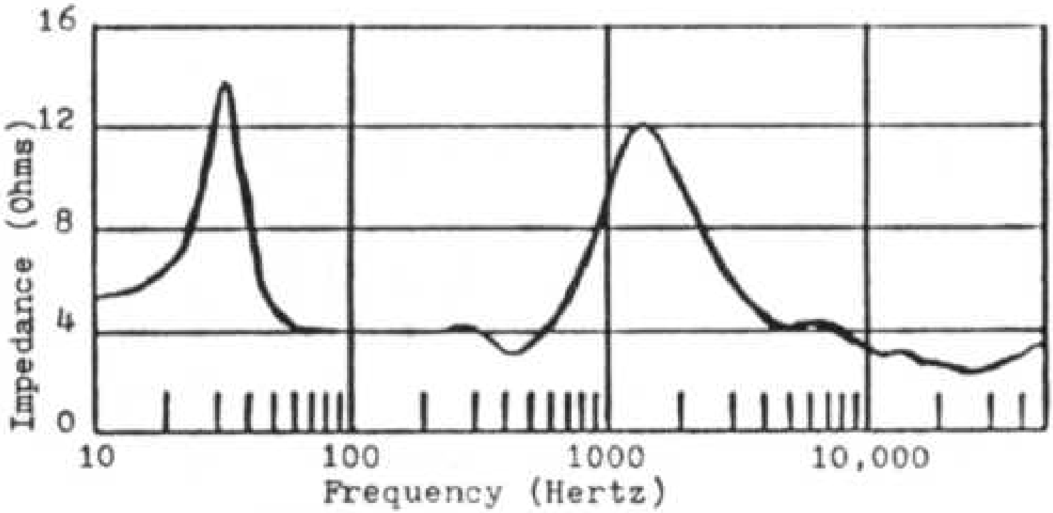

Figure 2: Impedance characteristic of a popular audiophile loudspeaker.

A loudspeaker is far from a constant impedance, and can vary appreciably at different frequencies. Figure 2 shows the impedance vs. frequency curve for a popular high end louspeaker. The manufacturer of this speaker states that is should be considered to be a load impedance of 6 ohms (the nominal impedance), but in fact it presents an impedance that varies from a low of 2.25 ohms to a high of 13 ohms at different frequencies within the audio spectrum.

As you might suppose, the performance of a tube also varies with the load impedance presented to it. In particular, the maximum power output available varies with load impedance, as does the distortion produced by the tube and the relative levels of the harmonics that make up the distortion. This performance is affected by other operational conditions as well. For example, a pentode tube may be operated as a pentode, or it may be connected to perform as a triode tube. It acts differently in these two modes.

