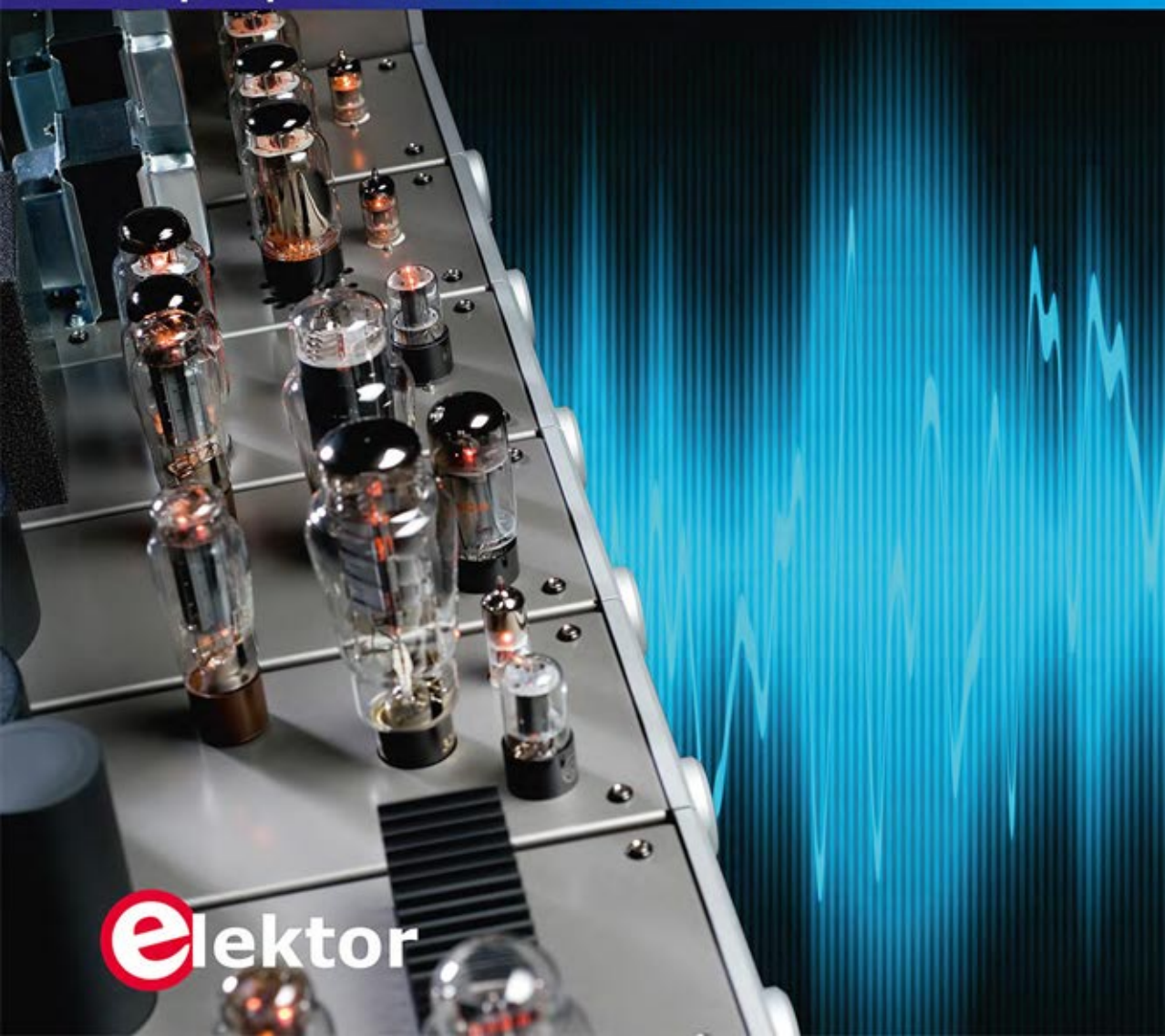


Menno van der Veen

# Designing Tube Amplifiers

concept, implementation and assessment



**e**lektor

# Table of Contents

Introduction	11
About the author	12
<b>1 Definition of objectives and requirements</b>	<b>15</b>
1.1 Output power	15
1.1.1 Power hunger and cost	15
1.1.2 Take a lesson from the Japanese	16
1.1.3 It all happens at 1 W or less	16
1.1.4 Tube amplifiers sound louder than transistor amplifiers	17
1.1.5 Power and amplifier class	17
1.1.6 The loudspeaker as the crucial factor	18
1.2 Frequency range	18
1.2.1 The range of the human ear	18
1.2.2 Frequency range and negative feedback	20
1.2.3 Frequency range and phase characteristics	20
1.3 Power range	21
1.3.1 High-frequency power range	21
1.3.2 Low-frequency power range	21
1.4 Input sensitivity and amplification factor	22
1.4.1 Amplification factor of the power amplifier	22
1.4.2 Amplification factor of the preamplifier	22
1.4.3 A nice volume control	22
1.4.4 Input impedance	23
1.5 Damping factor	23
1.5.1 Electrostatic versus dynamic speakers	23
1.5.2 Direct effects of the damping factor	24
1.6 Distortion	24
1.6.1 Harmonic distortion	24
1.6.2 Intermodulation distortion	26
1.6.3 Other types of distortion	27
1.7 Coherency	27

<b>2</b>	<b>Relationship between subjective and objective goals</b>	<b>29</b>
2.1	Hearing direction	29
2.2	Hearing details	29
2.3	Acoustic balance	31
2.4	Depth reproduction	33
2.5	Intermezzo	33
2.6	Forward reproduction	34
2.7	Immersion	34
2.8	Structure of the recording field	34
2.9	Involvement and attention	35
2.10	Summary	35
<b>3</b>	<b>Circuits and their consequences</b>	<b>37</b>
3.1	Push-pull amplifiers	37
3.1.1	Push-pull pentode	38
3.1.2	Ultra-linear	38
3.1.3	Push-pull triode	38
3.2	Enhanced push-pull	38
3.3	Typical characteristics of push-pull amplifiers	39
3.3.1	Distortion	39
3.3.2	Gain constancy and DDFD	40
3.3.3	Reproduction of microdetails	41
