AUDIOPAX

SE Amplifier Output Impedance - Part 2

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1. Introduction

This is the second part of our look at the output impedance (Zout) of triode single ended amplifiers using no negative feedback. Here I intend to examine carefully the effects at low frequencies. I believe this can help us understand the sometimes puzzling bass performance of SE amplifiers. I will show how the high output impedance modifies the response of the system. This will be done with the help of the Thielle-Small theory. Although this theory is more familiar to speaker designers, we will have to use it to arrive at some conclusions that may be relevant to the design of SE amplifiers. I will briefly describe the terms related to the theory as they appear but you may want to consult the original papers (ref. 1,2,3,4) or a book like *The Loudspeaker Design Cookbook* where these terms are much better presented.

As examples, I have only used closed and vented box loudspeakers types because they are by far the most common ones, but the same method can be extended to any other form of bass loading which has been correctly modeled.

2. How A High Zout Modifies The Loudspeaker T/S Parameters

Most loudspeakers today have their low frequency design based on the justly famous Thielle-Small theory. At the low frequencies, this theory uses an acoustical analogous circuit that allows the calculation of the actual acoustical output of the speaker driver in a box.

How can the T/S theory help us? If you consider the Zout a simple resistive value as was done in Part 1, it is easy to use the T/S theory to analyze the behavior at low frequencies. The loudspeaker designer has some formulas to take into account the output resistance of the amplifier and the cables. The original paper of Thielle (ref.1) addresses this point, and the work of Small (ref.2) show us very clearly what we should do. If you know the basic Thielle-Small parameters of the woofer used in the system (or better yet, if you measured it), you can use the equations (21) and (22) of ref.2 to calculate new parameters for a system. You can look at these equations in a slightly different way. It is as if you had a ?new? driver with a different Qes and Qts connected to a zero Zout amplifier. It will produce the same results.

Qes? = Qes (Rg + Re) (1)
Re

Qts? = Qms Qes? (2)
Qms + Qes?

where, Rg = output resistance of amplifier + cables
Re = DC resistance of the loudspeaker coil
Qes = Q of driver at resonance due to electrical resistances
Qms = Q of driver at resonance due to nonelectrical resistances
Qts = Q of driver at resonance due to all resistances
Qes?= electrical Q of ?new? driver
Qts?= total Q of ?new? driver

You should make the calculations for Rg equal to the Zout of the SE amplifier which is typically around 3 to 4 ohms, as we have seen in the *Part I*. If you have significant resistance in the crossover and cable, you should take this in account. You will have two sets of parameters with different Qts. Calculating the system response with these parameters can now be done easily with any loudspeaker design software (or going through the tables and formulas). You can now compare the two response curves.

All this is not suited for a quick analysis of a loudspeaker low frequency response because it requires a certain amount of work and access to the loudspeaker design parameters which may not be possible. But I have done it looking for the general patterns that could appear.

I used this approach with the loudspeaker referred in the past article which has a woofer with the following parameters:

fs = 22.5 Hz Qts = 0.274 Qes = 0.286 Qms = 6.547 Vas = 160 and Re = 6.8W.

The crossover resistance is a high 1.6W. The parameters will change with different values of Zout and how the system composed of this driver and a 70l lightly stuffed closed box will end up. The actual near field measurements were generated with a very low Zout amplifier and with 3.7 ohms and 2.7 ohms resistors connected between the amplifier and the loudspeaker. Although there were some low pass crossover contributions, these measurements are close to the expected.

I have used this method with other speakers and it has worked quite well. But I have always been worried about how to take into account the primary inductance of the output transformer. My measurements were made with resistors simulating a high Zout. As we have seen in *Part I*, the effect of the primary inductance changes the value of the Zout at the very low frequencies. Therefore this use of a fixed resistor value should not be completely accurate.

3. Taking Into Account The Primary Inductance

When the finite value of the primary inductance starts to show its effects, the output impedance starts to drop at the low frequencies. Which value of Zout should we use? There is no easy answer. We must consider what happens using a low frequency model of the output stage, which includesthe primary inductance of the transformer.

Although there is the provision for taking in account high values of Zout in the original T/S papers, only resistive values of Zout are considered. I could not find anything about the effect of reactive Zout. The closest I got was the work of Benson (ref.5) which looks at filters directly connected before the loudspeaker but it is apparently restricted to the zero output resistance amplifier case.

Here I will be using an acoustical analogous circuit of the whole system composed of output stage, driver and box. I have developed it by connecting the model for low frequencies of the SE output stage of *Part I* with the electrical equivalent circuit of the loudspeaker which can be found in any of the references. I have used the same assumptions and methods of the T/S theory to arrive at an acoustical circuit that will permit us to calculate the low frequency acoustical response of the system. The relevant new parameters needed are rp, R1, Lp and R2, n^2, already defined in the past article and repeated in the figure.

You should be aware of the assumptions needed to make this circuit valid. I have assumed that the output stage low frequency response is limited by the transformer primary inductance, that the iron core losses will be very small and that the loudspeaker is working as a piston and all the other assumptions of the T/S theory.

