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LOW LEVEL AUDIO SIGNAL TRANSFER THROUGH TRANSFORMERS CONFLICTS WITH PERMEABILY BEHAVIOR INSIDE THEIR CORES

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ABSTRACT: At the threshold of audibility, the signal and flux density levels in an amplifier with audio transformers are very small. At those levels the relative magnetic permeability of the iron transformer core collapses and the inductance of the transformer becomes very small. The impedances connected to the transformer plus its signal level and frequency dependant inductance behave as a high pass filter which corner frequencies slip into the audio bandwidth, resulting in a non linear signal transfer through the transformer. This research explains deviations in the reproduction of micro details at the threshold of audibility.

1. INTRODUCTION

The capabilities of our ears are amazing and it stays surprising what we can hear. Some amplifiers and speakers reproduce the sound in a fantastic open manner, others do not and it is not always clear why this is the case. To find clues and answers to these differences between sound systems, I decided to start a reverse thinking research, to start with the capabilities of our ears and to determine which minimal specs the electronics should have.

In this paper I give a simple but very effective demonstration of this reverse approach by using the well known audibility threshold curves of our ears. In this famous research the lowest SPL level per frequency was determined that the ear just can notice. Below that level only the happy few with golden ears can hear, but most people will have a threshold level close to measured in those days.

Imagine what happens there: for instance we can just notice at 4kHz at a SPL level of -4dB, which even is less than the 0dB level of 20 μPa at 1 kHz. Now take a loudspeaker in mind with an efficiency of 90dB/W,m and calculate the power which the speaker needs to reproduce such a weak sound level at 1 meter distance. Be stunned by the amazing $4 \cdot 10^{-10}$ Watts. The next understanding is that then the signal levels at the speaker terminals are extremely small as well.

My professional work is focused on valve amplifiers and audio transformers (1-5). So, I decided to continue the research in that area. A valve amplifier with output transformers needs to transfer such small voltages with great accuracy, because "watch the golden ears, they even listen below this level".

What happens inside an output transformer at such small voltage levels? Then the flux density in the core will be amazingly small as well, in the environment of 10^{-8} Tesla . There exist not so many handbook data about the relative magnetic permeability inside the core

at such low flux densities. This perm is closely related to the mobility of magnetic iron domains, called the Weiss-areas. At the indicated signal levels, the musical magnetic force on these domains will be almost negligible, they will be busy with each other and consequently their mobility will be very small. So, when we listen to sound at such small SPL levels, the transfer of sound through the audio transformer mainly depends on the capability of the small magnetic domains to move, and it is not sure at all if they can do this in the right manner.
In this research I started to do measurements there and noticed that interesting deviations from linear behavior occur, even that there is a real conflict between linear signal transfer and the actual mobility of the small magnetic domains.
The easiest way to explain this conflict is to realize that a transformer and its inductance, which is directly related to the permeability, in combination with the driving and loading impedances, acts as a first order high pass filter. At several frequencies and belonging SPL threshold levels, it is shown that the permeability of an iron core hardly is able to linear transfer the weak audio signal.
This means that with a given iron in the transformer core, with a given amplifier topology, with a given loudspeaker efficiency, it can be calculated in advance whether or not the transformer will be able to transfer the week audio signal in a linear manner or not.
From there it will be proven that SE amplifiers with low impedance triodes have a great advantage, not by miracle or belief, but just by their low impedance combined with gapped core magnetic behavior. Then it becomes understandable why these amps are able to create such a holographic soundstage, why we truly can hear the micro details because they are not weakened inside the output transformer.
This research combines many characteristics of valve amplifiers into a holistic picture, combining magnetism with the fantastic capabilities of our ears; it gives objective answers to what we subjective hear.

2. How to do the calculations

Figure 1 shows the well known ISO-curves of our ears, in this case taken from de famous book of Blauert (6). The lowest dashed line in this figure shows the threshold of audibility in a total silent environment. Now imagine a loudspeaker with an efficiency η of say 90dB/W,m. In order to reproduce the signal level at each given frequency at the threshold of audibility at a distance **d** between loudspeaker and ear, the loudspeaker needs a power **P** given by:

$$P(f) = 10^{[\,SPL(f) - \eta + 20\log(d)\,]/10} \qquad \text{1-1}$$

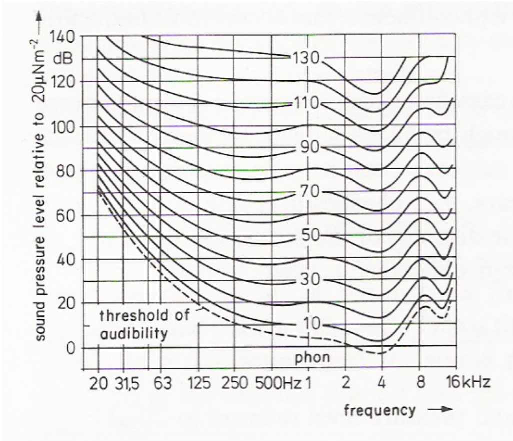

Figure 1: ISO-curves of human ears

For this study it is assumed that the frequency characteristic of the loudspeaker and its impedance are absolutely constant in the frequency range of interest. Later I will say more about these aspects. As an example the required powers at threshold are calculated for η = 90dB/W,m at d = 1 m and the results are shown in figure 2.

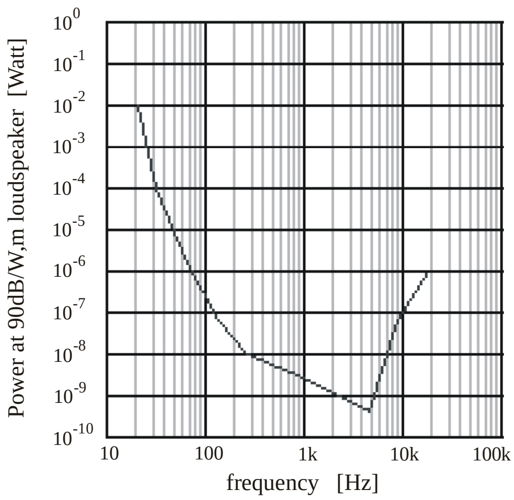

Figure 2: Required power for a 90dB/W,m loudspeaker to reproduce the threshold SPL at 1 meter distance.

Now let's focus on my profession: valve amplifiers with output transformers. We will assume that the valves used are fantastic and we only need to focus on the output transformer with a primary impedance **Zaa**.

Assuming negligible losses inside the output transformer, then the effective voltage **Vaa** delivered by the valves over the total primary winding is given by formula 1-2. Figure 3 shows the results of this calculation for a Zaa = 4000 Ohm primary.

$$Vaa = \sqrt{P \bullet Zaa} \qquad 1\text{-}2$$

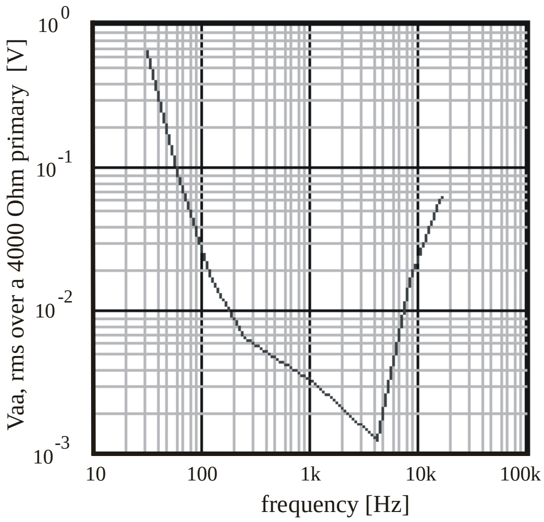

Figure 3: Primary rms voltages at threshold levels

Following we use a real world output transformer with **Np** = 2000 primary turns and a cross sectional core surface **A** = 10^{-3} m^2. With the primary voltages known, the amplitude of the magnetic flux density **B** can be calculated, using formula 1-3. See figure 4 for the results.

$$B = \frac{Vaa \cdot \sqrt{2}}{2 \cdot \pi \cdot f \cdot Np \cdot A} \qquad 1\text{-}3$$

This figure is one of the first reasons why I got concerned. Imagine, at threshold SPL the core is working at flux density levels which are very small. Then it might be the case that the relative magnetic permeability of the OPT core material will be too small to give the OPT any primary inductance. Core steel manufacturer information gives almost no clues about magnetic behavior at such small flux densities. Their info is in nice graphs from .1 to 2 Tesla, and we are looking now to what happens below .1 T.

I performed relative permeability measurements on two steels: GOSS (Grain Oriented Silicon Steel) and stamped lamination VM111 annealed steel. The results are shown in figure 5.

