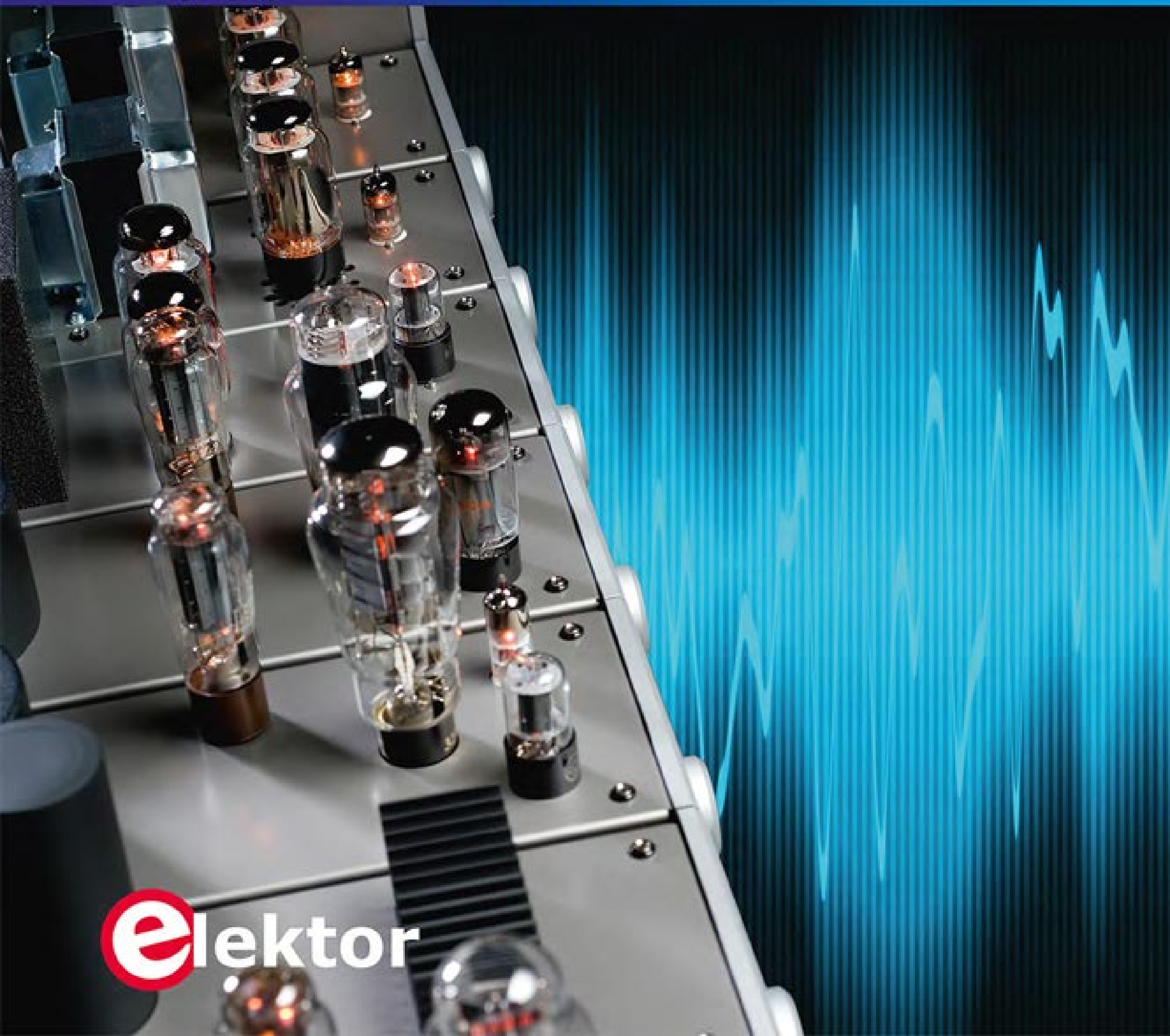
Menno van der Veen

Designing Tube Amplifiers

concept, implementation and assessment



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Introduction

Prior to this book, I have written a large number of articles and papers and two other books.[1,2] The first was a journey of discovery in the realm of tube amplifiers, with the emphasis on output transformers. The second provided a solid scientific basis for the theory and practice of tube amplifiers. You might therefore wonder why I should write a third book, when the subject has already been covered so thoroughly.