3.3.4	Supply modulation	41
3.3.5	Constancy and equality of quiescent currents	41
3.4	Single-ended amplifiers	42
3.4.1	Harmonic distortion	43
3.4.2	Constant load on the power supply	43
3.4.3	Sensitivity to supply ripple	43
3.4.4	Microdetail reproduction	45
3.5	Voltage drive versus current drive	46
3.5.1	Voltage drive	46
3.5.2	Current drive	47
3.5.3	Combined current and voltage drive	47
3.5.4	Recommendations	47
3.6	Alternative circuits	48
<b>4</b>	<b>Consequences for amplifier components</b>	<b>49</b>
4.1	Power supply	49
4.1.1	Power supplies for SE amplifiers	49
4.1.2	Power supplies for PP amplifiers	50

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4.2	Output stages	51
4.3	Phase splitters	52
4.3.1	Split-load	52
4.3.2	Phase inverter	53
4.3.3	Long-tailed pair	53
4.3.4	Transformer phase splitter	54
4.4	Driver stages	54
4.5	Preamplification	56
<b>5</b>	<b>Amplifier details</b>	<b>57</b>
5.1	Push-pull amplifiers	57
5.1.1	PR20HE	57
5.1.2	Le Miracle	60
5.1.3	UL40-S2	61
5.1.4	A simpler SPT amplifier	65
5.1.5	Amplifier with variable damping factor	67
5.1.6	High power amplifier for bass guitar	68
5.2	SE amplifiers	70
5.2.1	SE design by Bert Fruitema	70
5.2.2	SE design by Ari Polisois	72
<b>6</b>	<b>Negative feedback</b>	<b>75</b>
6.1	Negative feedback and nonlinearity	75
6.2	What signal is the amplifier busy with?	77
6.3	What is the effect of the time delay in the amplifier?	78
6.4	Negative feedback and harmonics	80
6.5	Negative feedback and coloration	80
6.6	Negative feedback and stability	81
6.7	Feedforward (error correction)	81
<b>7</b>	<b>Building the prototype</b>	<b>85</b>
7.1	Starting with a PCB restricts you too much	85
7.2	Sequence of operations	85
7.3	Earthing and grounding	85
7.4	Start with no negative feedback	86
7.5	Internal feedback	86
7.6	Logistics	86
7.7	Measure each stage separately	86
7.8	Measure the overall amplifier from input to output	86
7.9	Stability	86

