



The Ultra-Linear Power Amplifier

An adventure between triode and pentode

Rudolf Moers

1 Introduction

In 1951, David Hafler and Herbert Keroes introduced a pentode power amplifier, in which a tap of the primary transformer winding was connected to the screen grid of the power pentode [2]. They called this the Ultra-Linear power amplifier. This power amplifier shows the advantages of a triode, low anode AC internal resistance and low distortion, as well as the advantages of a pentode, large delivered anode AC power and good efficiency. The narrative given by David Hafler and Herbert Keroes is good and substantiated in practice; this is very important.

What I personally missed in their narration is a theoretical explanation of the operation of the ultra-linear circuit. I have several electronics books including the well known seven parts of the electron tube book range, written by scientists of the Philips Gloeilampenfabrieken Company at Eindhoven in the Netherlands. I also have all the electronics books of the company school written by A.J. Sietsma. In none of these books did I find a theoretical explanation of the operation of the ultra-linear circuit. I do not suggest that such an explanation does not exist; I just have not been able to find it. Therefore I went on an adventure between triode and pentode myself. In this adventure, theory will be checked against practice.

Opgave 5

Gegeven:

$$\begin{aligned} R_t &= 50 \text{ k}\Omega; S = 12\frac{1}{2} \text{ mA/V}; \\ \mu_{g2g1} &= 15; S_2 = 2,5 \text{ mA/V}; \\ n_1 : n_2 : n_3 &= 40 : 1 : 15; R_{isp} = 7,5 \Omega. \end{aligned}$$

Gevraagd:

1. Bereken $\frac{v_a}{v_t}$ indien men de eindtrap niet tegenkoppelt (d.w.z. g_2 ligt dan aan punt A).
2. Bereken $\frac{v_a}{v_t}$ indien men de eindtrap wel tegenkoppelt (zoals in het gegeven schema).
3. Welke soort tegenkoppeling treedt er hier op?
Opmerking: zie blz. 343, opgave 18.

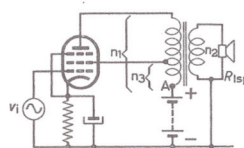


Figure 1. Homework exercise from the great book from 1959 by A.J. Sietsma [3].



When doing research for my book [1], I was pleasantly surprised to find the homework exercise of **figure 1**. Unfortunately, it is in Dutch but you should be able to understand the circuit.

Philips never published information concerning ultra-linear power gain because they never produced such an amplifier. I contacted Sietsma about the why and how of this homework exercise, but he is too old to be able to answer. His son told me that his father used to make up all homework exercises himself. He probably wanted to check the knowledge of his students concerning “screen grid negative feedback” which is the technical name for the marketing name Ultra-Linear.

It was this homework exercise which motivated me to do a close investigation of the ultra-linear power amplifier. Thanks to Sietsma I developed my own network analysis of the circuit, which he probably also did, although it was never published. Using my own network analysis method I solved this exercise in 2006, and achieved the same results as Sietsma. During the European Triode Festival (ETF) 2010, I presented a paper on this subject and for an extended narration I recommend reference [1].

2 An adventure between triode and pentode

You seldom encounter a single ended ultra-linear power amplifier. In principle, it is very well possible to construct one, but I do not know whether these power amplifiers perform satisfactorily. However, the single ended ultra-linear power amplifier is very suitable to explain the Ultra-Linear concept. We will see later that a *separate* explanation of the push pull ultra-linear power amplifier in classes A, B and AB with their calculations of powers and efficiencies is not required. This seems too good to be true, but I will show it to be so. In **figure 2** we have the single ended topology with anode AC external resistance r_a . The related anode characteristics $I_a = f(V_{ak})$ with the $V_{g1,k}$ -curve which lies halfway inside the control grid base are also given (see sidebar for explanation of terms and symbols). This is the most favorable working point because we are then in the middle of the upper and lower bends of the anode static/dynamic transconductance $I_a = f(V_{g1,k})$. We must avoid these bends because of the distortions they cause. The triode connection gives $V_{g2,k} = V_{ak} \neq \text{constant}$ and the pentode connection gives $V_{g2,k} = V_b = \text{constant}$. The reason that both anode characteristics are not linear is also visible with the related Child-Langmuir equations above in the anode characteristics of figure 2.

With the triode connection, we see a faint concave curvature. With the pentode connection, we see a steep convex curvature and after the knee it changes into an almost horizontal flat line. Anticipating what will come later, an x -coordinate is shown along the primary winding of the output transformer. The transformer terminal connected to V_b is the point where $x = 0$. Because V_b is a short circuit for AC currents, we can say that $x = 0$ = grounded. The terminal of the transformer connected to the anode is where $x = 1$. Scale x is divided linearly along the primary transformer winding.

What would we do, if we would want a linear anode characteristic in the form $I_a = k_{ultralinear} V_{ak}$?

If the triode and pentode anode characteristics are *concave* and *convex* respectively, we can then imagine that between *concave* and *convex* there is a *linear compromise*. Screen grid g_2 connected to the anode makes the anode characteristic *concave* and connected to V_b makes the anode characteristic *convex*.

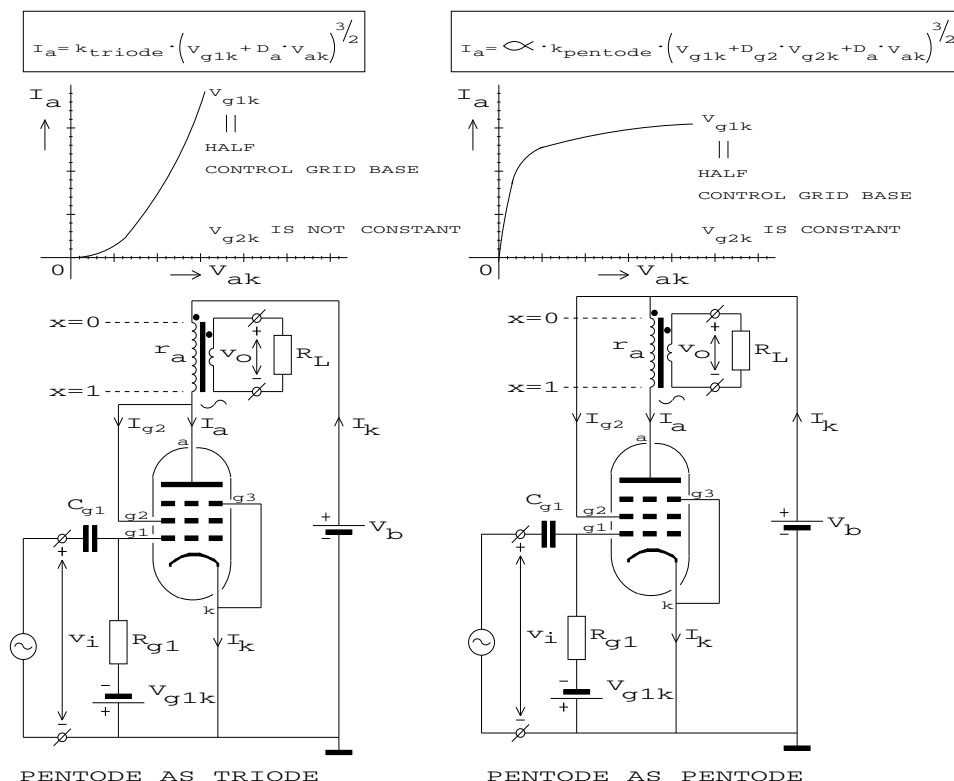


Figure 2. Pentode as triode and pentode as pentode in a power amplifier.

Thus, it is obvious that the connection of screen grid g_2 to the primary transformer winding, somewhere in between the anode and V_b , will give a more linear anode characteristic and that is shown in **figure 3**.