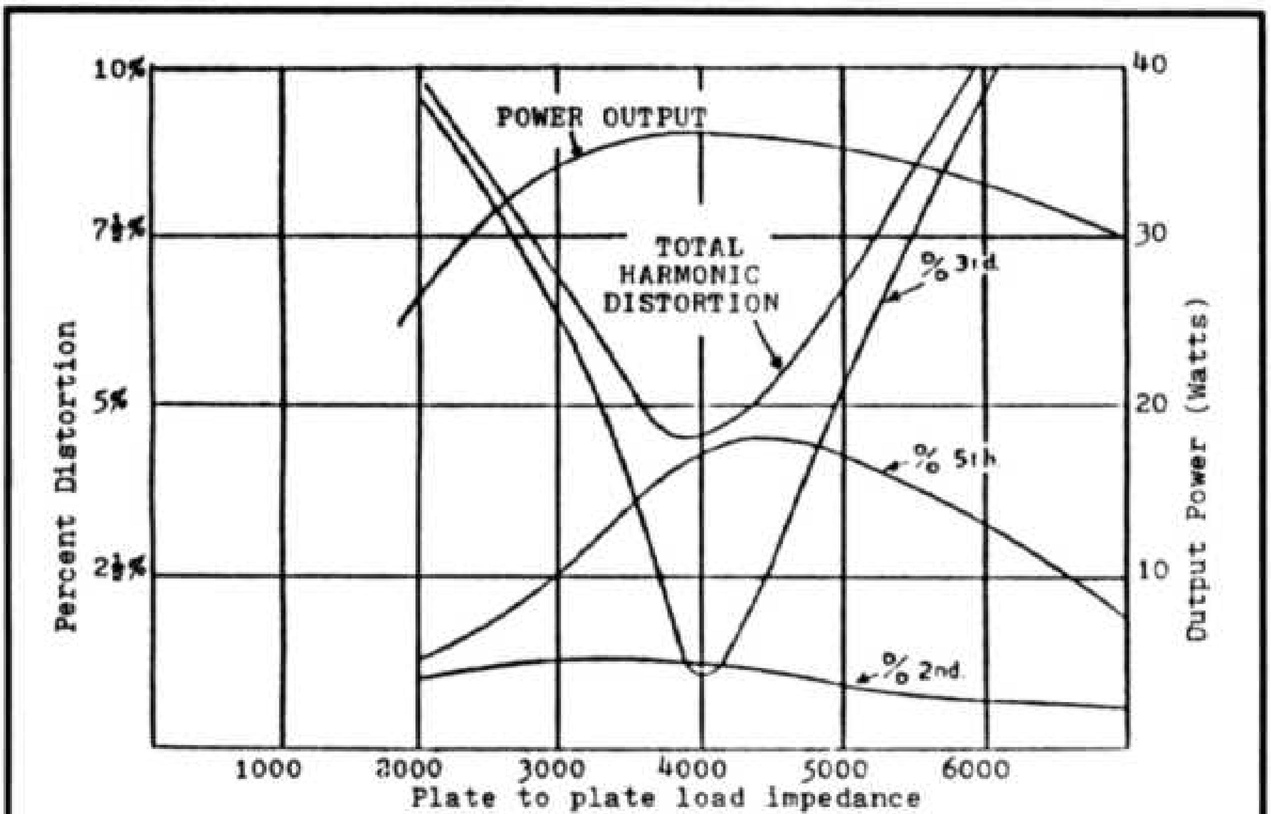

Figure 3: Performance of two push-pull EL37 as pentodes.

Consider the performance of a push-pull pair of EL37 power pentodes as shown in Figure 3. Here the tubes are operating in the pentode mode, which is rarely done in the output stage of high fidelity power amplifiers. It is at once obvious that the tube performs well over a very narrow range of load impedances. A designer might select 4000 ohms as optimal since power output is maximized and distortion (THD) is minimized. However, one might also argue for a slightly lower load impedance, sacrificing a bit of output power for a reduction in fifth harmonic distortion, which is subjectively more offensive than the second or third harmonics.

What happens when we connect the speaker from Figure 2 to this EL37 stage? Since the speaker is rated at 6 ohms and we think the tubes should be presented a 4000 ohm load, we might wind our transformer such that 6 ohms on the secondary is reflected as 4000 ohms to the tubes connected to the primary. This solution is confounded by the impedance curve of the speaker, since the impedance may be as low as 2.25 ohms and as high as 13 ohms at different frequencies. As a result, the reflected impedance to the tube may be as low as 1500 ohms at one frequency and as high as 8667 ohms at another. Both of these numbers are so extreme as to be off of our performance graph for the EL37. In fact, there is no way for this tube, operating as a pentode without negative feedback, to accommodate an impedance swing of this loudspeaker.