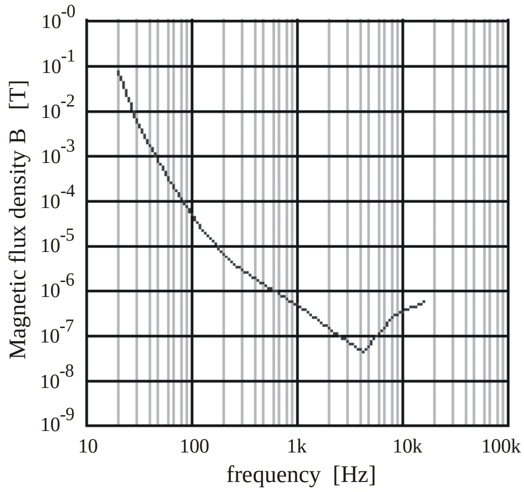

Figure 4: Magnetic flux density B inside the core at threshold levels.

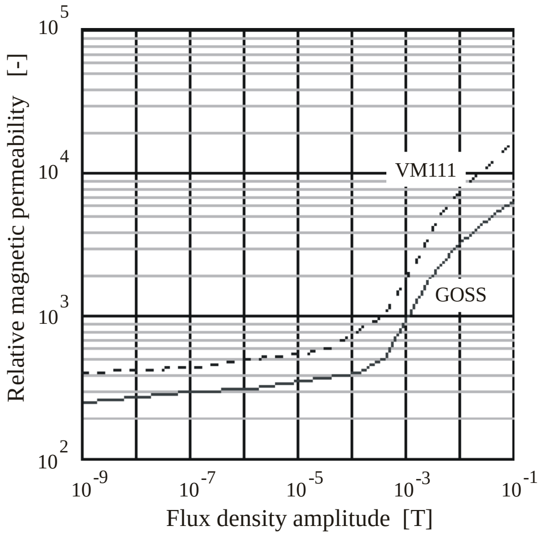

Figure 5: Measurements of μ_r from 10^{-8} to 10^{-1} T; extrapolation below 10^{-8} T.
The maximum error below 10^{-3} T is 20 %.

Below 10^{-3} T it is clearly visible that an initial permeability stays present, which depends also on the temperature of the core (the measurements were performed at 20 ^{o}C, while temperature rise makes the initial perm larger; not that much, about 0.07 % per

degree Celsius, according to measurements of L. Alberts and B.J. Shepstone).
With the flux densities known (figure 4) at threshold level, the permeability can be derived with figure 5, and following the inductance **Lp** of the primary winding can be calculated with formula 1-4. There lc is the mean magnetic path length en lg is the width of the gap in the core.

$$Lp = \frac{\mu_0 \cdot Np^2 \cdot A}{lg + lc/\mu_r} \qquad 1\text{-}4$$

Using $\mu_0 = 4\pi 10^{-7}\ Hm^{-1}$ for the permeability of vacuum and our example output transformer has lc = 0.236 m, while lg is negligible. At each threshold SPL level and belonging frequency the primary inductance Lp can be calculated. The results are shown in figure 6 for a transformer with a GOSS-core.

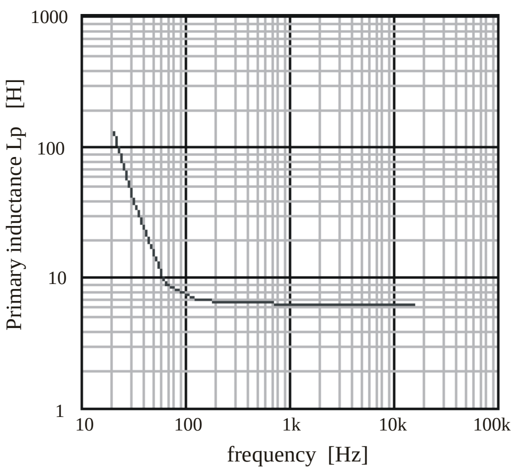

Figure 6: Primary inductance Lp for GOSS at threshold level.

It clearly is visible that Lp is not a constant and collapses to rather small values, especially at higher frequencies threshold SPL levels.

The next question is crucial in my line of reasoning in this research: "is Lp large enough to have no negative effect on the linear signal transfer at threshold level through the output transformer?"