The impedance between the screen grid primary transformer tap x and V_b is called $x \cdot r_a$ and the impedance between this tap and the anode is called $(1-x) \cdot r_a$. Because V_b is a short circuit for AC currents, we can say that screen grid cathode AC voltage $v_{g2,k}$ is a tap of anode cathode AC voltage v_{ak} . The screen grid cathode DC voltage $V_{g2,k}$ still applies to the screen grid, but from here on, screen grid cathode AC voltage $v_{g2,k}$ is superimposed. $(V_{g2,k} + v_{g2,k})$ changes dynamically and because of this, the attractive force on the electrons in the electron cloud around the cathode changes dynamically. The screen grid behaves slightly adversely as does the anode with triodes, but with a less attractive force than in a real triodes.

You can also see this in the pentode equation: $i_a = S \cdot \left(v_{g1,k} + \frac{v_{g2,k}}{\mu_{g2,g1}} + \frac{v_{ak}}{\mu} \right)$ see reference [1]

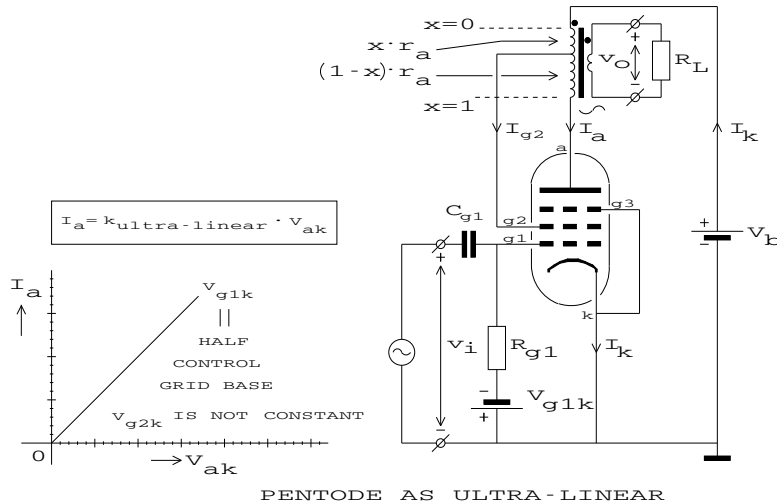


Figure 3. Pentode as ultra-linear power amplifier.

Because μ is large for pentodes, the factor v_{ak}/μ can be neglected. In addition, as long as the screen grid is decoupled by a C_{g2} or by an external voltage source $V_{g2,k}$, then $v_{g2,k} = 0$ and due to this factor, $v_{g2,k}/\mu_{g2,g1} = 0$. However, $v_{g2,k} \neq 0$ and $\mu_{g2,g1}$ is not large thus factor $v_{g2,k}/\mu_{g2,g1}$ can no longer be neglected and gives a significant contribution to anode AC current i_a . Output signals v_{ak} and $v_{g2,k}$ are opposite in phase to the input signal $v_{g1,k} = v_i$ and counteract anode AC current i_a . This is a classic case of *voltage negative feedback*. Figure 3 also shows the linear anode characteristic $I_a = f(V_{ak})$ and again with the $V_{g1,k}$ -curve which lies halfway inside the control grid base. Once again, this is the most favorable working point because here we are in between the upper and lower bends of the anode static/dynamic transconductance $I_a = f(V_{g1,k})$. Thus, the constant $k_{\text{ultra-linear}}$ is a real constant, and independent of $V_{g2,k}$ and V_{ak} . When we neglect the primary transformer copper resistance ($R_p = 0$), we can say $V_b = V_{ak} = V_{g2,k}$. We will see later that $v_{g2,k}$ is almost equal to $x \cdot V_{ak}$. This equation seems obvious, but

is not fully correct, although in practice it can be applied without large errors. I will come back to this issue later.

The next question is, at which screen grid tap or for which value of x do we get a linear anode characteristic? **Figure 4** shows the answer: for $x = 0.4$.

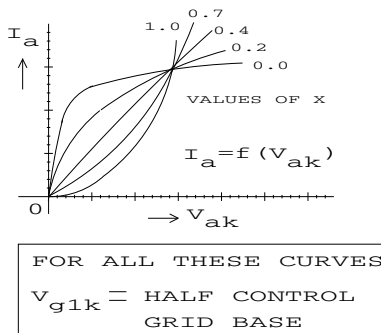


Figure 4. Dynamic ultra-linear anode characteristic $I_a = f(V_{ak})$ with x as parameter.



The value $x = 0.4$ is an “average opinion” of the manufacturers of output transformers and electron tubes. Some of them use $x = 0.33$ as an “average opinion”. Actually, x is different for each type of electron tube, sometimes on each specimen of one type. So what is the ideal value of tap x for a certain application? You must be pragmatic in this situation, because what if the ideal value would be $x = 0.38$? Should we then get a specific output transformer for this value? Or can we make do with an output transformer with several taps to choose $x = 0.30$, $x = 0.35$ or $x = 0.40$? All these taps do not contribute to the transformer bandwidth and other quality aspects. Maybe you should just choose $x = 0.4$ and accept that you don’t have an ideal linearity for each pentode specimen.

In section 5 of this article we will do a nice practical determination of x for a specific pentode specimen.

3 Power and efficiency

Figure 4 shows that we have a pentode behaving as a pentode for $x = 0.0$ and a pentode behaving as a triode for $x = 1.0$.

This corresponds with the x -values shown in figures 2 and 3. Additionally, all $V_{g1,k}$ -curves lie halfway inside the control grid base. How would it look for other $V_{g1,k}$ -curves? That can be seen in **figure 5**.

With a reasonable triode, see figure 5.a, curve $V_{g1,k} = 0$ goes through the origin of the anode characteristic. With a reasonable pentode, see figure 5.c, curve $V_{g1,k} = 0$ lies almost at the top of the anode characteristic. *Purely hypothetical*, imagine the screen grid tap is adjustable with a slider on the primary winding of a variable output transformer. When the slider moves from $x = 0$ to $x = 1$, the anode characteristic goes from pentode to triode, see figures 5.c and 5.a respectively. When the slider moves back to $x = 0.4$, you can see the situation of figure 5.b. Here, the $V_{g1,k}$ -curve which lies halfway inside the control grid base, goes through the origin of the anode characteristic and curve $V_{g1,k} = 0$ lies well above the origin. Even with an ideal triode, curve $V_{g1,k} = 0$ never lies above the origin. This gives great expectation and promise when we apply full-power drive to control grid g_1 .

Driving the control grid beyond $V_{g1,k} = 0$ is not desirable due to control grid current which must be avoided. We have the lowest drive level with v_{ap} (anode peak AC voltage) with the triode, because we are limited by curve $V_{g1,k} = 0$. We have the highest drive level with v_{ap} with the pentode, despite the limit of the knee which lies not far from the I_a -axis. With ultra-linear, the drive level with v_{ap} is significantly more than with the triode and is just slightly less with the pentode. The limit for ultra-linear is caused by the *constriction* of the $V_{g1,k}$ -curves.

In the ideal case of ultra-linear mode, the $V_{g1,k}$ -curves between 0 and halfway in the control grid base will end at the I_a -axis, and the $V_{g1,k}$ -curves between halfway in the control grid base and the complete control grid base will end on the V_{ak} -axis. Furthermore, curve $V_{g1,k} = \frac{1}{2} \cdot V_{g1,k0}$ will go straight through the origin of the anode characteristic. However, ideal pentodes do not exist; but we can recognize the following relationship: $V_{ap,triode} \ll V_{ap,ultra-linear} < V_{ap,pentode}$