7.10	Listening	87
7.11	The loop	87
7.12	What comes next	87
<b>8</b>	<b>Business approach</b>	<b>89</b>
8.1	Time investment	89
8.2	Hardware investment	89
8.3	Sales channels	89
8.4	Potential sales volume	90
8.5	Middlemen	90
8.6	Time scale	90
8.7	Designer or businessman?	90
8.8	Advertising	90
8.9	Unique features and innovations	91
8.10	Your image	91
8.11	Service and support	91
8.12	Project lifetime and follow-up activities	91
8.13	What about partners?	92
8.14	The state of the economy	92
8.15	What does the competition do?	92
8.16	Only in your home country, or all over the world?	92
8.17	What does it all cost?	93
8.18	Premises	93
8.19	Summary	93
<b>9</b>	<b>Holistic approach</b>	<b>95</b>
9.1	What does your heart tell you?	95
9.2	Thinking and acting in spheres	96
9.3	Your own personality	98
9.4	The adventure	99
<b>10</b>	<b>Introduction to measurements</b>	<b>101</b>
10.1	Analog test equipment	101
10.2	Measuring with a PC	102
10.2.1	Audio signal generator	103
10.2.2	ARTA analysis software	103
10.2.3	Digital oscilloscope	103
10.3	Test lab furnishings	104
10.3.1	Earthing and grounding	104
10.3.2	Emergency switch	104

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10.3.3	Attenuators	104
10.3.4	Overview	105
<b>11</b>	<b>Frequency domain measurements at 1 watt</b>	<b>107</b>
11.1	Introductory remarks on decibels	107
11.2	Measuring the -3 dB frequency range	110
<b>12</b>	<b>Frequency domain measurements at maximum power</b>	<b>115</b>
12.1	Maximum power of push-pull amplifiers at low frequencies	115
12.2	Maximum power of single-ended amplifiers at low frequencies	117
12.3	Maximum power limit at high frequencies	120
<b>13</b>	<b>Impedances</b>	<b>123</b>
13.1	Input impedance	123
13.2	Output impedance	125
13.2.1	Measuring the output impedance with the on/off method	125
13.2.2	Measuring the output impedance by driving the output	127
<b>14</b>	<b>Measuring amplifier gain</b>	<b>131</b>
14.1	Gain of input and driver stages	131
14.1.1	First disconnect the negative feedback	131
14.1.2	Measure with a 10× probe	131
14.1.3	Maximum output level of the input and driver stages	132
14.2	Gain of the output stage	132
<b>15</b>	<b>Distortion</b>	<b>135</b>
15.1	Watch out!	135
15.2	Analyzing harmonic distortion	137
15.2.1	Harmonic distortion as a function of frequency	137
15.2.2	Harmonic distortion as a function of amplitude	140
15.3	Intermodulation distortion	143
15.4	Measuring the output linearity	145
15.4.1	Viewing nonlinearity with a Lissajous measurement	145
15.4.2	Nonlinearity as a function of input voltage	146
<b>16</b>	<b>Measuring in the time and frequency domains</b>	<b>149</b>
16.1	Phase measurements	149
16.2	Impulse response	151
16.2.1	About the test signal	152
16.2.2	Viewing in the time and frequency domains	154

16.2.3	Viewing over an extended time	156
16.2.4	Time and frequency combined	158
<b>17</b>	<b>A new approach to measurement</b>	<b>161</b>
17.1	Where we stand	161
17.2	A new route?	162
17.3	Think different	164
17.4	Which route should we take?	165
<b>18</b>	<b>Appendix: reproduction of microdetails</b>	<b>167</b>
18.1	Introduction	167
18.2	The limits of our hearing	167
18.3	Structure of the microdetail model	169
18.4	Evidence for the microdetail model	175
18.5	The influence of the distance to the loudspeaker	176
18.6	The influence of the loudspeaker efficiency	177
18.7	The influence of the frequency characteristic of the loudspeaker	178
18.8	The influence of the primary impedance	178
18.9	The influence of the effective internal anode resistance	179
18.10	The influence of the air gap in the OPT core	180
18.11	The influence of the steel in the core	181
18.12	Discussion and conclusion	181
18.13	References	183
	Where to obtain the Vanderveen transformers, specialist modules and services	185

# Introduction

Prior to this book, I have written a large number of articles and papers and two other books.<sup>1,2</sup> 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



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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

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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.