To answer the question, the modeling of a valve power amplifier is used, as discussed in (1) to (4). There the power valve(s) are replaced in their operating point by a single voltage source with in series their summed plate resistances Ri,eff. This voltage source drives the primary inductance Lp plus the primary impedance Zaa in parallel (where we assumed that the loudspeaker impedance is a constant). Figure 7 shows the situation.

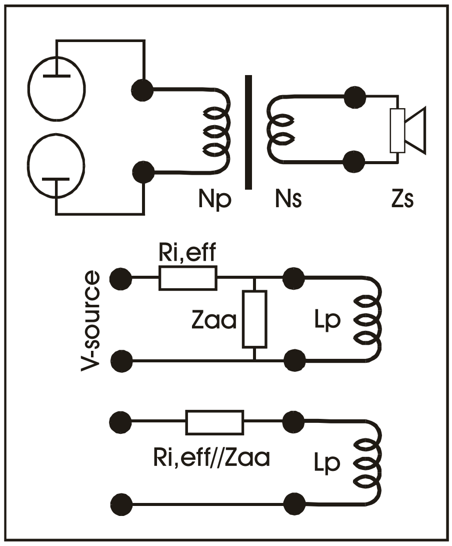

Figure 7: Equivalent circuit of valve amp driving a loudspeaker Zs.

In figure 7 it is clearly visible that the valves plus the OPT driving a speaker Zs can effectively be replaced by a pure voltage source with series resistance Ri,eff in parallel with Zaa driving an inductance Lp. This circuit is a first order high-pass filter and the transfer function of this filter is given by formula 1-5, where $s = j2\pi f$ and Req is Ri,eff in parallel with Zaa.

$$A = Vout / Vin = \frac{s.Lp}{Req + s.Lp} \qquad 1\text{-}5$$

Lets assume, as example, that we use a push pull power amp with pentode valves with a plate resistance of Rp = 15kΩ per tube. Then Ri,eff = 30 kΩ and Req is this 30 kΩ in parallel with Zaa = 4 kΩ, resulting in Req = 3.53 kΩ. With the Lp results of figure 6 the "amplification" of formula 1-5 of the transfer through the OPT can be calculated, as shown in figure 8.

My first guess was that at higher threshold frequencies, where Lp really collapses, the deviations from linear transfer would be the strongest. But it appears that in the region from 20 Hz to 1 kHz the deviations occur. Figure 9 explains this by drawing the actual Lp as function of threshold frequencies compared to a fictive Lp'(f) which creates a constant -1dB amplification in a first order Req-Lp' filter.

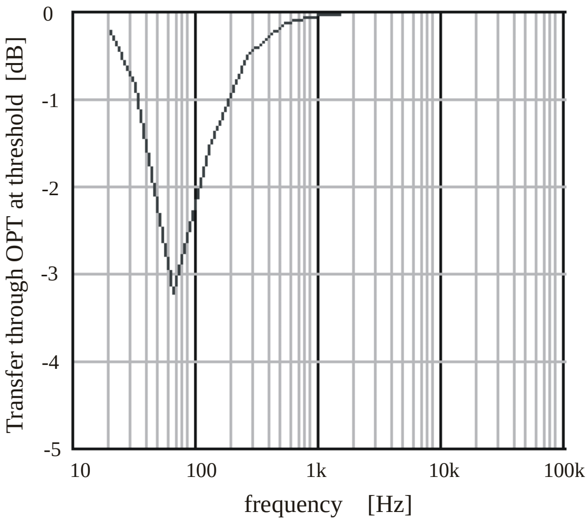

Figure 8: Deviation of linear transfer through OPT at threshold, for Zaa = 4 kΩ, Ri,eff = 30 kΩ, η = 90 dB/W,m, d = 1 m, GOSS.

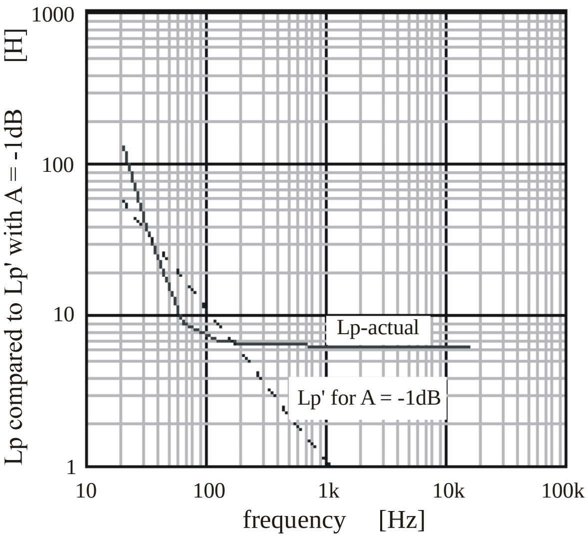

Figure 9: Lp-actual compared to Lp' which creates A = -1dB.