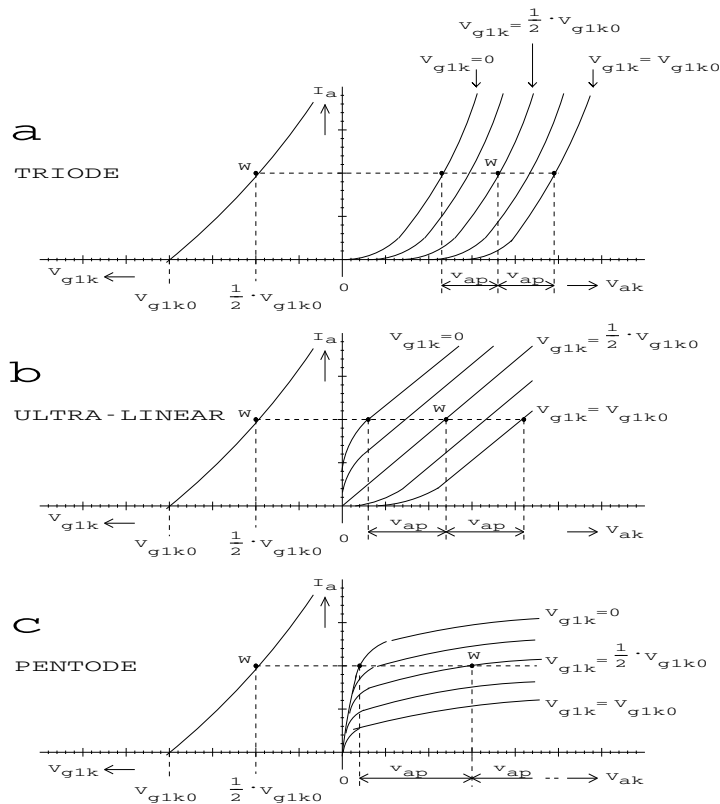


Figure 5. Comparison of the dynamic transconductance and dynamic anode characteristics for triode, ultra-linear and pentode mode.

Figure 6 from [6] shows the practical anode characteristics $I_a = f(V_{ak})$ of a KT88 pentode in triode, ultra-linear with $x = 0.4$ (40 % tap) and pentode mode. The lower right in figure 6 shows how the manufacturer specifies the ultra-linear anode characteristics $I_a = f(V_{ak})$ in practice. In this case, the $V_{g1,k}$ -curves lie between 0 V and -60 V. With some interpolation, the center curve $V_{g1,k} = -30$ V goes rather nicely through the origin. Curve $V_{g1,k} = 0$ V starts parallel on the I_a -axis and curves slightly horizontal at the top of the anode characteristic. Curve $V_{g1,k} = -60$ V lies almost flat against the V_{ak} -axis. The constrictions of all $V_{g1,k}$ -curves to the origin are not shown correctly. This part of the anode characteristic is probably different for each specimen, and moreover we must avoid drive levels in that v_{ap} range. Let us make a comparison between the distances of the curves $V_{g1,k} = 0$ and the I_a -axis for triode, ultra-linear and pentode mode (**table 1**):

Note: The vertical position of the $V_{g1,k}$ -curves in $I_a = f(V_{ak})$ depend on the magnitude of $V_{g2,k}$. For ultra-linear and for pentode this is similar.



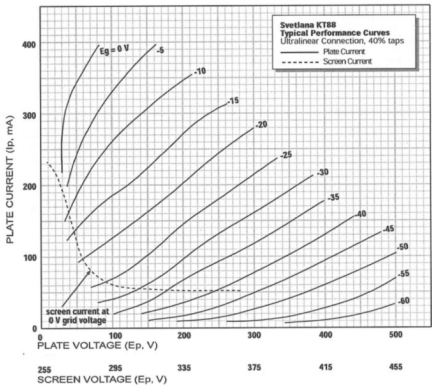
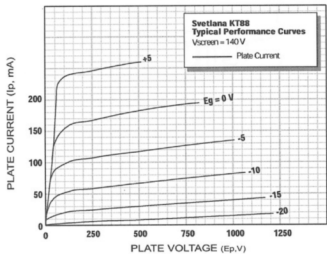
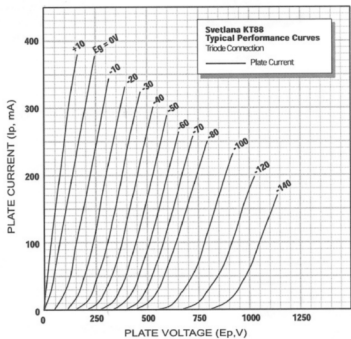
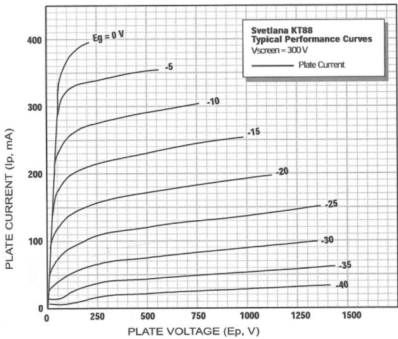
Triode	$V_{g2,k}=V_{ak} \ ; \ I_a=100\text{mA}$	$V_{g1,k} = 0 \text{ to } I_a\text{-axis:}$	75V
Ultra-Linear	$V_{g2,k}=276 \text{ V; } I_a=100\text{mA}$	$V_{g1,k} = 0 \text{ to } I_a\text{-axis:}$	30V
Pentode	$V_{g2,k}=300 \text{ V; } I_a=100\text{mA}$	$V_{g1,k} = 0 \text{ to } I_a\text{-axis:}$	20V

Table 1. Voltage distance between $V_{g1,k} = 0$ and the I_a -axis.

Svetlana KT88 High Performance Audio Beam Power Tetrode

Typical Operation Class A, (single tube)

DC plate voltage	400 V
Grid no.2 DC (screen) voltage	225 V
Grid no.1 DC (control) voltage	-16.5 V
Peak AF grid no.1 (control) voltage	16.5 V
Zero-signal plate current	87 mA
Max signal plate current	105 mA
Zero signal grid no.2 (screen) current	4 mAdc
Max signal grid no.2 (screen) current	18 mA
Transconductance	11.5 mA/Volt
Signal output	19 W



www.svetlana-tubes.com

Figure 6. KT88 Beam Power Tetrode in triode, ultra-linear ($x = 0.4 = 40\%$) and pentode mode.



Figure 7 shows the theoretical ideal versions of the practical figures 5 and 6. Anode AC peak voltage v_{ap} and anode AC peak current i_{ap} , which determine the delivered anode power, are smaller in triode mode than in ultra-linear mode. However, in pentode mode, anode AC peak voltage v_{ap} and anode AC peak current i_{ap} are equal to those in ultra-linear mode. This means that the *delivered anode power in ultra-linear mode is equal to the delivered anode power pentode mode*. This is very desirable. Furthermore, we can see that the $V_{g1,k}$ -curves in ultra-linear mode have the same linearity as the $V_{g1,k}$ -curves in triode mode. This too is very desirable.

Figures 7.b and 7.c show two “fictive rotation points”:

When we rotate all the $V_{g1,k}$ -curves of figure 7.b clockwise 45° we get figure 7.c.

When we rotate all the $V_{g1,k}$ -curves of figure 7.c counterclockwise 45° we get figure 7.b.

Once again, anode AC peak voltage v_{ap} and anode AC peak current i_{ap} are the same in ultra-linear mode and in pentode mode. Both modes have the same delivered anode power.

This means that we do not need to derive separate equations for ultra-linear mode; we can just take the results from the pentode case. This is applicable for single ended or push pull in classes A, B and AB, but only in theory, of course. How should we handle this in practice? We can not use the situation of figure 7, but we *can* use the situation of figure 6.

Earlier we saw that: $V_{ap,triode} << V_{ap,ultra-linear} < V_{ap,pentode}$

In reality, the mentioned “constriction” in ultra-linear mode is larger than the “knee area” of the pentode mode. We must not use these areas, to avoid non-linear distortions. Thus, if you want to calculate the delivered anode power in ultra-linear mode, first calculate the delivered anode power in pentode mode and decrease it by a certain factor. But how much should it be decreased?

It seems to me that an estimate of between 20 % and 30 % should be subtracted from the delivered anode power in pentode mode. Now where does your author get this insight?

In reference [4], some design examples are shown with the following results for output power:

Two EL34 with VDV6040PP transformer: $p_{triode} = 13 \text{ W}$, $p_{ultra-linear} = 33 \text{ W}$ and $p_{pentode} = 40 \text{ W}$

Four EL34 with VDV3070PP transformer: $p_{triode} = 30 \text{ W}$, $p_{ultra-linear} = 70 \text{ W}$ and $p_{pentode} = 80 \text{ W}$

Thus, the estimate of between 20 % and 30 % decrease seems reasonable. In addition, the delivered power in ultra-linear mode is quite sufficient for listening to in your living room. It is obvious that the efficiency of ultra-linear mode lies between the efficiencies of triode and pentode mode. In the practical section 7 of this article we will see that the power behavior and the efficiency of ultra-linear mode come closer to pentode mode than to triode mode.