The answer is that something remarkable happened to me. I was invited to teach masterclasses in Germany, and while preparing for this I realized that I was no longer interested in repeating my message on the fundamentals and science of tube amplifiers. In a manner of speaking, I had put it behind me.
I wanted to do something different, something to the effect of "I've laid a strong foundation now, but what can I actually *do* with it?" I therefore chose a new perspective while preparing the course material. I wanted to view things from above, to see how the scientific data fits together and interacts. I wanted to know how a change in one place affects a specification in another place. Above all, I wanted to know whether I can *hear* what happens – what the relationship is between what I hear and the scientific facts and measurements.

As a result of this approach, I started looking for coherency and examining the sensibility of measurements, the effects of negative feedback, holographic reproduction, and how they relate to the handling of microdetails. The common thread in all this is a previous study (see Chapter 18) on the reproduction of microdetails, in which I approached this question on the basis of the capabilities and characteristics of my ears, rather than distortion figures or other objective data. In this study I discovered that using the properties of our ears and our sense of hearing as a basis for investigation and measurement is a wonderful way to arrive at totally new insights.

1 *Modern High-End Tube Amplifiers*, Elektor, ISBN 978-0-905705-63-7
2 *High-End Tube Amplifiers 2*, Elektor, ISBN 978-0-905705-90-3

The effects of this approach can be seen everywhere in this book – I constantly ask questions such as "What is it good for?'' and "What does it get me?". In this approach I avoid being unnecessarily critical or skeptical. I regard it as new and challenging – at last I have my hands on something that opens new doors.
I am also trying new routes, such as using your feelings and emotions, taking a strong stance as a person in the task you perform, properly recognizing and appreciating your business abilities, trying out new measurement methods, and critically examining what they actually tell us. I have therefore largely left the world of formulas behind me; I already know it well. I am working now on integration. I try to make a whole of things, to create a sort of overview where you look down from above on all the wriggling on the earth and the fidgeting of electrons in tube amplifiers. This sounds a bit philosophical, but I think that's allowed after so many years of study and practice.

While preparing and writing this book, it struck me how much support I receive from the staff of Elektor, from colleagues such as Peter Dieleman and Rainer zur Linde, who keep encouraging me to write something about what I think.
I hope you enjoy reading my third book. Will there be a fourth? I don't think so, but my experience with one shows that you can never tell in advance.

Menno van der Veen
Zwolle, The Netherlands, September 23, 2009

About the author

He built his first tube amplifier at the age of 12, and since then tubes have been the main interest of his professional life. He studied engineering Physics at University and subsequently taught Physics at the upper secondary school level and in teacher training programs.
Around the age of 40, he founded his engineering firm and started devoting his attention to his old love: sound reproduction with tube amplifiers. His first major achievement there was the development of a new line of wideband toroidal output transformers, which he used in tube amplifiers of his own design.
During this period he also explored advanced audio equipment from around the world and published over 360 articles as a reviewer for audio magazines. One of the recurrent themes in these articles was the question: do we measure what we hear?

Intensive contacts with Canada led to new research in related areas. Here he focused on the clean transfer of electrical power, with the transformer acting as a bandpass filter. This led to the unique and patented 'Narrow Bandwidth' technology.

He has chaired the Netherlands section of the *Audio Engineering Society*, where he has published the results of many of his studies in the form of preprints and papers. Some of his findings have also been published by the Acoustical Society of the Netherlands and in two books published by Elektor.

Around 2004 he turned his attention to tube amplifiers for guitarists. This led to the development of a new series of low-cost EI transformers. They were fully elaborated in a large-scale study called 'The Project', which allows a large variety of tube amplifiers to be built from a minimum number of identical components.

Photo: Frans Paalman

In 2006 he expanded the activities of his engineering firm with the launch of the tube academy 'TubeSociety', where students are trained to design and build tube amplifiers.
In collaboration with Elektor, he conducts masterclasses in the Netherlands and other countries.

3
Circuits and their consequences

Nowadays it's fashionable to use various components to shape the sound domain of an amplifier. People use 'super' resistors, capacitors and tubes, and these components determine the price of the ultimate result.
I no longer follow this route. In my experience the quality and the sound are primarily determined by the circuit and the overall design, and the quality of the components has only a very small effect.
A virtually complete overview of the options is given in my second book[1] and on my website.[2] Here I discuss the key significant features.

3.1 Push-pull amplifiers

The output transformer is driven by two output tubes in a push-pull configuration. Pentode tubes are often used for this purpose, and the following versions can be created by connecting the screen grid in different ways: push-pull pentode, push-pull ultra-linear, and push-pull triode.