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.



*Photo: Frans Paalman*

## 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<sup>1</sup> and on my website.<sup>2</sup> 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.

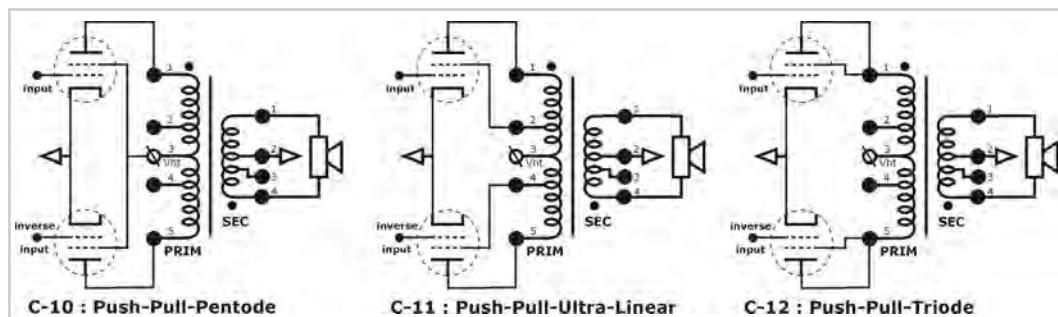


Figure 3.1: Three types of push-pull stage are possible with different screen grid connections.

1 Menno van der Veen: *High-End Tube Amplifiers 2*, Chapter 9, Elektor.

2 [www.mennovanderveen.nl](http://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 than 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.

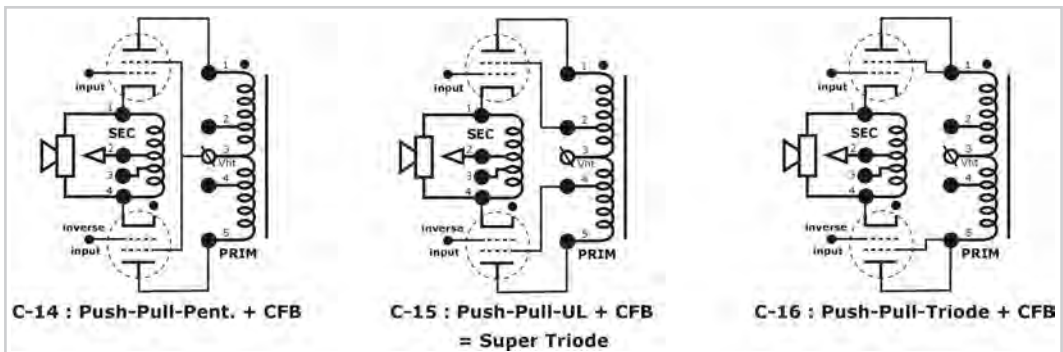


Figure 3.2: Supplementary negative feedback to the cathodes of the output tubes.

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

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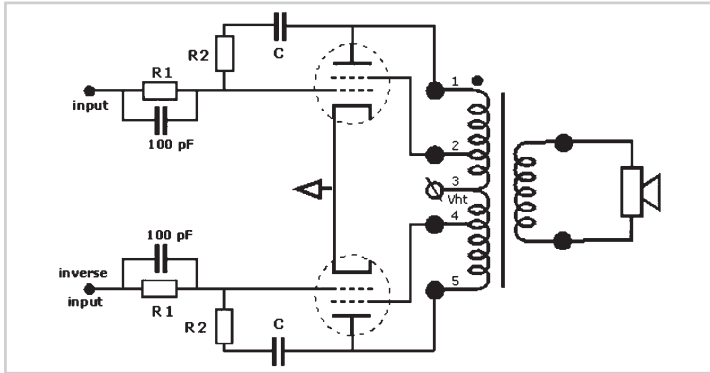


Figure 3.3:  
Vanderveen  
super triode circuit.