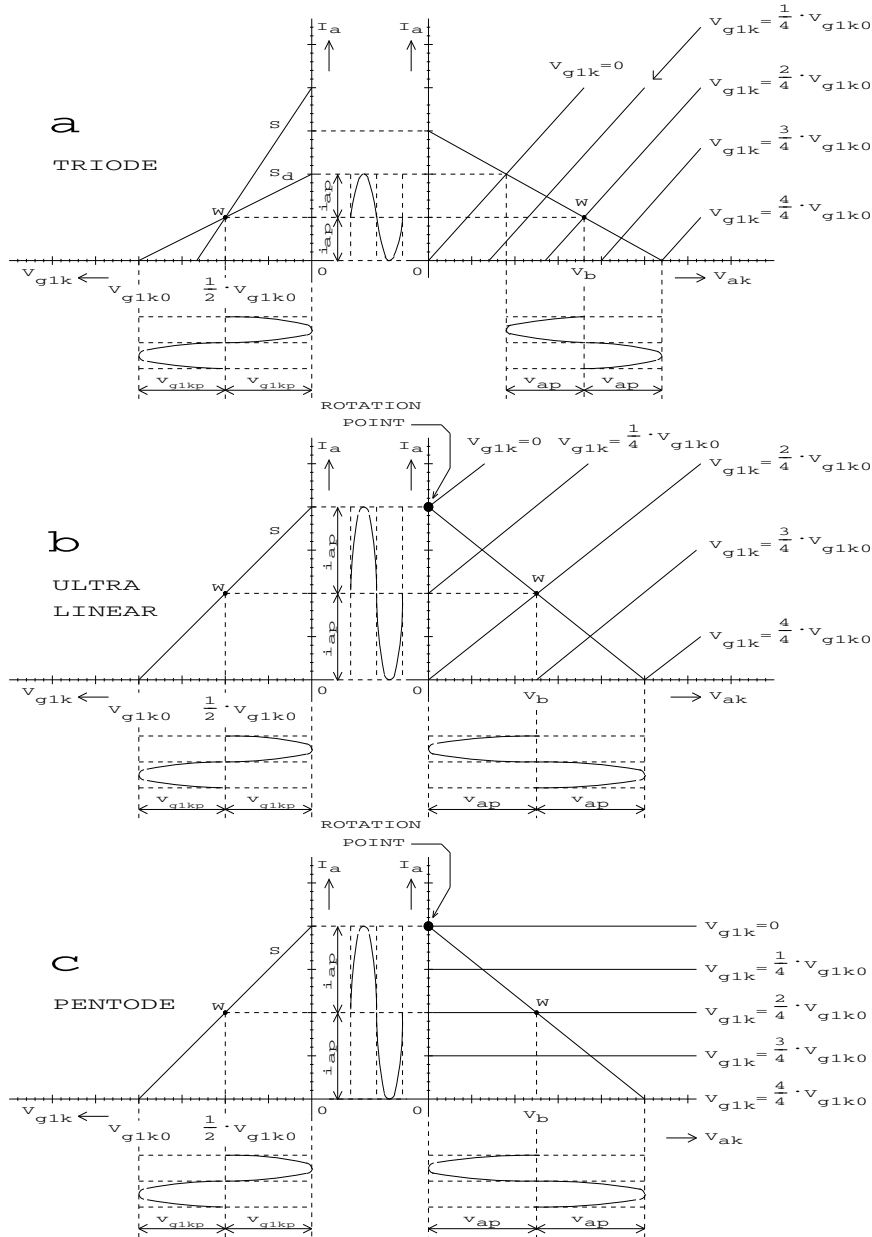


Figure 7. Comparison of the dynamic transconductance and the dynamic anode characteristics for an ideal triode, an ideal ultra-linear configuration and an ideal pentode.



Consider again the ultra-linear circuit of figure 3. My goal is to show you anode AC gain

of the screen grid tap position x on the primary transformer winding.

Before we apply a network analysis for the ultra-linear power amplifier, a review of the pentode characteristics and pentode quantities is necessary. Especially so because current manufacturers of pentodes deliver poor and inconsistent datasheets. One quantity has several names worldwide: conductance, transconductance, mutual conductance, slope, steilheid (Dutch) and steilheit (German) with symbol g , g_m and S . Another one is anode AC internal resistance which can be called r_i or plate resistance r_p or R_p or anode resistance r_a . It's important to have these definitions clear to understand the following narrative. I have listed the various expressions and symbols I use in this article in the sidebar.

Figures 8 and 9 show how the various pentode quantities can be determined from the pentode characteristics. There's nothing new here; you can find the same information in many vintage electronics books.

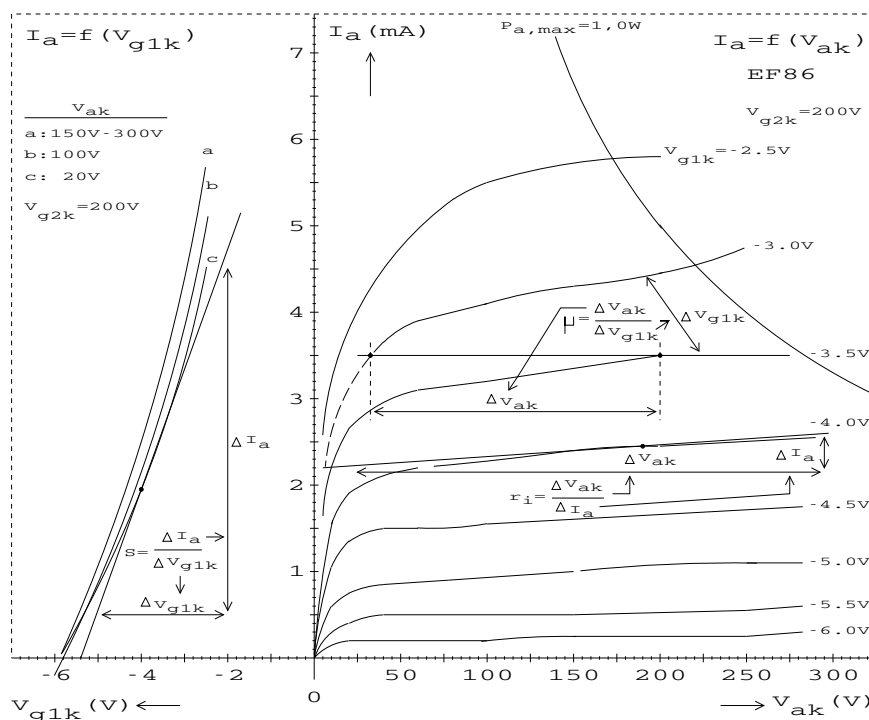


Figure 8. Determination of the anode quantities.

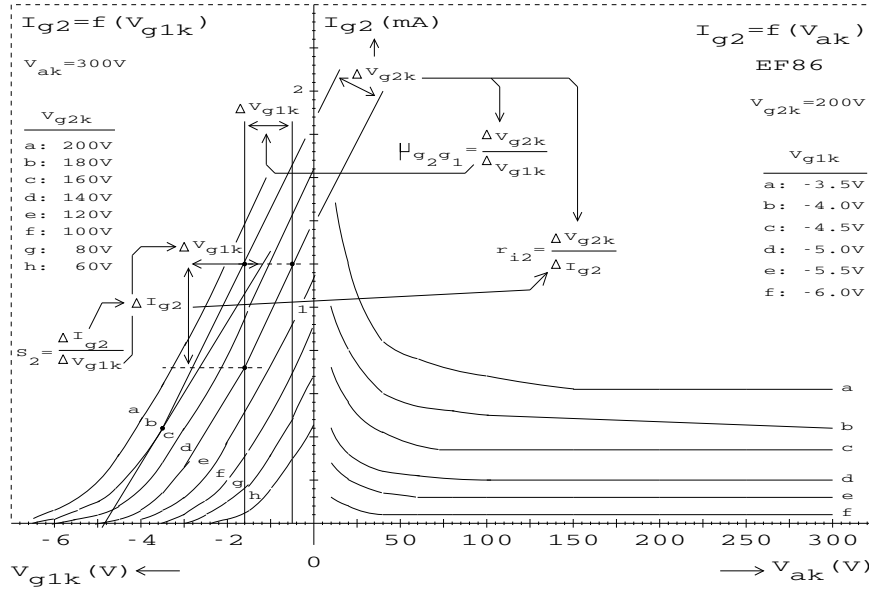


Figure 9. Determination of the screen grid quantities.