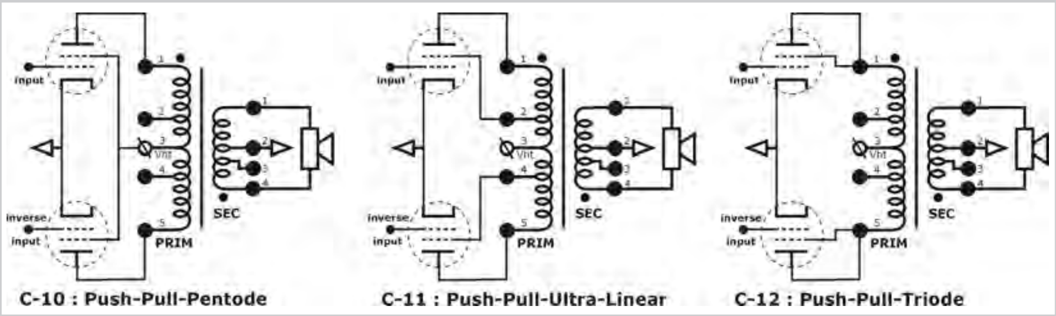


Figure 3.1: Three types of push-pull stage are possible with different screen grid connections.

1 Menno van der Veen: *High-End Tube Amplifiers 2*, Chapter 9, Elektor.
2 *www.mennovanderveen.nl* – The Project.

3.1.1 Push-pull pentode

Lots of power; warm sound; very low damping factor; microdetails not reproduced especially well; fairly high THD (5% at full power); outstanding as a guitar amplifier; negative feedback can reduce THD and increase the damping factor, but this comes at the cost of the 'easiness' of the reproduction.

3.1.2 Ultra-linear

About 20% less power that the pentode version; transparent sound; reasonable damping factor (approximately 2); THD can be reduced to around 2% at full power; better reproduction of microdetails.

3.1.3 Push-pull triode

About half the power of the pentode version; richly detailed, transparent sound; low THD (less than 1%); damping factor to around 4; good reproduction of microdetails.

3.2 Enhanced push-pull

Local negative feedback can be used to improve the characteristics. For example, negative feedback to the cathodes of the output tubes yields considerable improvement to the distortion figures, damping and frequency range. The basic options are shown in the following figure.

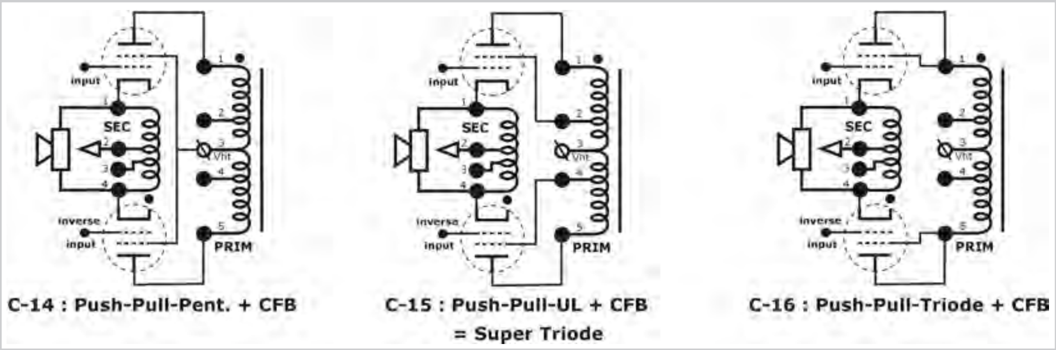


Figure 3.2: Supplementary negative feedback to the cathodes of the output tubes.

Another option here is negative feedback from the anode to the control grid, which is the second version of the 'super triode' circuit.

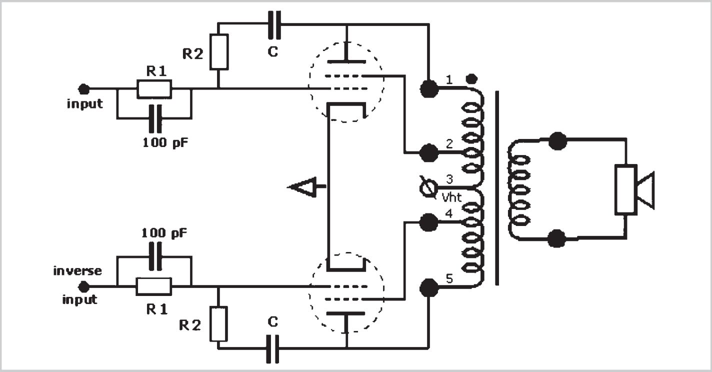


Figure 3.3: Vanderveen super triode circuit.