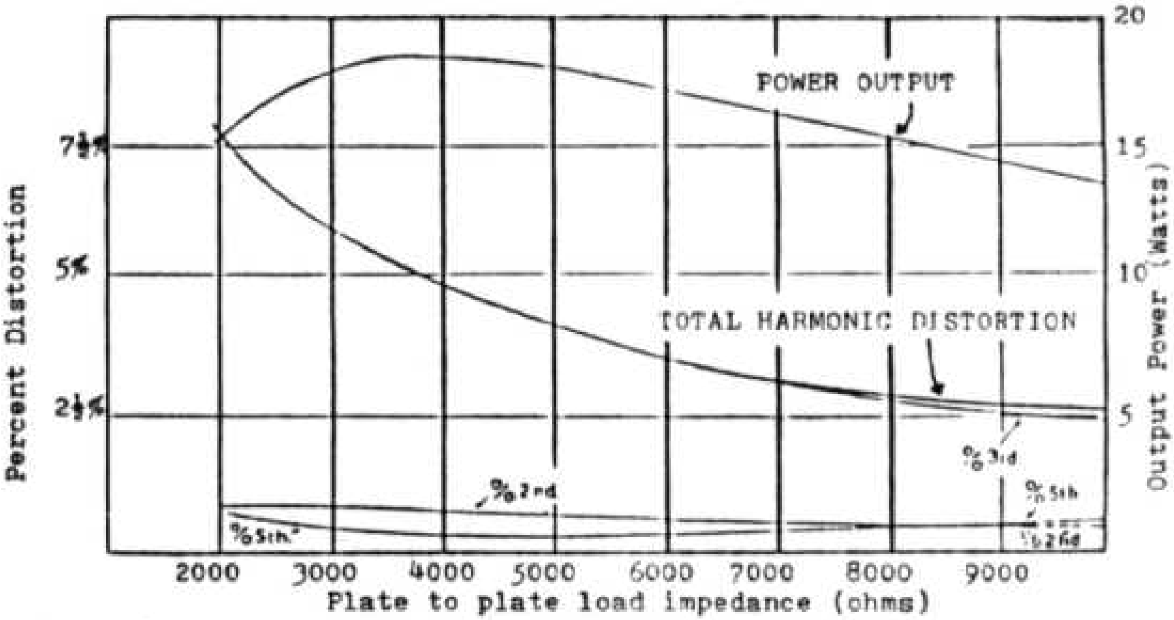

Figure 4: Performance of two push-pull EL37 as triodes.

Figure 4 shows the performance of the same tubes connected as triodes. While the power output is substantially reduced, sensitivity to changes in load impedance is also drastically reduced. Power output is still maximized for loads between 3000 and 5000 ohms. If we were to wind the output transformer to reflect 6 ohms as 4000 ohms, we still could not accomodate the entire impedance swing of the speaker.

However, suppose we wind the output transformer such that 6 ohms on the secondary reflects as 6000 ohms to the tube. Now we can then effectively accommodate all of the speaker's impedance range. True, the peak of 13 ohms at its bass resonant frequency and the peak at 1500 hertz will be off to the right of our graph, where available power is reduced. Fortunately, even though power is reduced, the distortion level will not be excessive, and overall sonic performance may be subjectively acceptable.