Figure 10 shows anode current I_a and screen grid current I_{g2} in one characteristic. We see that the cut-off points of both transconductance curves are positioned equally on the $V_{g1,k}$ -axis at a certain $V_{g2,k}$. So both control grid bases are equal: $\Delta V_{g1,k}$ for $S = \Delta V_{g1,k}$ for S_2

This gives $V_{g1,k} = \frac{\Delta I_a}{S} = \frac{\Delta I_{g2}}{S_2}$ and the relationship between anode current and screen grid current

$$\text{is: } I_{g2} = \frac{S_2}{S} \cdot I_a \quad \text{and} \quad i_{g2} = \frac{S_2}{S} \cdot i_a$$

We have already seen pentode equation:

$$i_a = S \cdot \left(v_{g1,k} + \frac{v_{g2,k}}{\mu_{g2,g1}} + \frac{v_{ak}}{\mu} \right)$$

But now we can see a second one:

$$i_{g2} = S_2 \cdot \left(v_{g1,k} + \frac{v_{g2,k}}{\mu_{g2,g1}} + \frac{v_{ak}}{\mu} \right)$$

You can now see the beginning of this section as an introduction for the next part of the narration and to recognize equations and symbols. From now on, in the rest of this section much will “fall from the sky” and normally I do not like that, but I do not want to bore you with equation derivation. In reference [1] all following mathematics are derived in small and easy steps. A piece of cake really, but now I will show you only the direction of the network analyses.

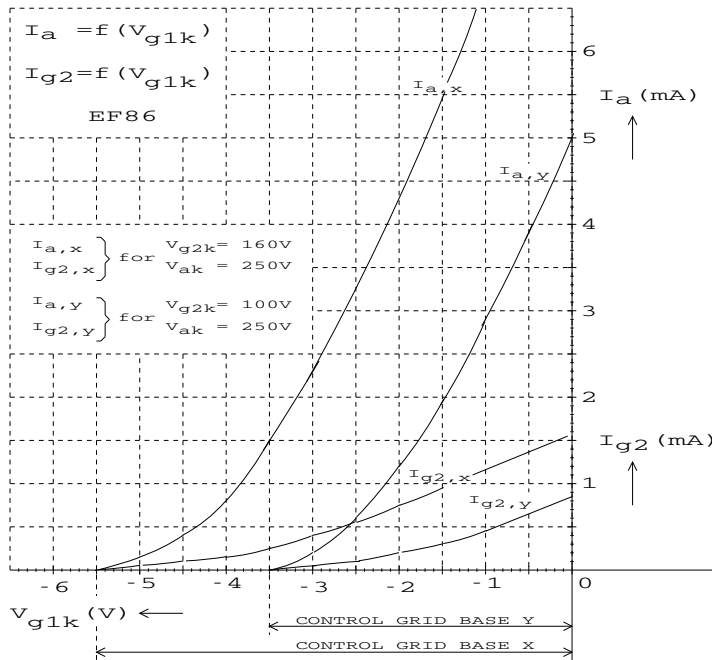


Figure 10. Anode DC current and screen grid DC current in a single steepness graph.

With help of both pentode equations and some mathematical tricks it is possible to obtain a *current source equivalent circuit* and a *voltage source equivalent circuit* for the pentode.

When we apply these equivalent circuits with an output transformer with screen grid tap, we then obtain the *current source equivalent circuit* and a *voltage source equivalent circuit* for the pentode as *ultra-linear power amplifier*.

These equivalent circuits have as original the circuit of figure 3, and are shown in **figure 11**.

We neglect the copper resistances of the transformer windings. Furthermore, we consider that transformer efficiency $\eta_{\text{transformer}} = 100\%$. Kirchhoff's first law is still $i_k = i_a + i_{g2}$ for AC and load resistor R_L is purely resistive. Using some mesh-network rules we can derive the important equation:

$$\frac{v_{ak}}{r_a} = -(i_a + x \cdot i_{g2}) = -i_{\text{total}}$$

Important note: total AC current i_{total} is not the same as cathode AC current i_k !

Anode AC current i_a and a fraction x of the of screen grid AC current i_{g2} deliver the primary power to anode AC external resistance r_a . This is really an algebraic approach. The approach from figure 11 is as follows:

i_a and i_{g2} together are active in the primary part $x \cdot r_a$ and i_a alone is active in primary part $(1 - x) \cdot r_a$.

What we do algebraically is to define a total AC current i_{total} which flows through the total anode AC external resistance r_a and which does not 'see' the tap to the screen grid.

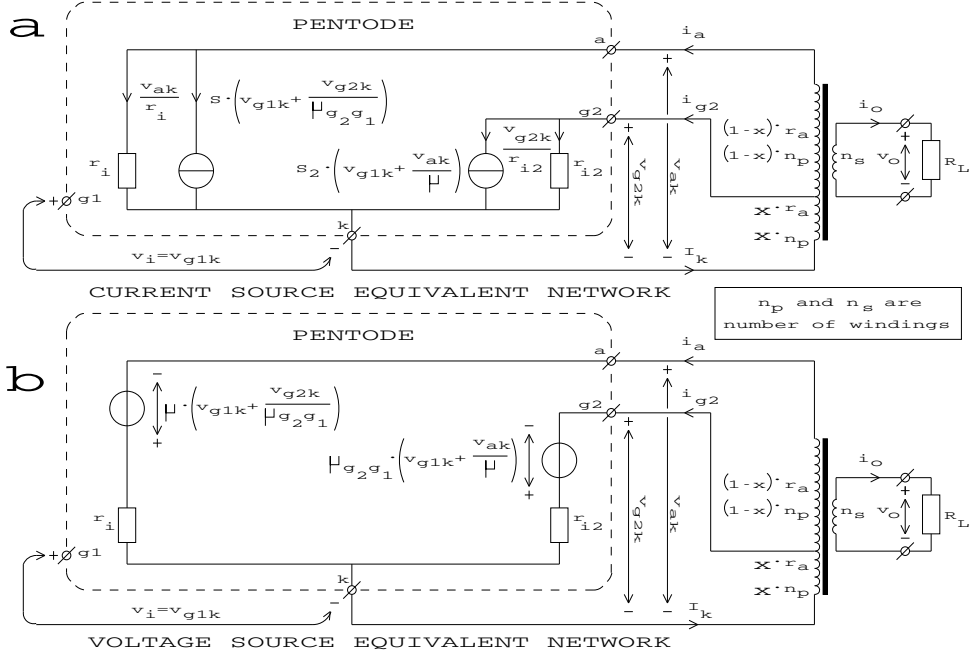


Figure 11. Current source equivalent circuit (a) and voltage source equivalent circuit (b) of the ultra-linear power amplifier.

Anode AC current i_a and screen grid AC current i_{g2} , which, in reality, see partially different AC resistances, are replaced by $i_{total} = (i_a + x \cdot i_{g2})$ which flows through one AC resistance. However, r_a without screen grid tap and i_{total} are both fictional. Admittedly, our imagination is put to the test. In section 8, I will show you that these assertions are actually allowed.

