AUDIOPAX

SE Amplifier Output Impedance - Part 1

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1. Introduction

Much has been said about triode SE amplifiers with no negative feedback - how good they sound, how lively they present a musical performance and so on. Two easily measurable characteristics that make this type of amplifiers sound different are, the amount of distortion produced with its particular spectrum, and the high output impedance. This raises the question of whether they sound so good and musical *because* of these characteristics or *in spite* of them.

The first time I listened to such an amplifier with no feedback was through a loudspeaker that apparently was not much affected by the high output impedance of these amplifiers. Since I was really impressed with the sound I heard, I decided to do some measurements to understand what was going on.

After making these measurements, I became more deepely involved with the subject, thinking about the design of a SE amplifier and the loudspeakers to use with it. Based on this work, my intention here is to examine the output impedance (Zout) and its role in the interface between SE amplifiers and the loudspeaker.

2. Listening To a SE Amplifier

Just after I finished a 300B SE amplifier kit, I connected it into my system and was really impressed with what I heard. I had never heard the violins and the voices in such a natural way. Although I have other speakers and amplifiers around, the amplifier and loudspeaker I was using in my system at that time was a Quad II with same parts upgraded, and a speaker I had designed and built in the mid 80s using a Kef bass unit, a Peerless mid and a JVC ribbon tweeter. This loudspeaker has only suffered minor changes and parts upgrade during the years. Although an old design, for me it still sounds good. It is not a high efficiency loudspeaker, but with the 300B SE amplifier I have been able to listen at levels that I?m used to without any problems (I have to admit that usually I don?t listen very loud).

After some days, I decided to look at the whole system trying to find clues to explain the differences between the amplifiers. I measured the Zout of the amplifier and found it to be almost 4.0 ohms. I knew the loudspeaker very well , and looking at the notes I made at the time I designed it, I remembered that it presents an almost purely resistive input impedance with a magnitude between 6.8 and 10.1 ohms from 100Hz to 20Khz . It is a closed box design with about 87 dB/W/m average sensitivity and a critically damped resonance (Q=0.5) at 39 Hz.

Using this loudspeaker driven by a SE amplifier with almost 4.0 ohm of Zout, the big difference I *should* hear would be the stronger bass caused by a less damped resonance. From the mid bass up, the expected differences in frequency response would all fall inside a 1.1dB total range (-0.5 dB / +0.6 dB referred to the nominal 8 ohm impedance). I compared the loudspeaker frequency response from 100Hz up with a low impedance conventional transistor amplifier and with a 3.9 ohms resistor in series, simulating the SE amplifier output impedance. We also have to consider the drop in the high frequency response of the amplifier of about 1 dB at 20 Khz.

I think that the differences I had heard were much bigger than what could be expected from my frequency response plot. Surprisingly, at least for me at that time, the most dramatic differences were in the mid range, with violins and vocals sounding remarkably open as stated before. The bass was stronger as should be expected, but this was a minor difference compared to the midrange sound. I have to say again that all these thoughts and measurements occurred several days after the initial listening tests, when the differences in sound were first noticed.

My reaction to this listening experience seems to be just like most of the described reactions to SE amplifiers. The fact that the loudspeaker used is reasonably insensitive to the high Zout made me conclude that we have to look elsewhere to find the reason for the good sound of SE amplifiers. This is why I started to look more closely at this characteristic of SE amplifiers in general. If I were to design my own SE amplifier, I could use this experience. Probably if we can lower the Zout without destroying the other aspects of the SE sound, we may be able to use these amplifiers with more predictable results with many more loudspeakers.

3. The Output Impedance Of Typical SE Circuits

I considered a practical equivalent circuit for a single ended output stage with simplified circuits at mid, low and high frequencies. These models were based on the description given by Terman (ref.1). I only changed the values to what they are at the secondary of the transformer instead of at the primary like in the book. Also, to calculate Zout, RL (the load resistance) is left out. From what I could test, these transformer equivalent circuits are good approximations. Only the equivalent circuit for high frequencies starts to became inaccurate at the highest frequencies. It does not take into account the distributed capacitance of the primary and secondary, therefore it can not predict a high frequency peak in the frequency response that appears in some of the transformers.