A noteworthy feature of these circuits is that the soundscape retains its openness, with little or no closing up due to the negative feedback. This closing up does occur with overall negative feedback (from the output to the input of the amplifier).

Incidentally, local and overall negative feedback should be used in combination as little as possible. They are not mutually compatible, and combining them results in a dead soundscape.

3.3 Typical characteristics of push-pull amplifiers

3.3.1 Distortion

The third harmonic is dominant if the push-pull stage is properly balanced.

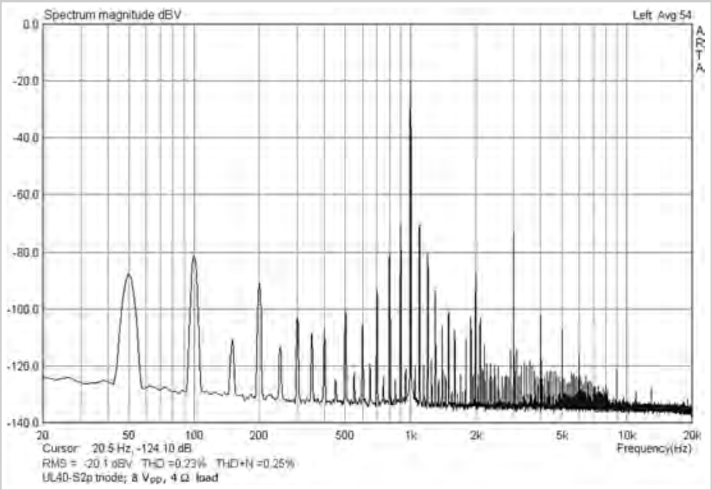
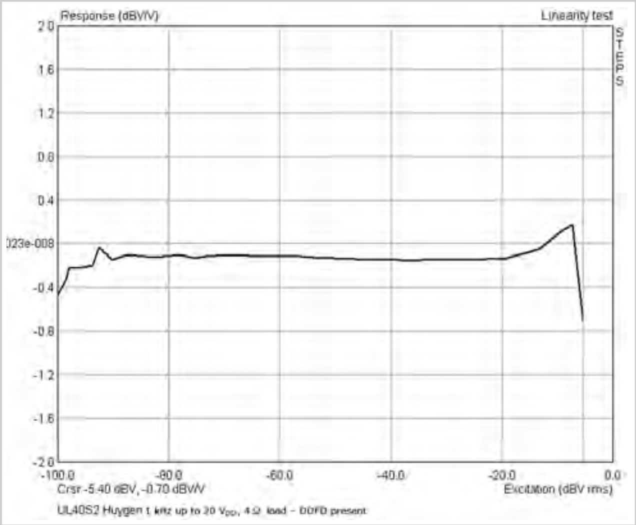


Figure 3.4: The third harmonic is dominant in the distortion products.

3.3.2 Gain constancy and DDFD

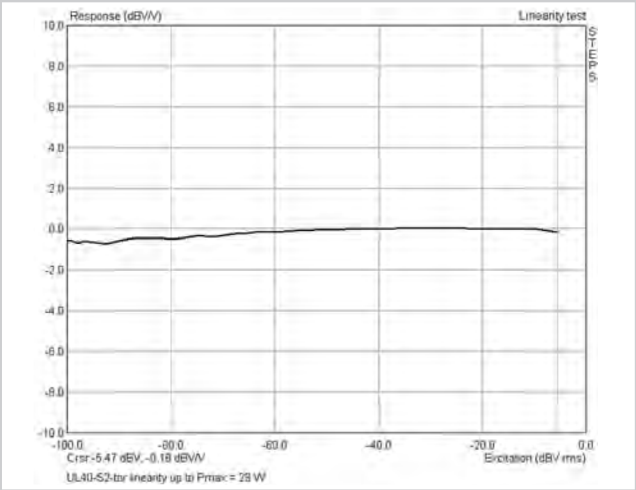
When a push-pull amplifier is operating in class AB, the output tubes are alternately cut off at high output levels. This has two effects: the amplification factor changes, and the effective output impedance of the amplifier changes. The following figure shows an example.

Figure 3.5: The gain and damping change at the transition from class A to class B.



These changes can be eliminated by using negative feedback (local or overall). I call the change in the damping factor 'dynamic damping factor distortion' (DDFD). This can also be eliminated by negative feedback.

Figure 3.6: Drop in gain at low signal levels (microsdetails).



3.3.3 Reproduction of microdetails

The internal anode resistances of the output tubes are relatively high in a push-pull circuit. This creates problems (as previously mentioned) in the reproduction of microdetails, since the transformer core has only low permeability at the corresponding signal levels. This can be seen in figure 3.6.