Further it would be nice if $x = \frac{v_{g2,k}}{v_{ak}}$ but in that case the current through $x \cdot r_a$ must be the same as the current through $(1-x) \cdot r_a$. Unfortunately that is not the situation, but in practice $x = 0.4$ and $i_{g2} \approx 0.2 \times i_a$.

Thus $\frac{v_{ak}}{r_a} = -(i_a + x \cdot i_{g2})$ becomes $\frac{v_{ak}}{r_a} = -(i_a + 0.4 \times 0.2 \times i_a) = 1.08 \times i_a = -i_{total} \approx i_a$.

Thus, statement $x = \frac{v_{g2,k}}{v_{ak}}$ is allowed.

Now we have all mathematical tools to derive anode AC gain $A_a = \frac{v_{ak}}{v_{g1,k}} = f(x)$, circuit AC gain



$$A = \frac{v_o}{v_i} = f(x) \text{ and circuit output AC resistance } r_{out} = f(x).$$

In 1959, Sietsma probably achieved the same results as I did in 2006. Unfortunately, he did not publish it, and I had to derive it independently; just a matter of brave calculations.

In section 6 I will prove the following equations:

Anode AC gain:

$$A_a = \frac{v_{ak}}{v_{g1,k}} = - \frac{(S + x \cdot S_2) \cdot r_a}{1 + \left(\frac{x}{\mu_{g2,g1}} + \frac{1}{\mu} \right) \cdot (S + x \cdot S_2) \cdot r_a}$$

Circuit AC gain:

$$A = \frac{v_o}{v_i} = - \frac{n_s}{n_p} \cdot \frac{(S + x \cdot S_2) \cdot r_a}{1 + \left(\frac{x}{\mu_{g2,g1}} + \frac{1}{\mu} \right) \cdot (S + x \cdot S_2) \cdot r_a}$$

Circuit AC output resistance:

$$r_{out} = \left(\frac{n_s}{n_p} \right)^2 \cdot \frac{1}{(S + x \cdot S_2) \cdot \left(\frac{x}{\mu_{g2,g1}} + \frac{1}{\mu} \right)}$$

The quantities shown in these equations have already been explained and are constant at a certain working point. The only variable quantity is screen grid primary transformer tap x . When you apply $x = 0$ and $x = 1$ in these equations, you get the anode AC gain, circuit AC gain and circuit AC output resistance for pentode and triode respectively. Again, in reference [1] these are derived in small and very easy steps.

5 Practical determination of the screen grid tap

It would be nice if figure 4 could be made visible on an oscilloscope screen. During the European Triode Festival 2007, Yves Monmagnon demonstrated his Tube Curve Tracer. Later I saw some results of this equipment on the internet, see reference [7], but at that time I was not aware of the ETF event. Many years before, while attending secondary technical school, I learned how to display transistor characteristics on an oscilloscope screen, but making voltage sources for control grid, screen grid and anode which can increase from 0 V to an adjustable maximum voltage of more than |400| V seems to me not easy. Before I had seen photos of Yves's presentation in 2007, I had already developed another method, see **figure 12**.

Supply voltage V_b is a short circuit for AC current, and the amplitudes of anode cathode AC voltage V_{ak} and screen grid cathode AC voltage $V_{g2,k}$ start from point $V_{ak} = V_b$ on the V_{ak} -axis of figure 12.

On curve $x_{TR} = 1.00$ for the triode, $V_{g2,k} = V_{ak}$ is always valid. To get $V_{ak} = 175$ V in point TR at an anode DC current of $I_a = 14$ mA, we must get $V_{g2,k} = 175$. By coincidence that is also V_{ak} .

On curve $x_{PE} = 0.00$ for the pentode, $V_{g2,k} = V_b = 300$ V is always valid. To get $V_{ak} = 175$ V in point PE at an anode DC current of $I_a = 72$ mA, we must get $V_{g2,k} = 300$ V. By coincidence that is also V_b .

The curves $V_{g1,k} = \frac{1}{2}$ control grid base for the triode and the pentode cross at working point W

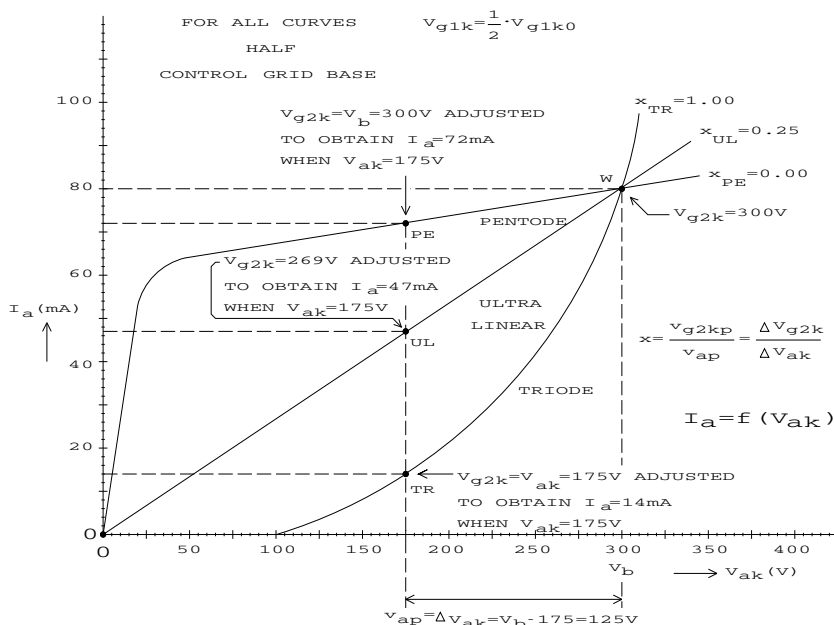


Figure 12. Explanation of the method to determine the screen grid tap x.

at $I_{aw} = 80$ mA and $V_{akw} = 300$ V. We can now draw a straight line, ultra-linear, between working point W and the origin. We call this line x_{UL} .

From point x_{UL} at $V_{ak} = 175$ V, we can read $I_a = 47$ mA. Now we must offer a certain voltage of $V_{g2,k}$ to get $I_a = 47$ mA at $V_{ak} = 175$ V. In this case $V_{g2,k} = 269$ V.

The characteristics for triode and pentode of figure 12 are measured with the test circuit of **figure 13**.

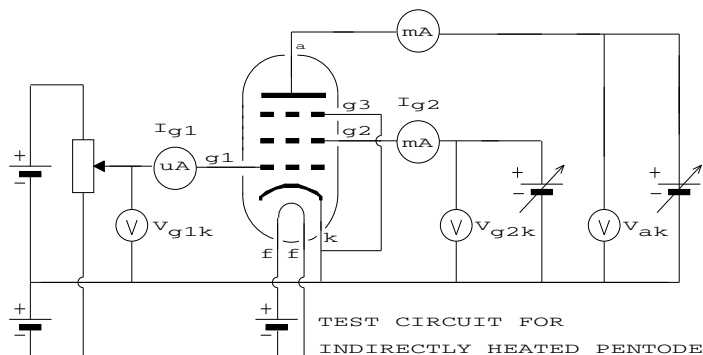


Figure 13. Test circuit for research into the static pentode characteristic.



We can now determine screen grid primary transformer taps x_{TR} , x_{UL} and x_{PE} .

At point PE:

$$v_{g2,kp} = \Delta V_{g2,k} = V_b - 300 \text{ V} = 0 \text{ V}$$
$$v_{ap} = \Delta V_{ak} = V_b - 175 \text{ V} = 125 \text{ V} \rightarrow x_{PE} = \frac{v_{g2,kp}}{v_{ap}} = \frac{\Delta V_{g2,k}}{\Delta V_{ak}} = \frac{0 \text{ V}}{125 \text{ V}} = 0.00$$

At point UL:

$$v_{g2,kp} = \Delta V_{g2,k} = V_b - 269 \text{ V} = 31 \text{ V}$$
$$v_{ap} = \Delta V_{ak} = V_b - 175 \text{ V} = 125 \text{ V} \rightarrow x_{UL} = \frac{v_{g2,kp}}{v_{ap}} = \frac{\Delta V_{g2,k}}{\Delta V_{ak}} = \frac{31 \text{ V}}{125 \text{ V}} = 0.25$$

At point TR:

$$v_{g2,kp} = \Delta V_{g2,k} = V_b - 175 \text{ V} = 125 \text{ V}$$
$$v_{ap} = \Delta V_{ak} = V_b - 175 \text{ V} = 125 \text{ V} \rightarrow x_{TR} = \frac{v_{g2,kp}}{v_{ap}} = \frac{\Delta V_{g2,k}}{\Delta V_{ak}} = \frac{125 \text{ V}}{125 \text{ V}} = 1.00$$

If the explanation of this method is not 100 % clear, it will be soon because we now apply this method in a practical case. **Figure 14** shows the anode characteristics for five different values of screen grid primary transformer tap x of specimen KT88 no.1.