After measuring the required parameters for one transformer, I used the complete practical equivalent circuit with a circuit simulator for calculating the magnitude and phase of the Zout. This was followed by the actual measurements at some frequencies. Although the incremental primary inductance (Lp) is not a very constant parameter, the measured results were close to the simulation values. Only at the highest frequencies was there some appreciable difference. Measuring other transformers confirmed that these curves were fairly typical of this kind of output transformers. The decrease in the Zout at low frequencies came together with a rapid rolloff at the low end frequency response of the transformer. One very interesting example has been the review of a commercial 300B SE amplifier which has a 2.5 ohm Zout at 1Khz, 2.7 ohm at 20Khz and 0.76 ohm at 20Hz. This low value of Zout at low frequencies *may* look like a good thing but only happens because the primary inductance of the output transformer is probably much lower than it should be for extended low frequency response. This is confirmed in the frequency response plot shown in the review. The amplifier is 9dB down at 20Hz. The low value of the output impedance at 20Hz only shows that the limiting low frequency factor is the output transformer, not any other coupling in the amplifier.

SE Amplifiers with good output transformers should have the Zout with a more extended region of flat impedance. The phase plot except for the frequencies extremes should be resistive. The region of flat impedance with resistive behavior corresponds to the region where the equivalent circuit is valid. We will use this extremely simplified model in all the following analysis. This is a very important assumption, and one that has to be made to simplify the first visualization of the effects of the high Zout. As we go along I will try to show when we should expect this most simplified model to fail, making the use of the other equivalent circuits necessary.

As a first approximation to calculate the output impedance of a tube amplifier with no negative feedback, we can simply divide the plate resistance by n^2 (n = turns ratio between primary and secondary of the output transformer). Several books state as a practical rule that output triodes should be loaded with an impedance of about three times its plate resistance for maximum undistorted power output (although some theoretical calculations find a ratio of two to one. ref.3, ref.4, ref.5). If this rule is followed, the Zout of SE amplifiers with any triode will always be about the same. At first look, its value should be one third of the nominal load impedance of the output tap of the transformer, or around 2.7 ohms for an 8 ohm tap. But we should look more carefully using the simplified model and take into account the transformer resistances.

To do this, we will choose one output triode and work out an example. Lets pick a typical 300B SE amplifier and do same quick calculations. The 300B according to the WE manual has a 700 ohm plate resistance. Using an output transformer with a 2.5K primary reflected impedance we can calculate the output impedance. We need to measure or estimate its primary and secondary DC windings resistances and use it in the following formula:

$$Zout = \frac{(rp + R1)}{n^2} + R2 \quad (1)$$

$$\text{where } n^2 = \frac{Zp - R1}{R2 + RL} \quad (2)$$

Zout = Output impedance
rp = Output tube plate resistance
RL = Nominal load resistance
R1 = DC Resistance of the primary of the output transformer
n = Ratio of primary to secondary turns (it can be measured directly)
R2 = DC Resistance of the secondary of the output transformer
Zp = Reflected primary impedance

If we estimate R1 to be 200 ohms and R2 to be 0.5 ohms, for Zp of 2500 ohms and a RL of 8 ohms, using formula (2) we get n2=270. Using formula (1) we arrive at the value of 3.8 ohms for Zout.

I have actually measured many parameters of four output transformers for use in single ended applications and calculated its Zout when used with 300B tubes. These Zout measures were taken at 1Khz. All the results were within 10% of the calculated values. The measurements of low values of resistances like 0.6 ohms using a digital multimeter may introduce a sizable error. Although I have not further investigated the differences between measured and calculated Zout, I believe they can be explained mainly by this factor and by the fact that we didn?t account for the Rp of the particular 300B tube used for the measurements, relying on the 700 ohms value given by the manual. All the transformers were measured with the same 300B tube and changing the tube during one measurement gave just slightly different results.