This effect can be prevented by using local negative feedback to the cathodes or the control grids to reduce the impedance of the output tubes, or by wiring the output tubes in triode configuration. This effect can also be countered by using overall negative feedback.

3.3.4 Supply modulation

The current demand is not constant; it rises with increasing power. This changes the ripple level on the supply voltage, which causes an inaudible (but measurable) increase in the hum level. The following figure shows an example.

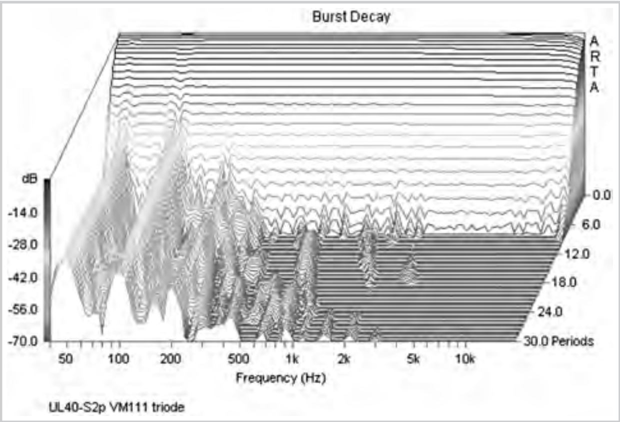


Figure 3.7: Supply modulation after a signal burst.

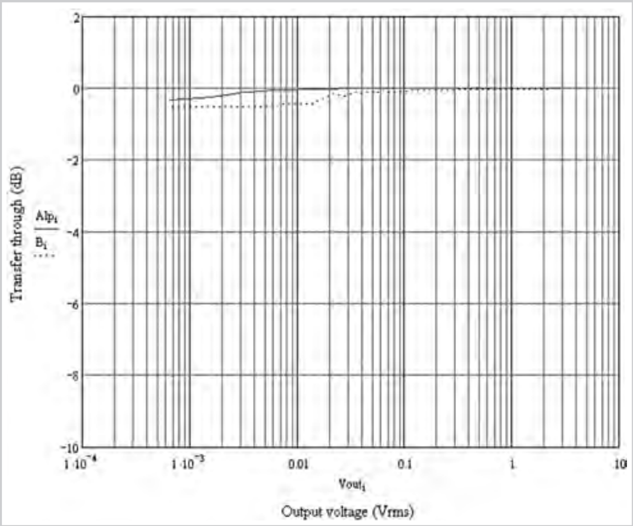
3.3.5 Constancy and equality of quiescent currents

The quiescent currents of the output tubes must be set in some way or another to achieve a suitable balance between the optimal class A range and the lifetime of the output tubes. This can be done by using cathode resistors in parallel with electrolytic capacitors (R_k/C_k method), by using adjustable negative grid voltages, or by using active auto-bias circuits. I discuss this in detail on my website[1]. If the quiescent currents are not equal, the amplifier generates hum and the output

1 *www.mennovanderveen.nl* – Tube amplifiers; Auto-bias largely improves base and microdetail reproduction.

transformer goes into saturation, which degrades the reproduction of microdetails. The following figure shows that when the quiescent currents are unequal (lower, dotted, line), the transformer core has more trouble passing the microdetails properly.

Figure 3.8: Detail reproduction degrades with unequal quiescent currents.



Drawbacks of the R_k/C_k method are that the quiescent current setting varies with the magnitude of the output power and that the quiescent currents are not guaranteed to be the same at different output power levels, due to intrinsic differences between the output tubes.

3.4 Single-ended amplifiers

The output transformer is driven by a singe output tube. No phase splitter is necessary, and the output tube operates entirely in class A. Only half of the magnetic range of the output transformer is used, which means that the transformer core must be four times as large as the core of a transformer for a push-pull amplifier with the same power. The output transformer also has an air gap to prevent core saturation by the quiescent current of the output tube. As the amplifier operates in single-ended mode, the ripple voltage on the supply line is not suppressed, so more attention must be given to the design of the high voltage supply than with a push-pull amplifier. A choke is often used to achieve the necessary result. In many cases the filament is used as the cathode, which means that the filament supply must be especially clean. The efficiency of an SE triode output stage is approximately 25%, in contrast to push-pull stages, which can achieve efficiency figures up to 75%. From all this, it is clear that you need a lot of iron in an SE amplifier and you have to work very carefully to get a bit of usable output power. Nevertheless, SE amplifiers are very highly regarded for their wonderful sound, and fortunately in the last while a good deal has been learned about why they work so well.