Line 1 is measured in advance with the pentode in triode mode: $x = 1.00$.

Line 2 is drawn afterwards "freehand", but we do not know yet that the corresponding $x = 0.42$.

Line 3 is drawn afterwards with a straight ruler, but we do not know yet that the corresponding $x = 0.25$.

Line 4 is drawn afterwards "freehand", but we do not know yet that the corresponding $x = 0.13$.

Line 5 is measured in advance with the pentode in pentode mode: $x = 0.00$.

From all lines we can read I_a for each V_{ak} . We must now search for the necessary value of $V_{g2,k}$ at each point on these lines. Therefore, we need the test circuit of figure 13 which I have used to measure the lines 1 and 5. At a certain anode DC current I_a and at an adjusted anode cathode DC voltage V_{ak} , the value of screen grid cathode DC voltage $V_{g2,k}$ which I have measured, must be subtracted from $V_b = 300 \text{ V}$. Also V_{ak} must be subtracted from $V_b = 300 \text{ V}$. This gives you $\Delta V_{g2,k}$ and ΔV_{ak} respectively.

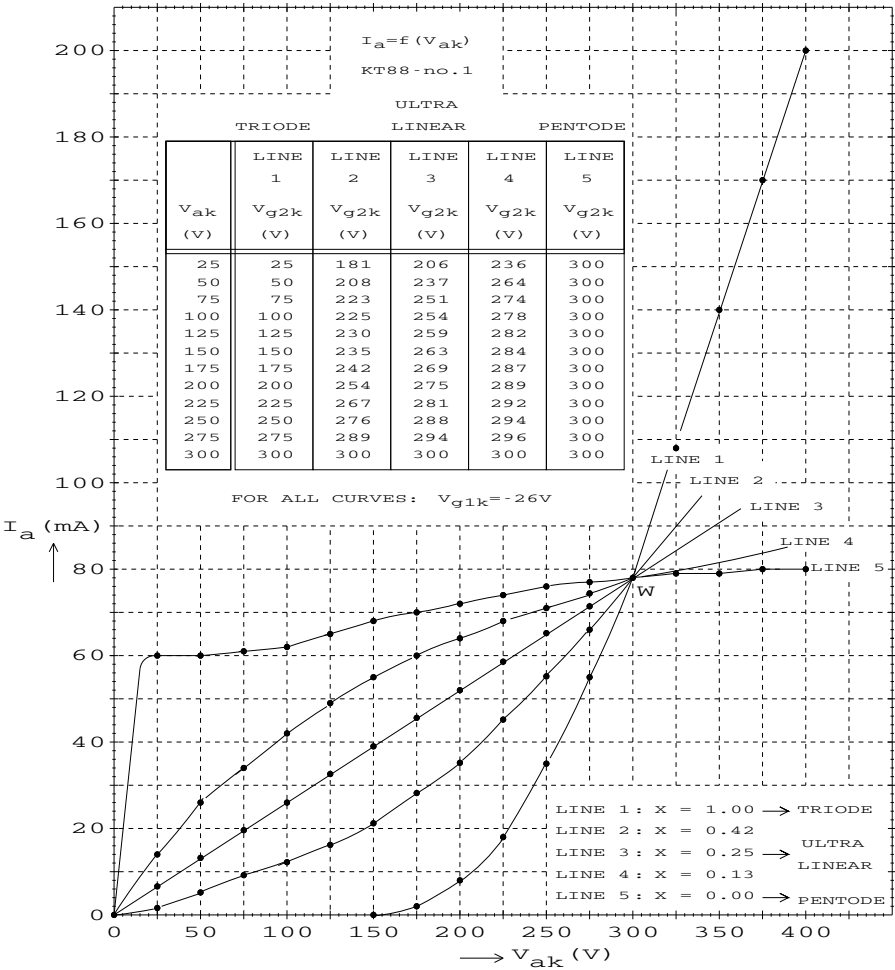


Figure 14. Anode characteristic of KT88 no.1 for different values of screen grid primary transformer tap x . The corresponding values of V_{g2k} at each measured point is shown in the table.

The next five tables show the method of figures 12 and 14 explained in practice and deliver the evidence that for all measured values (the dots on the lines), the screen grid primary transformer tap x is the same for the corresponding line. We also measure the screen grid DC current I_{g2} for later use.



V_{ak} (V) adjusted	I_a (mA) read on I_a -axis	I_{g2} (mA) measured	$V_{g2,k}$ (V) adjusted to read I_a	ΔV_{ak} (V) [300V - V_{ak}]	$\Delta V_{g2,k}$ (V) [300V - $V_{g2,k}$]	$x = \frac{\Delta V_{g2,k}}{\Delta V_{ak}}$
0	0	0	0	300	300	1
25	0	0	25	275	275	1
50	0	0	50	250	250	1
75	0	0	75	225	225	1
100	0	0	100	200	200	1
125	0	0	125	175	175	1
150	0	0	150	150	150	1
175	2,6	0,1	175	125	125	1
200	8,5	0,7	200	100	100	1
225	19,2	1,6	225	75	75	1
250	35,6	2,9	250	50	50	1
275	55	4,6	275	25	25	1
300	79	7	300	0	0	unknown
325	110	9,2	325	Not further than point W		
350	140	12,1	350			
375	170	16,5	375			
400	200	21	400			

Table 2. Measured values for line 1, fig 14. The adjustment of $V_{g2,k}$ happens automatically of course, because the screen grid is connected to the anode. The screen grid primary transformer tap $x = 1.00$ but that will surprise nobody, so this is the pentode in triode mode.

V_{ak} (V) adjusted	I_a (mA) read on I_a -axis	I_{g2} (mA) measured	$V_{g2,k}$ (V) adjusted to read I_a	ΔV_{ak} (V) [300V - V_{ak}]	$\Delta V_{g2,k}$ (V) [300V - $V_{g2,k}$]	$x = \frac{\Delta V_{g2,k}}{\Delta V_{ak}}$
0	0	0	unknown	300	unknown	unknown
25	2	0,9	181	275	119	0,43
50	5	5,5	208	250	92	0,37
75	9	8,9	223	225	77	0,34
100	12	7,6	225	200	75	0,38
125	17	5,9	230	175	70	0,40
150	22	4,2	235	150	65	0,43
175	28	3,6	242	125	58	0,46
200	36	4	254	100	46	0,46
225	46	4,7	267	75	33	0,44
250	55	5,3	276	50	24	0,48
275	66	6,2	289	25	11	0,44
300	78	7	300	0	0	unknown

Table 3. Measured values of line 2, fig 14. The average value of all screen grid primary transformer taps $x_{average} = 0.42$.



V_{ak} (V) adjusted	I_a (mA) read on I_a -axis	I_{g2} (mA) measured	$V_{g2,k}$ (V) adjusted to read I_a	ΔV_{ak} (V) [300V - V_{ak}]	$\Delta V_{g2,k}$ (V) [300V - $V_{g2,k}$]	$x = \frac{\Delta V_{g2,k}}{\Delta V_{ak}}$
0	0	0	unknown	300	unknown	unknown
25	6,5	3,8	206	275	94	0,34
50	13	12,5	237	250	63	0,25
75	19,5	16	251	225	49	0,22
100	26	13	254	200	46	0,23
125	32,5	10,4	259	175	41	0,23
150	39	8	263	150	37	0,25
175	45,5	7	269	125	31	0,25
200	52	6,5	275	100	25	0,25
225	58,5	6,5	281	75	19	0,25
250	65	6,5	288	50	12	0,24
275	71,5	6,5	294	25	6	0,24
300	78	7,1	300	0	0	unknown

Table 4. Measured values of line 3, fig 14. The average value of all screen grid primary transformer taps $x_{average} = 0.25$. For this specimen KT88 no.1 we have pure ultra-linear at $x = 0.25$.