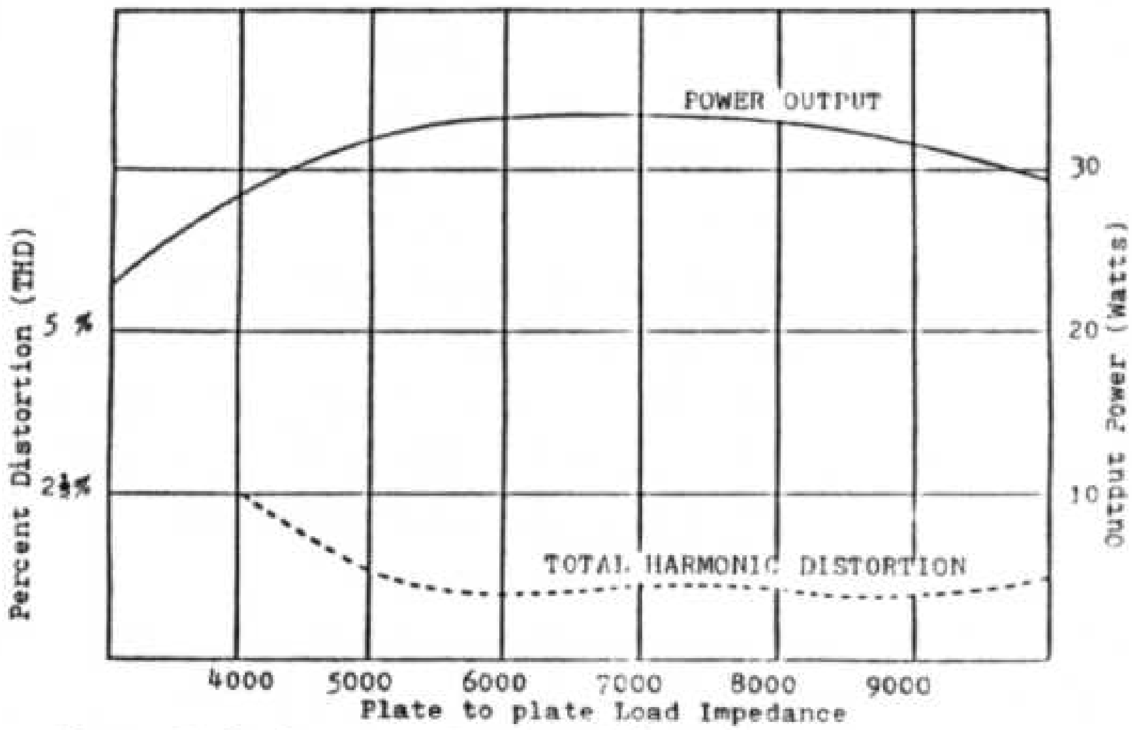

Figure 5: Performance of two EL34/6CA7 in Ultra-linear circuit.

There are other ways to operate an output stage than as straight pentode or triode. An example of this is the ultra-linear (or partial-triode) circuit, in which negative voltage feedback is provided to the screen of the tube from a tap on the transformer's primary. Figure 5 shows the relative insensitivity to load impedance for an ultra-linear output stage using a push-pull pair of EL34 power pentodes. Power output from an ultra-linear circuit is greater than for the same tubes connected as triodes, while the measured distortion over a wide range of load impedances is comparable to that of triodes.

Another output circuit was popularized in the U.S. and the U.K. by McIntosh and Quad, respectively. This circuit, called "unity coupled" or cathode-coupled, is similar to the ultralinear circuit, in that negative feedback is applied to the tube from a winding on the output transformer. Now, however, the feedback is current feedback, and it is applied to the cathode rather than the screen of the tube. The relative merits of the ultra-linear and cathode-coupled circuits have been debated at length with no clear winner emerging (see Reference article by Williamson & Walker, also article by Wireless Engineer staff).

The application of negative feedback around the output stage will improve on the performance shown in Figures 3, 4, and 5, making the tubes somewhat less sensitive to changes in load impedance.

ARE MULTIPLE MATCHING TAPS NECESSARY?

In the preceding section we saw that it is possible to accommodate a fairly wide speaker impedance swing with a tube output stage. To do so, however, requires a very careful choice of turns ratio, such that the impedance swings will be reflected within a range in which the tube works well. Clearly, a single turns ratio for a particular amplifier ("one size fits all") will work well with a relative minority of loudspeakers, and will have major difficulty with many loudspeakers.

To overcome this problem, many designers specify that the secondary winding of the transformer have multiple tap points on the coil. These taps are led out to separate connectors to which the audiophile may attach the loudspeaker. Selecting different taps changes the number of utilized turns in the secondary, thereby changing the effective turns ratio of the transformer. The user may thus position the loudspeaker load in different portions of the output tubes' performance curve. When a tap is labelled X ohms (i.e., 2, 4, or 8 ohms), it means that a resistance of X ohms connected to that tap will reflect to the tubes as what the designer considers to be the optimal value.

Some good sounding single tap amplifiers exist. In general, such amplifiers pick an average value for loudspeaker impedance (say 5 to 6 ohms) and fix the turns ratio accordingly. A speaker in the impedance range from 4 to 8 ohms will be matched to the tubes fairly well provided that its impedance does not vary too much with frequency. Fortunately, many modern speakers have a well controlled impedance curve, staying between 4 and 12 ohms. Also, a speaker with a widely varying impedance may still be well matched provided that the transformer is by chance wound to exactly the correct ratio for that particular speaker. Unfortunately, many high performance speakers fail to meet these criteria, and available power will be substantially reduced and/or distortion increased.

Single tap amplifiers, therefore, limit the user in choice of loudspeaker, now and in the future. Some manufacturers can reconfigure their transformer connections at a user's request, although the choice of alternatives is in some cases limited to a single questionable value, such as 1 ohm. Such amplifiers also represent an unknown on the used market, as it is not easy for a perspective purchaser to know what custom reconfiguration has been carried out.

CRITICISMS OF MULTIPLE TAP TRANSFORMERS

Given all of the technical disadvantages of the single tap amplifier, why are they still manufactured? In some cases, the answer may be cost, the single tap unit being slightly easier and less expensive to wind. (In a high quality tube amplifier, the transformers are the most costly components, and are often the focus of cost control attention.) In other cases the designer may have elected to use a replica of a "classic" transformer, lacking the expertise, finances, or time necessary to design a high quality unit for the specific application.