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.

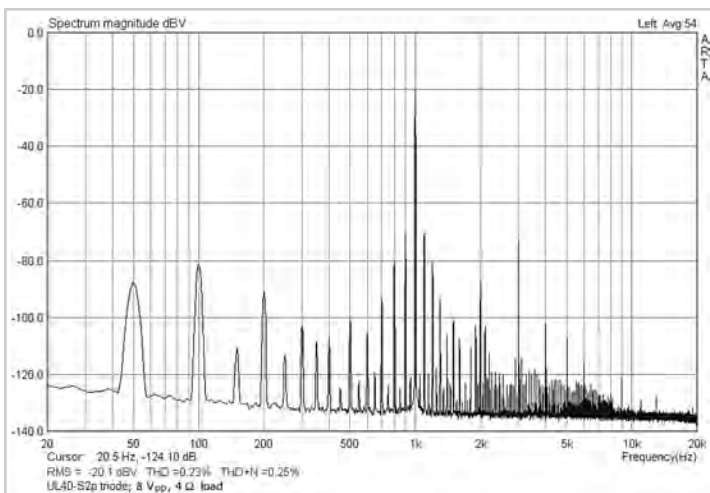
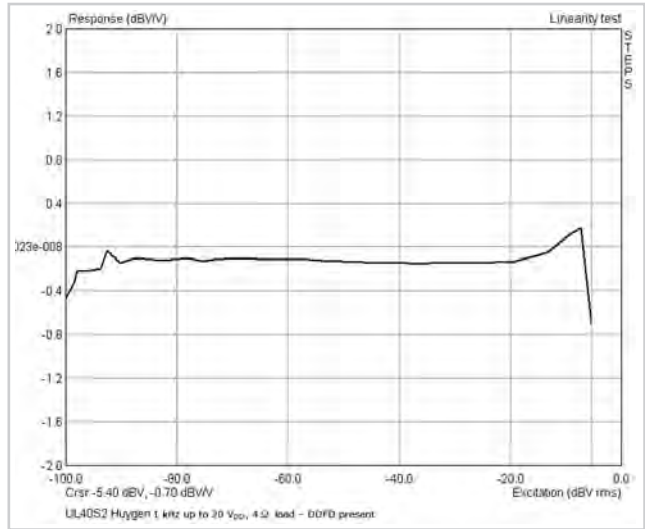


Figure 3.4:  
The third harmonic is  
dominant in the  
distortion products.

3.3.2 Gain constancy and DDFD

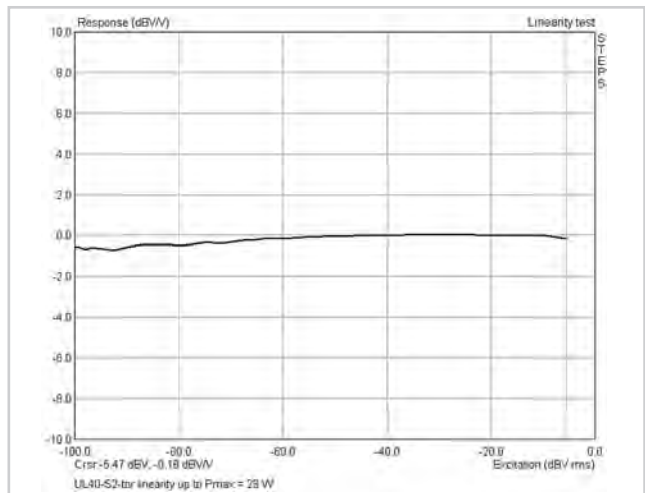
When a push-pull amplifier is operating in class AB, the output tubes are alternately cut off at high output levels. This has two effects: the amplification factor changes, and the effective output impedance of the amplifier changes. The following figure shows an example.

*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).*



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## 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.