From figure 8 I can conclude that at threshold SPL levels, especially between 20 Hz and 1 kHz, an extra weakening occurs inside the OPT, caused by a too small value of the relative magnetic permeability of the core material. This weakening will make the perception of micro details in the reproduced recording more difficult to impossible.

Before researching this in more detail, the next question is: "is their any proof available of the discussed weakening at threshold levels?"

Yes there is. Firstly, I measured tube amplifier open loop amplification at 20 Hz with output voltages at levels needed to create the threshold SPL with 90dB/W,m loudspeakers. I measured that the amplification gradually got smaller at smaller output voltages, as indicated in foregoing theory. Secondly, a private discussion with Tim de Paravicini (7) who explained that frequency characteristics of tube amplifiers with output transformers (and also at magnetic pick-up heads of tape recorders) at lower levels have a higher value of the lowest -3dB frequency. Thirdly, the results of an experiment by Joe Rasmussen (8), who applied high frequency bias on an OPT in order to keep the effective relative magnetic permeability large enough, even at weak audio signal levels. He reported that with bias the micro details in recordings could be heard more clearly, compared to the same OPT without bias. For now this is enough proof.

In the sections following I will discuss more in detail the effects of the parameters as used in the foregoing introduction, like distance d, speaker efficiency η, Zaa and Zs, Ri,eff and Req plus core material, and so. In these discussions I will use the results of figure 8 as a reference to compare with.

3. The influence of the distance d

When we make d larger, the amplifier shall have to deliver more output voltage to the speaker in order to create the same threshold SPL. Figure 10 shows the results when we go from 1 m to d = 3 m while all the other specs are the same as in figure 8.

As expected the deviations from linear transfer have got less than in figure 8, so this approach is valid. It is of no use to enlarge d further, because we are not dealing with Public Address situations and 3 m distance is a fine distance in a normal listening environment.

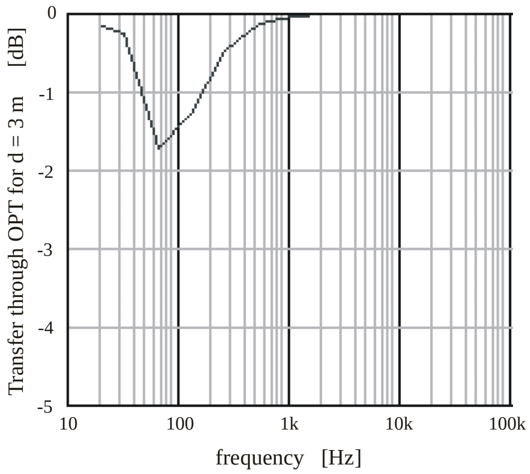

Figure 10: Transfer at d = 3 m; compare to figure 8.

4. The influence of the loudspeaker efficiency

Suppose that we now use a high efficiency horn loudspeaker, its efficiency is at 105dB/W,m. Such loudspeakers are getting common amongst high end audiophiles. Going back to d = 1 m is reasonable now, knowing the radiation pattern of these horns, even if we listen at 3 m distance. Figure 11 shows the results.

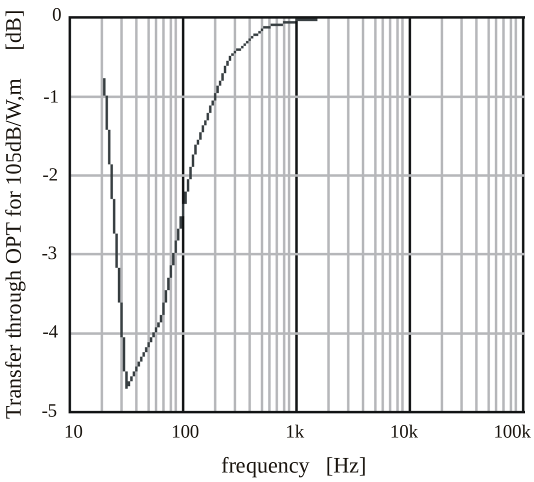

Figure 11: Transfer at η = 105dB/W,m; compare to figure 8 with 90dB/W,m

This result is as expected, because the larger efficiency demands less output power for the same SPL levels. Consequently the voltages and flux densities will be smaller, resulting in smaller relative perm values.