Occasionally a designer will utilize a single tap approach due to well intended misunderstanding. One occasionally encounters the assertion that if we connect a loudspeaker to a 4 ohm tap, power will be lost due to the unused portion of the secondary winding from 4 ohms to 8 ohms. Fortunately for the audiophile, this is not the case. Power can not be dissipated unless current is flowing. For current to flow, there must be a complete circuit. The unused portion of the winding is not included in a completed circuit. Hence, no current flows through the unused section of the secondary and no power is lost.

Another criticism of a multiple tap transformer involves the wire size (diameter) required to carry a given level of current. As Ohm's law indicates, the current required for a particular power level is greater for a lower impedance. For example, in a 100 watt amplifier, 5 amperes must flow into a 4 ohm load, while only 3.5 amperes is required for an 8 ohm load. Accordingly, the section of the secondary up to the 4 ohm tap must be wound with a wire large enough to support a 5 ampere current flow. A smaller wire size will probably be used in the section of the secondary to 8 ohms. If we omit the 4 ohm tap, the smaller wire size could also be utilized in both sections of the secondary, and the transformer could thus be slightly smaller, lighter, and less expensive. Fortunately, the use of the slightly larger wire size needed for the low impedance tap introduces no significant difficulties to the competant transformer engineer, and the transformer performance need not suffer apart from cost.

Similarly, if one had no need for the 8 ohm tap we could wind the transformer stopping at 4 ohms, again with a savings in cost and size. However, we have already seen that there is a genuine need for alternate taps. Fortunately, the savings from omitting a higher impedance tap is not as great as one might at first imagine. For example, since the impedance ratio is a function of the square of the turns ratio, fully one half of the secondary exists in the winding up to 2 ohms! A relatively small proportion of turns is needed to reach 8 ohms, so omitting the 8 ohm tap is of little consquence. Small capacative and inductive effects are again easily dealt with by the competant transformer engineer, and the transformer performance need not suffer apart from cost.

LOOSE ENDS

The tube performance graphs shown in this Monograph depict the performance of representative tubes operating under specific circuit conditions. The same tubes operated with different voltages may display somewhat different results. However, the comparative performance between triode, pentode, and ultra-linear operation will hold true for a given set of operating conditions.

Output-transformer-less (OTL) tube amplifiers are a special case. They generally employ the lowest impedance power triodes possible. One such tube is the 6AS7, originally designed for power supply regulation service, which works well into a load impedance of 1000 ohms. Operating multiple tubes in parallel reduce the optimum load. Two 6AS7 provide twice the power into a load of only 500 ohms. Sixteen such tubes in parallel will deliver their full power capability into a load of only 62.5 ohms. Thus, if a sufficient number of tubes are employed, enough power may be available to generate adequate listening volume when conneceted to a loudspeaker in spite of the impedance mismatch. An unusual characteristic of such a design is that it can deliver significantly greater power levels where a speaker has an impedance peak, while conventional amplifiers deliver less power at an impedance peak. Most speakers are not designed for such an amplifier characteristic, which may help explain the frequent observation that OTL tube amplifiers are quite picky about their associated loudspeakers. OTL amplifiers also often employ circuit connections somewhat different from the normal push-pull configuration. The relative merits and demerits of these circuits are well discussed in the literature.

In the last 25 years, some designers have sought to avoid output transformers by replacing the output tubes with transistors, which are much lower impedance devices. In effect, this is a hybrid design, employing tubes in the front end and solid state devices at the output end. This is no longer a pure tube amplifier, and thus falls outside of the scope of this Monograph. Good test bench performance can be achieved in this manner, but the sonic merits must be judged by each listener. In some cases, using both vacuum tube and solid state technology results in the sonic problems of both and the advantages of neither.

Some degree of overall loop negative feedback (from the output of the transformer to an earlier amplifier stage) will improve on the measured performance of any output circuit discussed in this Monograph, lowering total harmonic and intermodulation distortion levels. However, additional feedback loops multiply the order of distortion and can lead to less desirable clipping behavior. For example, if an amplifier generates third harmonic distortion, the introduction of a feeback loop will lower the level of the third harminic, but will also introduce the ninth harmonic. Since higher order distortion products and odd order distortion products are subjectively the most offensive, feedback is best used in moderation. The relative merits of the circuits presented here remain the same with feedback.