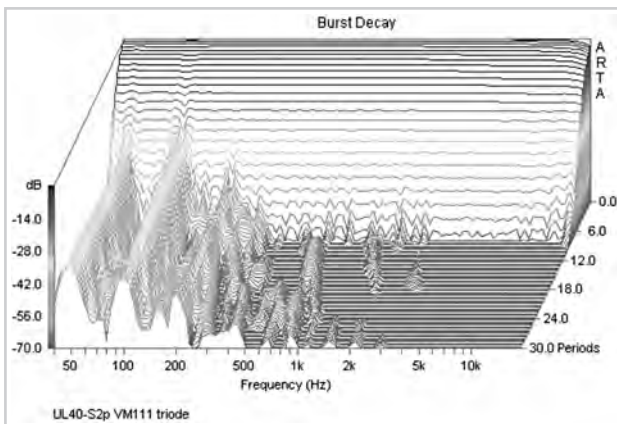


Figure 3.7:  
Supply modulation after a  
signal burst.

## 3.3.5 Constancy and equality of quiescent currents

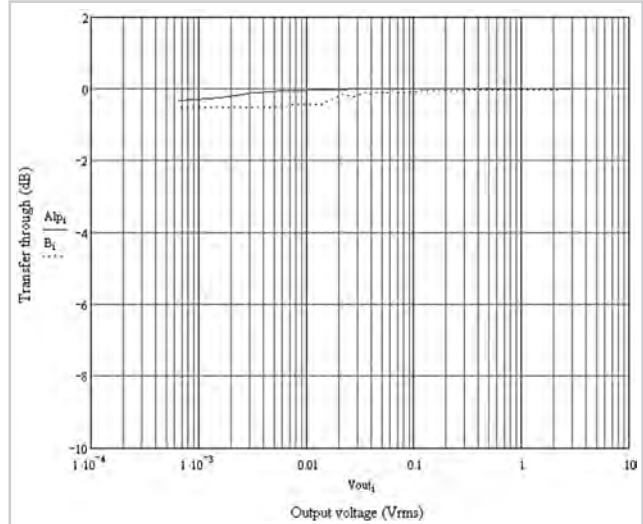
The quiescent currents of the output tubes must be set in some way or another to achieve a suitable balance between the optimal class A range and the lifetime of the output tubes. This can be done by using cathode resistors in parallel with electrolytic capacitors ( $R_k/C_k$  method), by using adjustable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

1 [www.mennovanderveen.nl](http://www.mennovanderveen.nl) – Tube amplifiers; Auto-bias largely improves base and microdetail reproduction.

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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 single 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

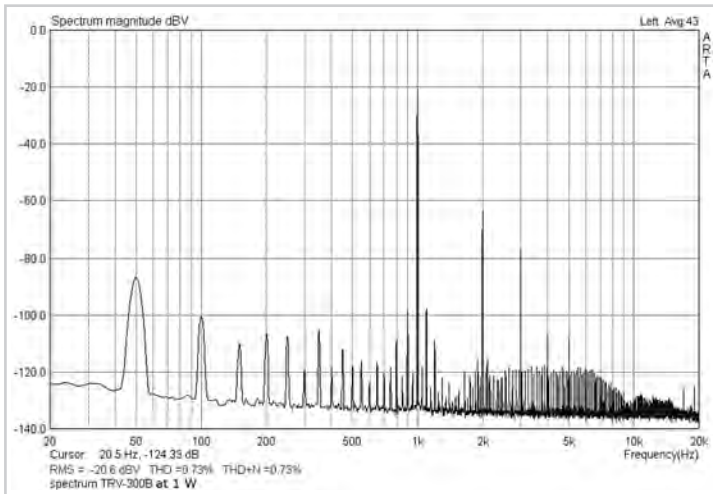


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figures up to 75%. From all this, it is clear that you need a lot of iron in an SE amplifier and you have to work very carefully to get a bit of usable output power. Nevertheless, SE amplifiers are very highly regarded for their wonderful sound, and 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.*