3.4.1 Harmonic distortion

Primarily second harmonic, which is always dominant. See figure 3.9.

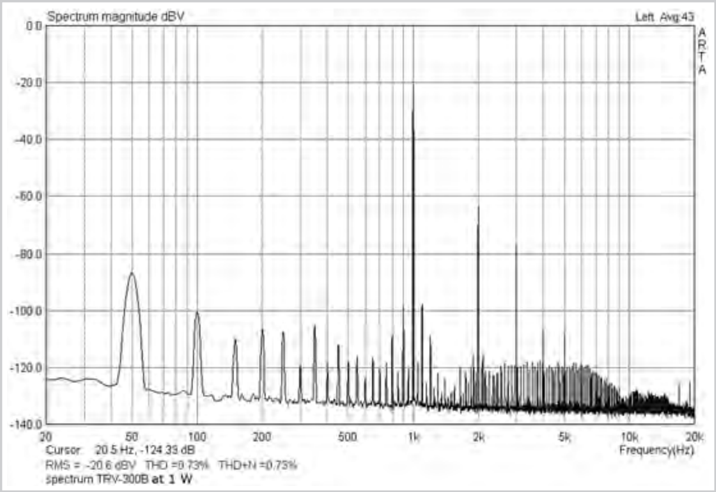


Figure 3.9: The second harmonic is dominant in SE amplifiers.

3.4.2 Constant load on the power supply

Unless an SE amplifier is overdriven, it draws a current varying from 0 to $2 \cdot I_0$, where I_0 is the quiescent current. The average current from the power supply is I_0, which effectively means that the current demand is constant.

3.4.3 Sensitivity to supply ripple

Chokes are commonly used in power supplies for SE amplifiers. They have a reasonably low resistance to DC current and a high impedance to AC current ($2 \cdot f \cdot L_{choke}$). The high impedance of the choke provide good suppression of the higher-order harmonics of the AC mains frequency. I don't have a figure to illustrate this, so instead I present figure 3.10 on the next page with a measurement made on a version of my UL40-S2 amplifier with a choke placed in the supply line to see what effect it would have. Note the absence of higher-order harmonics of the AC powerline frequency.

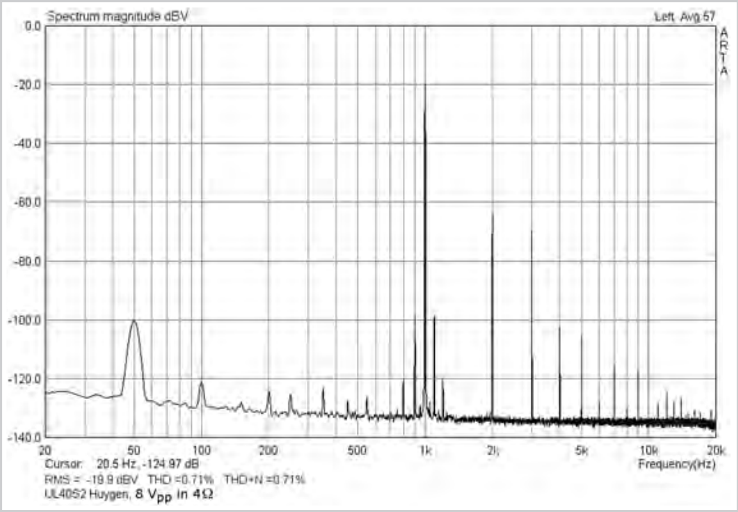


Figure 3.10: The choke filters out the higher-order harmonics of the AC grid voltage.

The next figure shows a measurement made with a genuine 300B SE amplifier with a choke, which nevertheless has substantial higher-order AC mains harmonics. Where do they come from?

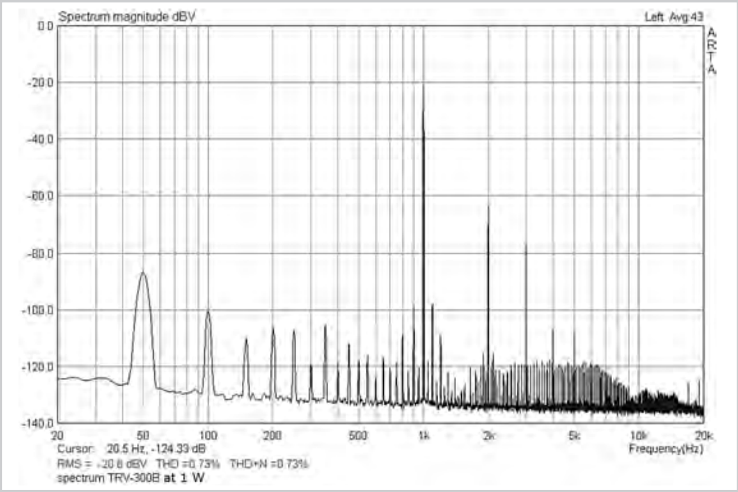


Figure 3.11: AC grid harmonics present despite the use of a choke.