All circuits referred to in this Monograph have had the load connected to the plate circuit of the tubes, with the exception of the partially cathode-coupled amplifier, in which the load is split between the plate and cathode circuits. The ultra-linear may also be thought of as a distributed load circuit, where part of the load is in the screen circuit. However, this design is usually analyzed in terms of feedback to the screen circuit.

Finally, this Monograph has not gone into the details of the construction of loadlines on the plate curves of a tube, although this is commonly done by engineers. Our discussion in this Monograph has been based on the actual measured performance of an output stage, and thus subsumes this more complex topic in a form that is more meaningful to the audiophile. Nor have we discussed the effects of the reactance of a complex impedance on performance, which also argues for careful impedance matching. Both of these topics are well covered in the references.

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Graph Credits

Figure 3 after Moir, page 289.
Figure 4 after Moir, page 288.
Figure 5 after Moir, page 305.

Appendix A

The proportions of voltage across and current through a load are dictated by Ohm's law, which states that the current flowing through a resistance is equal to the applied voltage divided by the resistance (ohms). This is usually written as

$$I = E / R$$

where I is the notation for current expressed in amperes, R is the resistance in ohms, and E represents voltage in volts. It is also a basic fact that power is the product of voltage and current, commonly written as

$$P = E \times I .$$

Combining these two facts tells us that P = E2 / R. So, 100 watts at 5000 ohms (typical for a tube) requires 707 volts at .14 ampere, while the same power at 10 ohms (typical for a speaker) requires 28 volts at 3.5 amperes.

For measurements involving alternating current, such as audio signals, current and voltage are expressed by their effective or r.m.s. (root mean square) values. For a sine wave, this is simply the peak value divided by the square root of two.

Appendix B

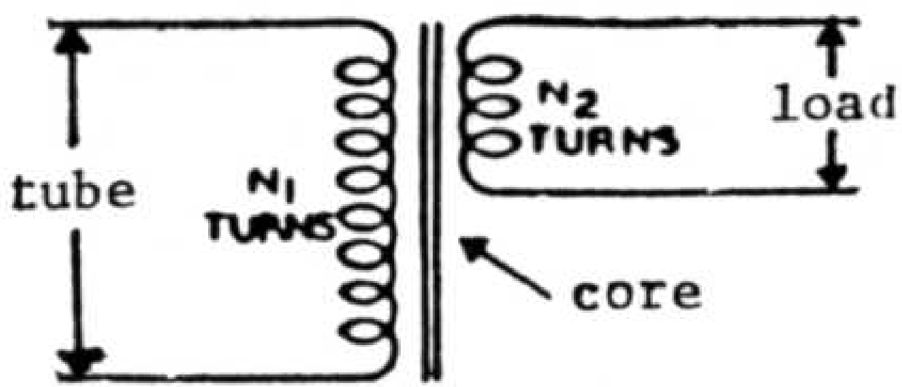

Figure 6: Idealized transformer.

Figure 6 presents a pictoral representation of a transformer and its connections.

The voltage ratio between the primary and the secondary is determined by the ratio of the number of turns in the two coils, written as

$$E2 / E1 = N2 / N1$$

where N refers to the number of turns of wire and the subscript 1 refers to the first coil, etc. Similarly, the current ratio between the coils is also a function of the turns ratio, written as

$$I2 / I1 = N1 / N2.$$

Thus, by having more turns in the primary coil than in the secondary coil we can reduce the voltage available to the load while simultaneously increasing the current available to the load. Of course, some power is lost in the transformer, so these ideal ratios do not hold exactly.

Using the formulae already presented, we can work out an impedance ratio for the transformer. The impedance ratio winds up being the square of the turns ratio, written as

$$R1 / R2 = (N1 / N2) 2.$$

Thus, the impedance that the tube "sees" through a transformer is a function of the transformer's turns ratio and the impedance of the attached load. We may refer to the load presented to the tubes as the transformed or reflected load. If a transformer having a 10 to 1 turns ratio is connected to a load of 8 ohms, the reflected impedance on the primary coil will be 800 ohms.

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