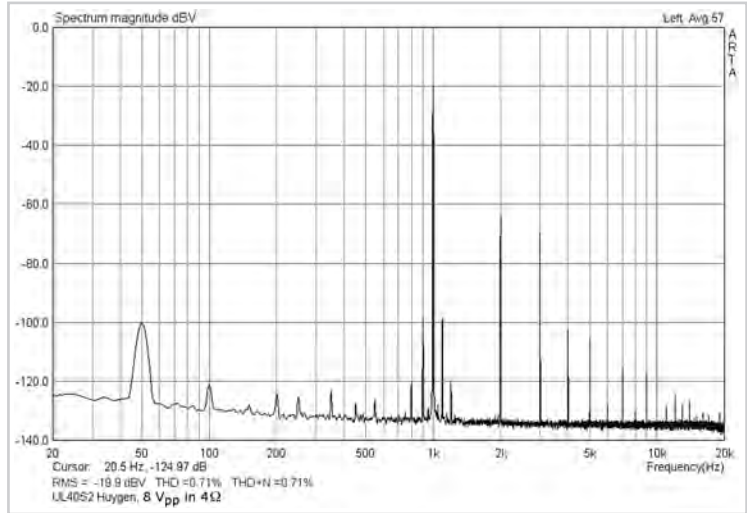
### 3.4.2 Constant load on the power supply

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

### 3.4.3 Sensitivity to supply ripple

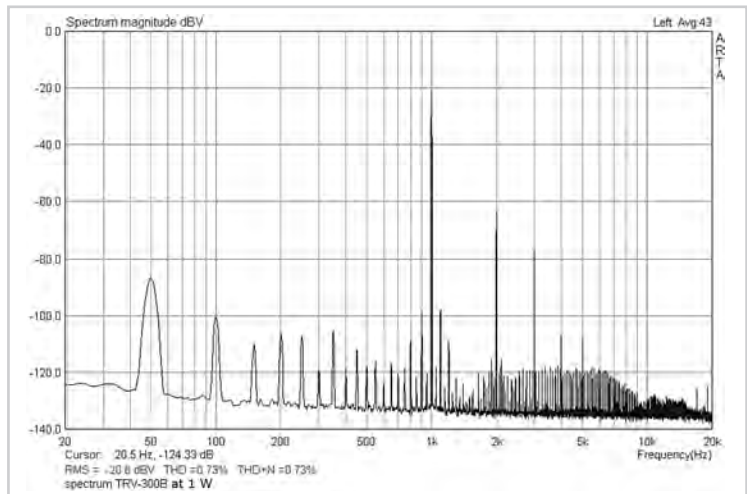
Chokes are commonly used in power supplies for SE amplifiers. They have a reasonably low resistance to DC current and a high impedance to AC current ( $2 \cdot f \cdot L_{\text{choke}}$ ). The high impedance of the choke provide good suppression of the higher-order harmonics of the AC mains frequency. 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.

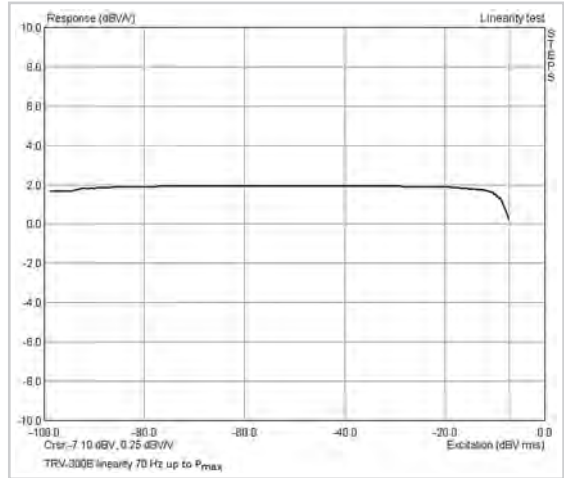


In this case the harmonics come from the filament of the 300B output tube, which is powered by a rectified 5 V AC supply. This example shows that additional attention is needed here, such as powering the filament from a constant-current source (see [www.tentlabs.com](http://www.tentlabs.com)).

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



**Figure 3.13:**  
*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

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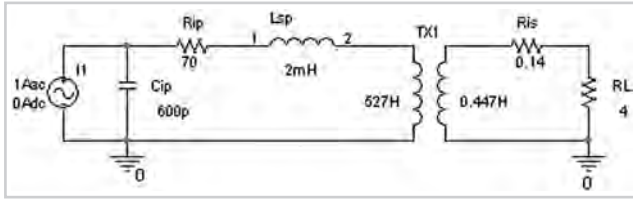


Figure 3.14:  
Equivalent circuit of the  
VDV6030 toroidal output  
transformer.

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

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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.