In this case the harmonics come from the filament of the 300B output tube, which is powered by a rectified 5 V AC supply. This example shows that additional attention is needed here, such as powering the filament from a constant-current source (see *www.tentlabs.com*).

With regard to designing capacitor-choke-capacitor (CLC) power supplies, I recommend visiting the website of Ben Duncan, who has developed handy

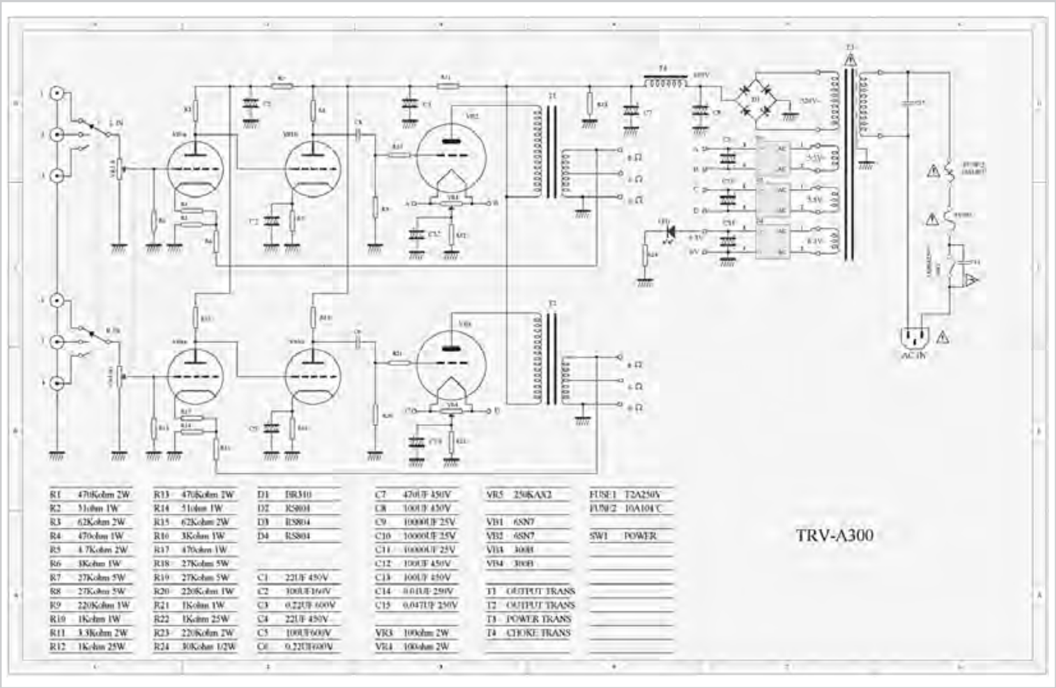


Figure 3.12: Example of a 300B amplifier. The filaments are powered by a rectified voltage, which contains a lot of higher-order AC mains harmonics.

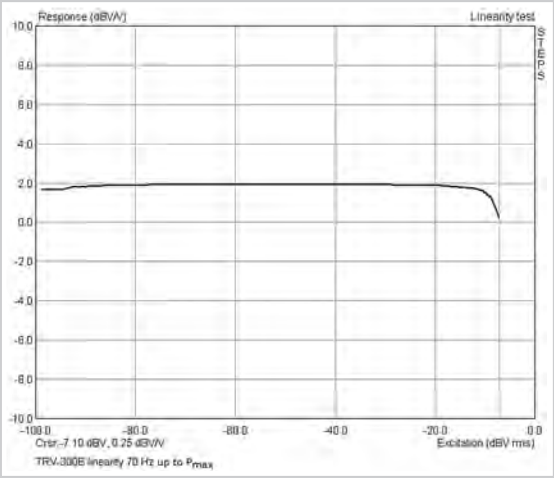
programs for this. In my own research I am now devoting attention to electronic equivalent circuits for chokes, since chokes produce fairly strong leakage fields due to their air gap and these fields can cause problems elsewhere in the circuit.