You must also consider the acoustical circuits of the output stage and loudspeaker in a closed box and in a vented box. Several questions may arise. Will the transformer plus loudspeaker be a third order system? If we put the speaker in a closed box, will we also have a third order system? Also, will fourth order vented systemsbecame fifth order systems? The answer to all these questions is yes they will, but depending mostly on the value of Lp, we can ignore it and the acoustical circuit will, with some use of circuit theory, revert to the original T/S circuits with the values of $(rp+R1)/n^2$ and R2 added to form the amplifier output resistance (Rg). But what are these values of Lp? Trying to answer this question, I have written a program to calculate the response of the complete system based on the models. This program can be used for closed and vented boxes when you supply the driver parameters, the box data and the amplifier values of rp, R1, R2, n^2 and Lp. It calculates the system response computing not only the frequency response of the driver in a box with the variations introduced by the high (and complex) Zout but also accounting for the low frequency response of the output transformer as well. This is also true for all the phase responses too.

I have used the program to calculate the response of the same loudspeaker I have been using connected to a SE amplifier using two different output transformers. This was followed by the actual near field measurements of the loudspeaker connected to the SE amplifier.

4. Simulation Of Classical Alignments

I have tested the model and the program with other speakers and transformers and they have worked fairly well. With the program on hand, I have simulated countless loudspeakers designs with many different SE output stage parameters. From these simulations, I have selected some that may give a good picture of the overall effect you should expect from connecting a SE amplifier to a loudspeaker.

I have used a fixed relation between the Qes and Qms of the driver such that Qms/Qes = 5. This was a guess at what I believe is a typical driver and is important because systems which have lower relative value of Qms will be less affected by the high Zout. While the opposite is true for systems with high Qms, I performed one simulation for speakers with the same Qts but with different relations of Qes and Qms. I have used extreme cases such that all normal drivers response would be within these two cases.

5. Low Values Of Lp

I believe that the first important fact that emerged from all the simulations I have done was the confirmation that the values of Lp/n^2 found in normal SE transformers have little effect in the system response. The use of Lp/n^2 permits the comparation of the low frequency performance of transformers designed for different tubes with different impedances. Looking at the specification in the listings of some transformers manufactures, I have found that the smallest value for Lp/n^2 for different type of transformers is usually around 35mH. This kind of value means that only if you have a loudspeaker that has very good low frequency extension (something like f3 below 30 Hz), you need to consider more carefully the primary inductance values with traditionally designed SE transformers.

Therefore if you are using off-the-shelf SE output transformers with gaps in your projects, I believe that for most practical situations you can ignore this whole primary inductance issue. The assumption of resistive behavior for the Zout will be a sensible one, allowing the use of the given formulas (1) and (2) from the T/S theory to account for the high Zout.

The second fact is an interesting effect. When the primary inductance begins to have a noticeable effect on the system low end response, it can be a beneficial one in some cases! It is not just the reduction we could expect from the falling low frequency response of the amplifier measured into resistive load, because the reduction is greater for higher impedances like in the resonance peak, where the high Zout introduces the hump. For loudspeakers designed to be used with normal amplifiers, the initial effect of a low inductance will be to reduce the hump, bringing the response a little closer to the intended one. This is clear in the simulations for the unusually low 3H value of Lp. A lower value of Lp could make the loudspeaker low frequency response closer to the expected by its designer and include a 6 dB/octave filter to limit cone excursion below resonance.

I should return to the same review I mentioned in the first article (Stereophile 03/96 pg.109). A manufacturer has came up with an amplifier that has a high Zout but a very low primary inductance. How did they arrive at it? It probably works correctly with its partnered loudspeaker, taming the resonant peaks at low frequency. (Although I believe that this was achieved in a rather strange way. The same review says that they used a huge output transformer without gap for SE operation).

For SE amplifiers used with normal loudspeakers, there may be a possibility for optimizing the system performance at low frequencies by balancing the effects of the high Zout with the effects of the primary inductance of the transformer. Since this points to lower values of Lp, we may get other interrelated benefits like better high frequency response, better power bandwidth, lower cost and smaller size.

Another open possibility is to *optimize the design of the whole system of amplifier and loudspeaker together*. (This idea spawned the eventual LM3 circuit and today's PTS topology of the AUDIOAX Model 88! - *Avantgarde-USA comment*.) I am exploring this route right now. What remains to be verified more carefully is the effect of the variation of the Lp with power levels and frequency. Although transformers operating with DC in the primary and with air gap exibhits much less Lp variation than transformers for push pull operation, the sensibility of the system to these variation may be important. With high relative values of Lp the difference between its effect and that of an infinite value is very small for frequencies above 20 Hz. But if we depend on its (low) value for an alignment we may need to control it more tightly than usual. Or find ways to take the variation in account.