However, the results are surprisingly at the same time. Are not those high efficiency horns regarded highly amongst audiophiles for their excellent and clean sound reproduction? Yes, they are and later I will show that it is the often used low mu single ended triode concept that saves this reproduction from the flaws shown here.
I performed a listening experiment with a good non feedback push pull valve amplifier, which sounds great on standard efficient 90dB/W,m magneto dynamic loudspeakers. With a 105dB horn this amp sounded granular with loss of micro details. Seeing the results shown above, this is not surprisingly.

5. The influence of the speaker frequency characteristics

Every speaker has different frequency characteristics and impedance and radiation pattern. The goal of this study is not to discuss these properties, but to look at what happens inside the iron of the OPT-core. With a given loudspeaker, which characteristics are considered to be constant in time, and when using different OPT situations as discussed in this paper, one can conclude after several serious listening tests, if less or more micro details can be noticed. Therefore, if agreed on, I would like to keep the frequency characteristic of an actual loudspeaker outside the discussion and topic of this paper. One gets used to his own loudspeaker, and it is there where the comparisons are made between different OPT situations. It surprises me how forgiving the human ear plus brain is to deviations in actual characteristics at normal listening levels around 80 dB-SPL. See also the remark of Morgan Jones (11) in "Discussions and Conclusions" on this topic. The absence of micro details however if mostly noticed very well and described as an empty sound character, no fluency, loss of resolution and so on.

6. The influence of Zaa, created by Zs(f)

It is often said that an output transformer has a primary impedance. However, everybody knows that this is not the case. The actual primary impedance is created by the loudspeaker impedance Zs(f), multiplied with the squared Np/Ns turns ratio, and added to the magnet wire resistances in the correct manner. At higher frequencies the leakage and inter winding capacitances play a significant role, while at lower frequencies (as we are dealing with here) the primary inductance plays a major role. See (1) to (4) about much details on this issue.
As an example I would like to discuss the effects of an actual bass reflex loudspeaker, which impedance versus frequency behavior is given by figure 12. For the calculation I take Np/Ns such that Zaa equals 4kΩ at

1kHz. The influence of the magnet wire resistances is neglected because their influence is small and constant over the frequency range. Also the leakage and inter winding capacitances are not used, because they apply to much higher frequencies than considered in this study.
When we compare these results with figure 8 (watch the vertical scale), then especially the second impedance resonance at 70 Hz in figure 12 has a large influence and creates extra losses. Van Maanen and Zonneveld (13) designed a method for impedance correction of dynamic loudspeakers. The results of this paper strongly support the importance of their work.

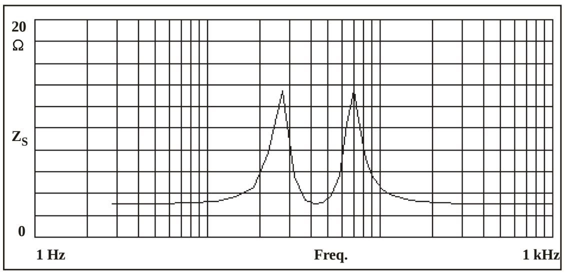

Figure 12: Example of the impedance Zs(f) of a bass reflex loudspeaker (9)

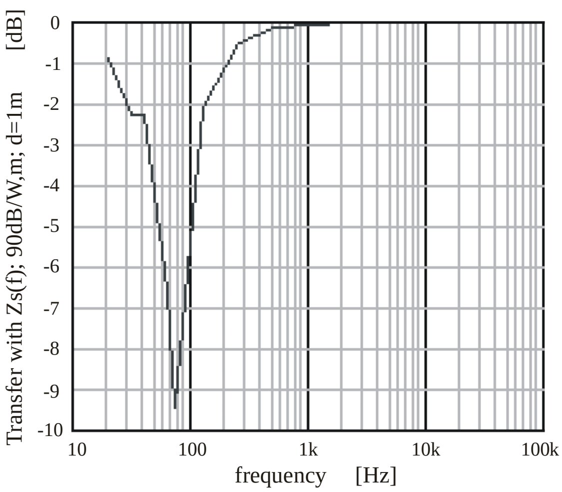

Figure 13: Transfer at η = 90dB/W,m with Zs(f) of figure 12.