3.4.4 Microdetail reproduction

Single-ended output tubes usually have low impedance and therefore do not have much trouble driving the output transformer. The output transformer has an air gap, which has a more dominant effect than the variation in the permeability (mobility of the Weiss domains). This means that the primary inductance of the output transformer is constant and is independent of the signal level.

The measurement of figure 3.13 on the next page illustrates this (and also shows the drop in gain shortly before the point where the output tube starts clipping). Also note that I made this linearity measurement at 70 Hz. This is an ideal frequency, right in the middle of the range where deviations in detail reproduction can occur.

Figure 3.13: The air gap in the output transformer of an SE amplifier yields outstanding microlinearity. Note the limiting effect shortly before the clipping level.



3.5 Voltage drive versus current drive

Output tubes must transfer their power to the output transformer. The output tubes can be configured as current sources, as voltage sources, or somewhere in between. This has quite a few consequences for the frequency range, distortion, reproduction of microdetails and the damping factor. They are discussed in this section.

3.5.1 Voltage drive

The output tube is configured as a voltage source, which means that its internal anode resistance is as low as possible. This can be attained by: (a) using a triode or a pentode wired as a triode; (b) using local negative feedback to the cathode (by connecting it to an extra winding on the output transformer); (c) using local negative feedback from the anode to the control grid (ST circuit).

All of these options drastically reduce the internal anode resistance of the output tube. The anode(s) of the output tube(s) is/are connected to the primary winding of the output transformer. Along with its primary inductance and the winding resistances R_{ip} and R_{is}, the output transformer has another two properties that limit its frequency range: the primary capacitance C_{ip} and the primary leakage inductance L_{sp}. For example, see the equivalent circuit sketched in figure 3.14 of my VDV-6040 toroidal transformer.
The effect of C_{ip} is negligible because the internal anode resistance of the output tubes is low and effectively shorts out C_{ip}, so the effect of L_{sp} is dominant. The combination of L_{sp} and the internal anode resistance forms a first-order low-pass

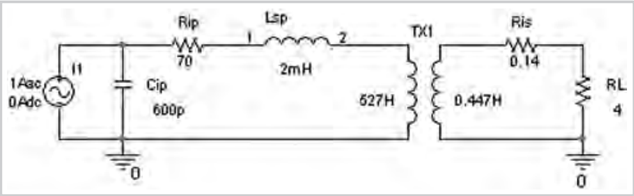


Figure 3.14: Equivalent circuit of the VDV6030 toroidal output transformer.

filter, which will exhibit stable behaviour even in the presence of negative feedback (Vanderveen approach).
The low internal anode resistance yields a high damping factor and excellent reproduction of microdetails.

3.5.2 Current drive

If the output tubes are configured as pentodes or fitted with cathode resistors that are not bridged by electrolytic capacitors, the internal anode resistance of the output tubes increases dramatically. They then act essentially as current sources with virtually infinite internal anode resistance. In this case the output tubes interact primarily with the primary capacitance (C_{ip}) of the output transformer, with which they form a first-order filter that also remains stable even in the presence of strong negative feedback if it is intelligently configured (Putseys approach). With this configuration the damping factor is low and the reproduction of microdetails is not optimal. Supplementary overall negative feedback is necessary to correct this.

3.5.3 Combined current and voltage drive

In practice the most common situation is that the output tubes have a reasonably high internal anode resistance, resulting in a combination of voltage and current drive – i.e. somewhere in the middle. This means that the output tubes interact with both C_{ip} and L_{sp}, resulting in a second-order filter effect. This filter has disastrous consequences with negative feedback because at some point it produces a 180-degree phase shift, converting the negative feedback into positive feedback. The result is an oscillator. I already mentioned that you need an extra first-order filter (with a lower corner frequency) in order to comply with the applicable stability criteria. Then the damping factor will still be reasonable, as will the reproduction of microdetails.

3.5.4 Recommendations

The above extremely concise description of the consequences of current or voltage drive is not something you encounter very often. Thanks to the good work of

Bart van der Laan, who studied this topic for his graduate thesis, we now have more insight into the consequences of the various approaches. In light of the fact that designers have the choice of voltage drive or current drive, I considered it desirable to include this brief discussion of some of the effects of this choice.

3.6 Alternative circuits

There's not enough space here to mention them all. The Internet is full of other circuit topologies, including PPP, bridge circuits, Circlotron and Joe Rasmussen's approach with a constant current power supply instead of a voltage supply, and so on. Fortunately most designers explain their own inventions enough to enable others to adopt them for their own use.