The Zout of these amplifiers with triode output tubes can only be lowered (without using feedback) by changing the output transformer parameters. Increasing n^2 and lowering R1 and R2 will make the Zout decrease. How low can we get? Lets go back to the 300B example. The biggest part of the impedance is made up by the tube Rp (around 700 ohms for the 300B) divided by n^2. Higher n^2 means higher primary reflected inductance. Usually 300B amplifiers use 2K5 to 3K primary reflected impedance. The higher this impedance, the lower proportionately would be the Zout. Therefore if we want to lower the Zout, we should pick a transformer with a higher primary reflected impedance. In the WE manual, 300B tubes are shown operating with loads up to 6K5, although the 6K and 6K5 data is shown only at maximum dissipation ratings. Therefore it looks like we can assume that 5K is a reasonable high target. An amplifier using a transformer with this primary reflected impedance should be better from the standpoint of output impedance. But we will need to use higher voltages to keep the output power, and its harder to have good frequency response from output transformers of higher primary impedance.

To see what happens using higher turn ratios, we can calculate the Zout for an hypothetical transformer the same way we have done before. Lets use a 5K primary, and estimate a R1 of 150 ohms and a R2 of 0.4 ohms. For the 8 ohm tap n^2 will be 577. We will end up with Zout of 1.87 ohms. Since the characteristics of this hypothetical transformer are of one very optimized for low Zout, I believe that 2.0 ohms should be about the lowest we could expect from a 300B SE amplifier with no feedback and still reasonable output power (for a 300B). Also, for any other output triode and even for parallel use of tubes, we probably cannot get much lower Zout unless we deviate even more from the old rule about load impedance for maximum undistorted power output (?undistorted? here usually meaning 5% distortion).

Everything I have said above applies to the nominal 8 ohm tap. The 4 ohms tap will usually have half of the Zout of the 8 ohm tap. Actually what we have described above for the 5K transformer is like using the 4 ohm tap in an amplifier with a 2K5 output transformer. Therefore when using speakers rated as 8 ohms, if you are willing to sacrifice the output power, you can see how it will sound with a lower output impedance using this tap. But it should be clear that an amplifier designed to reflect a 5K impedance from 8 ohms should have details in the output transformer and the biasing and power supply such that it would be optimized for the right impedance, extracting more power and being a better overall solution if done right. And, of course, you could have still a lower output impedance using its 4 ohm tap!

I have to say that this whole issue of which output tap should be used and of specifying the nominal loudspeaker load is not a simple one. With tube amplifiers using the tap that better reflects the average loudspeaker impedance will usually result in more output power. To get lower output impedance the 4 ohm (or lower) tap is always the better option *regardless* of the loudspeaker impedance. Balancing these points, and also the change in frequency response extension and the different amount of distortion for different power levels among other factors is not easy. This is why listening to all tap options is sometimes the only way to decide which tap is better for a loudspeaker with a particular amplifier.

4. Looking At The Effects Of Hight Output Impedance

As we have seen, the lower limit on the value of the Zout of the SE amplifiers, being high, makes it very important for us to consider its effects on the system response. Driving a loudspeaker with a high Zout seems to be a bad idea. Loudspeakers, in general, have been designed under the assumption that they will be used with amplifiers that closely resemble an almost perfect voltage source, which means Zout close to zero. Although contacts and cable resistance usually make reducing the Zout of an amplifier below some point like 0.1 ohm useless, in the SE amplifiers, as we have seen, we are talking about values around 4 ohms. This value of Zout interacting with typical loudspeakers input impedance will produce a deviation from the loudspeaker intended frequency response of several dB.