7. The influence of Ri,eff

In the previous examples I used push pull pentode power valves with a plate resistance of 15kΩ each. These resistances are large and therefore the Req-Lp filter structure creates reasonable losses inside the 20Hz to 1kHz range. For the next research I replace these valves by a single low mu low plate resistance device, like the famous 300B triode. This valve has a plate resistance of approximately 700Ω. For the sake of comparison I use Zaa = 4kΩ and the horn loudspeaker with an efficiency of 105dB/W,m. Figure 14 shows the striking results.
Under these conditions there is almost no weakening at threshold level noticeable. This example explains clearly why high end audiophiles so often use this combination. They claim high resolution and a holographic soundstage with lots of micro details. These claims are fully supported by the foregoing theory and calculations.

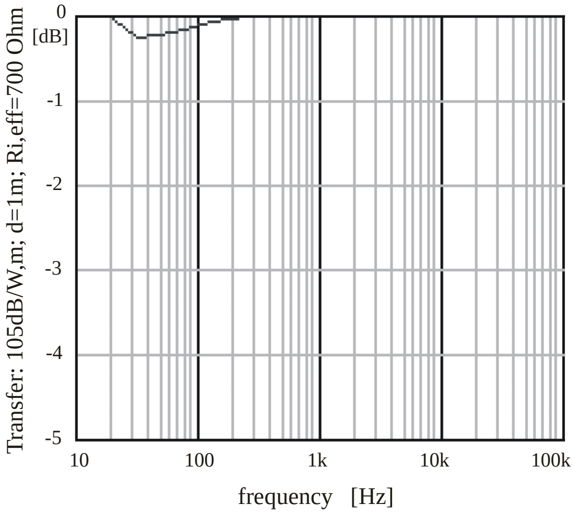

Figure 14: 300B triode with 105dB/W,m horn at 1m.

8. The influence of the OPT core construction

The influence of the variations in the relative permeability as function of the actual flux density can be diminished by introducing an air gap inside the core with width **lg**, see formula 1-4. Because lg mostly is larger than lc divided by the relative perm, the inductance Lp becomes almost a constant, although its value will be smaller than without gap. Also, a gap is mandatory when a constant quiescent DC current flows through the primary winding, as is the case in single ended amplifiers. In the next calculation I apply a gap of 1 mm, combined with the horn and the 300B tube of the previous example. The results are shown in figure 15.

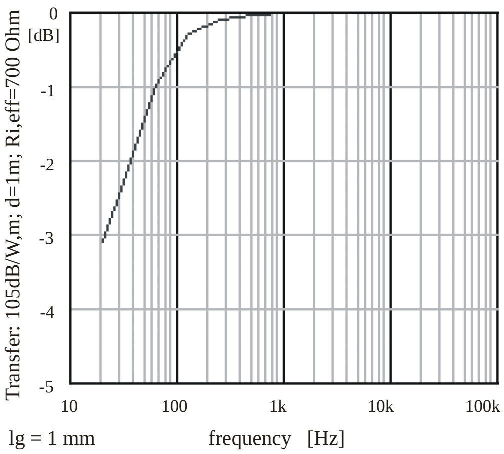

Figure 15: Transfer with 300B plus horn with air gap inside the core.

In this example it is clearly visible that Lp has an almost constant value, creating a well defined first order high pass filter with the driving valve, with a -3dB corner frequency at 20 Hz. This filter behavior does not depend on the actual momentary flux density. So, at every SPL level, this filter will be present. The conclusion can be drawn that such a filter will have a constant amplitude independent influence, like the frequency characteristic of a loudspeaker, and will be hardly noticeable.

9. The influence of the iron

The larger the relative magnetic permeability, the less influence can be noticed at threshold level. Under the same conditions as in figure 8 (90dB/W,m; 1m; Ri,eff = 30kΩ and Zaa = 4kΩ), the GOSS core is now replaced by a VM111 core. The results are shown below.