6. Do SE Amplifiers Have Poor L.F. Response?

It has been taken for granted that tube amplifiers, especially single ended ones of the type we have been looking at, do not have good bass response. Actually, the main problem seems to be that *loudspeakers have not been designed to work with the high output impedance of these amplifiers*. And if the loudspeaker has been designed for use with normal amplifiers, it will develop a hump in the low frequency response and its transient response will be degraded. But this picture can change if you design the loudspeaker to work with a high Zout. This can be done quite accurately using the same formulas (1) and (2) for the low frequency design and you may even get some additional benefits.

When designing loudspeakers, the efficiency, the box volume and the low frequency response are interrelated in such a way that for any two of these parameters that you fix, the third one is already fixed for a given bass alignment. A high output impedance in the amplifier is one way to change this balance. If you model it correctly and use it to your advantage, the high output impedance can give you more efficiency with the same low frequency response and box volume. Lets see what I mean. The speaker efficiency is fixed whenever you select a driver. Choosing the box type and alignment will define the box size and the low frequency extension. With the same box type, alignment and size you can have an efficiency gain for the same low frequency response with amplifiers of high output impedance by choosing another driver.

This result also comes from formulas (1) and (2) as I will show in the following example. If you design a box for a loudspeaker to have a f3 of 40Hz in a vented B4 alignment you will need a woofer with Qts = 0.40. When this system is used with a high Zout amplifier it will develop the already expected hump. To correct this we could use another speaker driver with all the parameters unchanged but Qes and Qts. The Qes of the new driver will need to be the Qes of the old driver divided by (Zout+Re)/Re. Therefore, when this new driver is used with the SE amplifier it will have again a Qts of 0.40.

Also from the T/S theory , the efficiency of a driver is given by equation (33) in ref.2:

_1 0

Kfs^{3}Vas , where K = constant = 9.64 x 10 for Vas in liters

Qes fs = resonant frequency of driver

Vas = Equivalent Compliance Volume in liters

Since K, fs and Vas can remain unchanged and the Qes of this new driver will be smaller, its reference efficiency will be 10log((Zout+Re)/Re) greater in dB. For typical values of 3.5 ohms for Zout and 6 ohms for Re we will have a gain of 2.11 dB for any type of bass alignment. This can be seen at fig.17, where I have simulated four different responses. Of course it may be difficult to find exactly this ?new? driver but this gain will always exist and may appear translated into more efficiency, a smaller box volume, a lower f3 or any combination of the three.

We don?t need to use single ended tube amplifiers to get high Zout. We could as well use solid state amplifiers with current feedback to get this same characteristic. It may be hard to have the same mids and highs, but this is another debate and as much as the high output impedance is inherent to a single ended amp design, we could use it in our favor. Surprisingly, it is one way to get a better compromise between efficiency, box size and low frequency response for any kind of bass alignment.

7. Conclusions

This article and the past one show that the high Zout can produce important changes in the frequency response of loudspeakers. I believe that we cannot talk about meaningful listening tests for SE amplifiers without taking it in account. Probably the only thing that usually masks part of the high Zout effects is the room interaction with the loudspeaker, which may be responsible for even bigger variations of the frequency response in the listening position.

Here I have shown how the bass alignment of typical loudspeakers is altered by a high Zout and also what is the influence of the finite value of the primary inductance of the output transformer. I have done this last part with the help of an acoustical model which includes the typical output stage of a SE amplifier. This whole article deals with the small signal behavior of the system composed of output stage, speaker and box, and although large signal considerations are also needed for the pratical use of the information contained here, I believe that it can be used for tree basic purposes:

- To help in the design of SE amplifiers more suitable to drive an existing normal loudspeaker. This could even include the use of much smaller than usual primary inductance to partially compensate the high Zout effects. This could mean several benefits in other areas of transformer performance like, size, low frequency power response, high frequency extension and cost.
- To help design loudspeakers, which not only will work correctly with common SE amplifiers but can even achieve a better bass performance with an improved relation between size, efficiency and low frequency response.
- To design the amplifier and loudspeaker as a system optimized to work with each other and using all the above possibilities.

Finally I have to say that the high output impedance might even have more subtle effects on the system composed of amplifier, cable and loudspeaker which I have not been able to figure out. Thus far, I have tried to detail and understand the more easily measurable effects it produces. Next time I intend to describe an amplifier and loudspeaker that were designed together using some of the above ideas.

8. References

ref. 1 - A. N. Thielle - Loudspeakers in vented boxes -Part 1 & 2 - Loudspeaker Anthology Vol.1 pg.181 & pg.192.

ref. 2 - R. H. Small - Direct Radiator Loudspeaker System Analysis - Loudspeaker Anthology Vol.1 pg.271.

ref. 3 - R. H. Small - Closed-Box Loudspeaker Systems - Part 1 & 2 - Loudspeaker Anthology Vol.1 pg.285 & pg.296.

ref. 4 - R. H. Small - Vented-Box Loudspeaker Systems - Part 1,2,3 & 4 - Loudspeaker Anthology Vol.1. pg.316, pg.326, pg.333 & pg.339.

ref. 5 - J. E. Benson - An Introduction to the Design of Filtered Loudspeaker Systems - Loudspeaker Anthology Vol.1 pg.365.

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