From the midbass up, we can calculate the probable maximum deviation from the original frequency response if we have the amplifier Zout value and an input impedance curve of the loudspeaker. We can roughly look at what will happen with the loudspeaker response as a kind of ?modulation? of the frequency response curve via the input impedance curve (although not correct, I can think of no other way to quickly describe the effect). Trying to visualize it, you should keep in mind that because of the difference in the effect of the peaks and dips of the input impedance of the loudspeaker and also because of the complex nature of the impedances, the peaks will be reproduced broader and the dips sharper in the frequency response curve than in the original input impedance curve.

To calculate the change in the response we should use the following formula:

$$D(f) = 20\log \frac{Z_{in}(f)}{Z_{in}(f) + Z_{out}} \quad (3)$$

where, D(f) = deviation in dB at frequency f
Zin(f) = input impedance of the loudspeaker at frequency f

We can see that this formula will always give a negative value, which corresponds to a loss for any value of Zout that is not zero. But we are looking for the difference between the loss at the maximum Zout and the loss at the minimum Zout. This will give the range of deviation from the intended frequency response curve of the loudspeaker. Ideally we should use the complex values of Zout and Zin but the output transformer model we are using implies a resistive behavior for Zout. Also the peaks and dips in the magnitude of the loudspeaker input impedance usually correspond to points where its phase angle is 0 or very close to it. Because of these facts using just the magnitude of the input impedance and assuming a resistive behavior, it will give us the most probable maximum deviation from the intended frequency response of the loudspeaker.

I went through 12 issues of Stereophile (Jan/95 to Dec/95) and looked at 31 loudspeakers that were tested and had the input impedance curve published. The maximum values for input impedance had to be estimated as the curves are limited to a maximum of 20 ohms. Considering only the frequencies well above the low frequency resonance of the system, the average loudspeaker had an input impedance varying from 4.3 ohms to 15.0 ohms. with the phase going from -28 to +29 degrees. Very seldom a loudspeaker had phase angles of more than 45 degrees or less than -45 degrees (only 2 cases, the worst being a 55 degrees angle). This is fortunate because the error introduced assuming resistive behavior will be small.

Now we must look at what will happen at the very high frequencies. Should the equivalent circuit be used here? With dynamic loudspeakers, the voice coil inductance of the tweeters will usually have an effect on the phase of the loudspeaker input impedance corresponding to an inductive behavior. This is similar to the effect of the leakage inductance of the transformers on the phase of the amplifier Zout. This will keep the difference in phase angle small, and this reduces the need to use the model for evaluating the effects of the high Zout at high frequencies with dynamic loudspeakers. As long as the change in the magnitude of the Zout at high frequencies is reasonable, we should have no surprises here and can still consider the Zout resistive. This also holds even when impedance compensating networks (Zobels) are used. Only with output transformers with very limited high frequency response driving loudspeakers with capacitive behavior (like piezo tweeters) we should need to take a closer look at these frequencies, because of the probable high phase difference.

All the considerations above are valid through the frequency region far from the resonant frequency of the woofer in the system. Near the resonant frequency of the system, we can still try to use the same approach as a rough guess but it may give wrong results. We can not just use the idea of ?modulation? of the frequency response curve via the loudspeaker input impedance curve without further care. Not only does the falling frequency response make it difficult to visualize the effect of the output impedance, in vented systems the change in the alignment produced by the high Zout will change not only the value but also the frequency of the impedance peaks. There are other factors that also may have a big effect on the frequency response of the system, including the primary inductance of the output transformer, making the use of the equivalent circuit necessary to understand what happens. But this alone deserves its own article which I hope will follow this one soon.

5. References

ref. 1 - Terman - Electronic and Radio Engineering (1955) - pg. 341
ref. 2 - Stereophile - March/1995 - pg. 120
ref. 3 - Reich - Theory and Application of Electron Tubes (1944) - pg. 228 - 232
ref. 4 - Dammers, Haantjes & Van Suchtelen - Application of the Electronic Valve in Radio Receivers and Amplifiers. Vol II (1951) - pg. 97-101
ref. 5 - Langham - High Fidelity Techniques (1950) - pg. 38 - 41

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