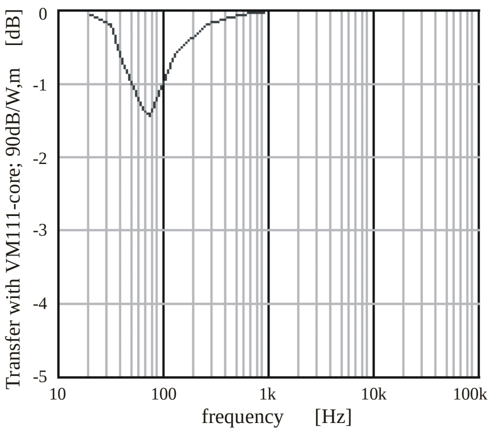

Figure 16: Transfer with VM111 core

The results of this comparison are clear and totally as expected; higher perm cores have enough perm at threshold levels to create almost no weakening between 20Hz and 1kHz.

10. Discussion and conclusion

I might investigate more elements of the OPT and driving valves and loudspeakers, but for now I am sure that the impact of permeability behavior at low flux density levels is clear. Between 20Hz and 1 kHz around threshold SPL level, a weakening of the musical signal takes place. Its amount depends on the valves used, the OPT construction and core materials. Essential in this research is the line of reasoning that the primary inductance gets too small around threshold SPL levels. With the driving impedances of the valves and loading impedance of the loudspeaker, a first order high pass filter is created, causing an extra weakening of the signal in a limited frequency band between 20Hz and 1kHz. As a consequence those audio signals will be under the threshold of audibility, and thus not noticed anymore. Missing musical information on that level is often indicated by audiophiles as "the absence of micro details in the sound stage".

The next stage of the research might go into the direction of: "why don't you put the amp louder, then you can hear the micro details". True, and why not, but please not always, I happen to have neighbors. Or one might argue: "why not apply overall negative feedback or local negative feedback?". True again, clearly understandable. Local feedback directly at the power valves surely is in favor because effectively this will lower the plate resistances of the applied valves and then automatically the weakening at threshold will become less. A practical application of this is found in my SuperTriode circuitry (12).

So, I would like to stick to a very basic question: "*can we hear the effects as discussed in this paper, or can't we hear them*?" I consider audiophiles as people with good ears who clearly are able to focus on the sound heard, even at threshold levels. This being the case, then every weakening, which brings the actual SPL under the threshold, will be noticed, simply because the micro information is not heard anymore. Maybe some audiophiles can hear at lower levels than the indicated threshold of audibility. They might be in problems, because probably they then also can hear the collisions between air molecules (10). I assume that the major distinction between audiophiles with golden ears and normal people lays in the simple fact that the audiophiles are able to focus much better. Then every missing information will be noticed.

Morgan Jones (11) added the following statement, which might shed an extra light on the hearing capabilities of the audiophiles in this special regard and study: "*It's my opinion that an amplifier with flaws that change with amplitude or frequency is less tolerable than one with constant flaws. Perhaps this is because the ear/brain combination is able to adapt to a constant flaw but has to work harder to try to adapt and compensate for constantly changing flaws*". I could not have explained this better and fully agree.

Having listened to many valve amplifiers of all sorts, and also having designed many, I always came to the following subjective conclusion: "*it sounds as if single ended amplifiers reproduce micro details louder and clearer, that is what makes the music to envelope me and creates the holographic experience; with push pull amps this can be approached when triode or alike power valves are applied*". The theory and explanations of this paper exactly explain and predict this subjective experience. Again I have found an answer, what's next? Having said this, I rest my case.

11. References

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6: Jens Blauert; "Spatial Hearing, The Psychophysics of Human Sound Localization"; translated by John S. Allen; MIT Press; ISBN 0-262-02190-0

7: Tim de Paravicini; private discussions at European Triode Festival ETF2006 in The Netherlands

8: Joe Rasmussen; Custom Analogue Audio; private discussions at ETF2006 and e-mail exchange following about advantages of high frequency bias of an OPT.

9: Menno van der Veen; "High-End Buizenversterkers 2"; chapter 5; Segment bv; ISBN 90-5381-204-0 (at this moment only available in Dutch language).

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11: Morgan Jones; private discussions at ETF2006 and e-mail exchange following.

12: Menno van der Veen; www.mennovanderveen.nl ; go to "the project" and "tube amps" with the description of the Vanderveen "SuperTriode" circuitry.

13: Hans R.E. van Maanen & E.T. Zonneveld; "An Extended Model for Impedance and Compensation of Electro-Dynamic Loudspeaker Units and an Algorithm for their Determination"; 96th AES conference, Amsterdam, paper 3823.