V_{ak} (V) adjusted	I_a (mA) read on I_a -axis	I_{g2} (mA) measured	$V_{g2,k}$ (V) adjusted to read I_a	ΔV_{ak} (V) [300V - V_{ak}]	$\Delta V_{g2,k}$ (V) [300V - $V_{g2,k}$]	$x = \frac{\Delta V_{g2,k}}{\Delta V_{ak}}$
0	0	0	unknown	300	unknown	unknown
25	15	9,5	236	275	64	0,23
50	26	19,7	264	250	36	0,14
75	34	20,6	274	225	26	0,12
100	41	17,7	278	200	22	0,11
125	49	14,2	282	175	18	0,10
150	55	11,2	284	150	16	0,11
175	60	9,4	287	125	13	0,10
200	64	8,1	289	100	11	0,11
225	68	7,6	292	75	8	0,11
250	71	7,1	294	50	6	0,12
275	74	7	296	25	4	0,16
300	78	7	300	0	0	unknown

Table 5. Measured values of line 4, fig 14. The average value of all screen grid primary transformer taps $x_{average} = 0.13$.



V_{ak} (V) adjusted	I_a (mA) read on I_a -axis	I_{g2} (mA) measured	$V_{g2,k}$ (V) adjusted to read I_a	ΔV_{ak} (V) [300V - V_{ak}]	$\Delta V_{g2,k}$ (V) [300V - $V_{g2,k}$]	$x = \frac{\Delta V_{g2,k}}{\Delta V_{ak}}$
0	1	54	300	300	0	0
25	60	30	300	275	0	0
50	60	30	300	250	0	0
75	61	28	300	225	0	0
100	63	22	300	200	0	0
125	65	19	300	175	0	0
150	68	14	300	150	0	0
175	70	12	300	125	0	0
200	72	9,5	300	100	0	0
225	74	8,5	300	75	0	0
250	75	7,8	300	50	0	0
275	76	7,2	300	25	0	0
300	77	7	300	0	0	unknown
325	78	6,5	300	Not further than point W		
350	79	6,3	300			
375	80	6	300			
400	80	6	300			

Table 6. Measured values of line 5, fig 14. The adjustment of $V_{g2,k}$ happens automatically of course, because the screen grid is connected to V_b . The screen grid primary transformer tap $x = 0.00$ but that will surprise nobody; this is pentode mode.

With this method you can determine screen grid primary transformer tap x for each specimen pentode and from each curvature in $I_a = f(V_{ak})$. In practice, we are only interested in the ultra-linear application.

Lines 2 and 4 in fig 14, drawn “freehand”, are just an illustration to show how the value of x can lie between triode and ultra-linear and between ultra-linear and pentode.

I have also recorded screen grid DC current I_{g2} during this measurement because it is interesting to see the influence of screen grid primary transformer tap x on I_{g2} , see **figure 15** for the results.

Line 1 shows triode behavior. Screen grid DC current I_{g2} increases the same as anode DC current I_a . Less steeply of course, because screen grid static transconductance S_2 is smaller than anode static transconductance S .

Line 5 shows pentode behavior. Because $I_k = I_a + I_{g2} \approx \text{constant}$, the curvature of screen grid DC current I_{g2} is mirrored with respect to anode DC current I_a . The strange “step” of specimen KT88-no.1 in the area where $25 \text{ V} < V_{ak} < 50 \text{ V}$, which is typical for Beam Power Tetrodes, can be found in both currents mentioned. We already know the curvature of I_{g2} , see figure 9.

Lines 2, 3 and 4 are very different. We first see “fast” triode behavior at low values of V_{ak} because now the positive screen grid is seen as the “anode” by the electrons of the electron cloud around the cathode. Hence, I_{g2} is increasing. Thereafter pentode behavior is more dominant. The result is a maximum value of I_{g2} at approximately $V_{ak} = 75 \text{ V}$.

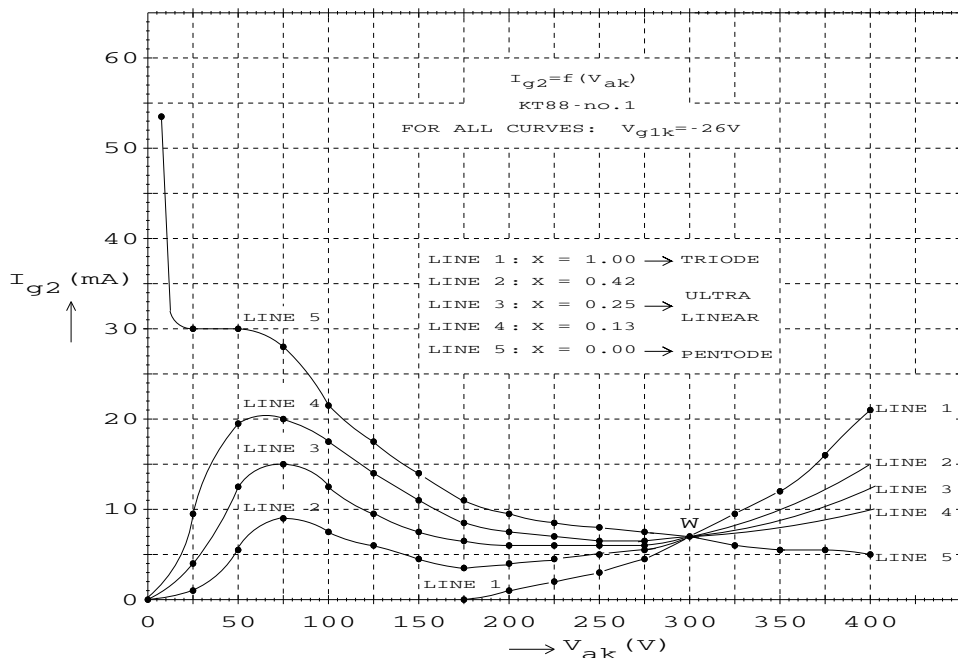


Figure 15. Characteristic of $I_{g2} = f(V_{ak})$ for different values of screen grid tap x .

6 Practical anode AC gain and circuit AC output resistance as function of the screen grid tap

In the network analysis of section 4, we have seen the influence of the screen grid primary transformer tap x on the anode AC gain, circuit AC gain and the circuit AC output resistance: $A_a = f(x)$, $A = f(x)$, and $r_{out} = f(x)$. Now it is time to find out what happens in a real circuit. **Figure 16** shows the test circuit. What immediately is apparent is the output transformer with the 10 taps. Once, before I had ever heard about the ultra-linear power amplifier, I did an investigation about the maximum delivered anode power of a 300B triode versus the normalized anode AC external resistance r_a/r_i . When you know that for a 300B in normal operation $r_i = 700 \Omega$, then it does not seem strange that the taps of the primary transformer winding (r_a) of figure 16 are multiples of 700Ω . Although that anode power investigation was quite interesting, it is beyond the scope of this article. See chapter 4 of reference [1] for that investigation.

For those of you who want to do the same experiments I did, you can order this test output transformer from the Dutch transformer manufacturer AE-europe. The type number is 27844 and its maximum DC current is 200 mA. Do not expect enough bandwidth and other audio qualities, but it is useful for power investigations at medium audio frequencies.

I again used pentode specimen KT88-no.1 at the following working point: $V_{ak,w} = 300 V$, $I_{a,w} = 80 mA$, $V_{g1,kw} = -26 V$, $V_{g2,kw} \approx 300 V$ and $I_{g2,w} \approx 8 mA$

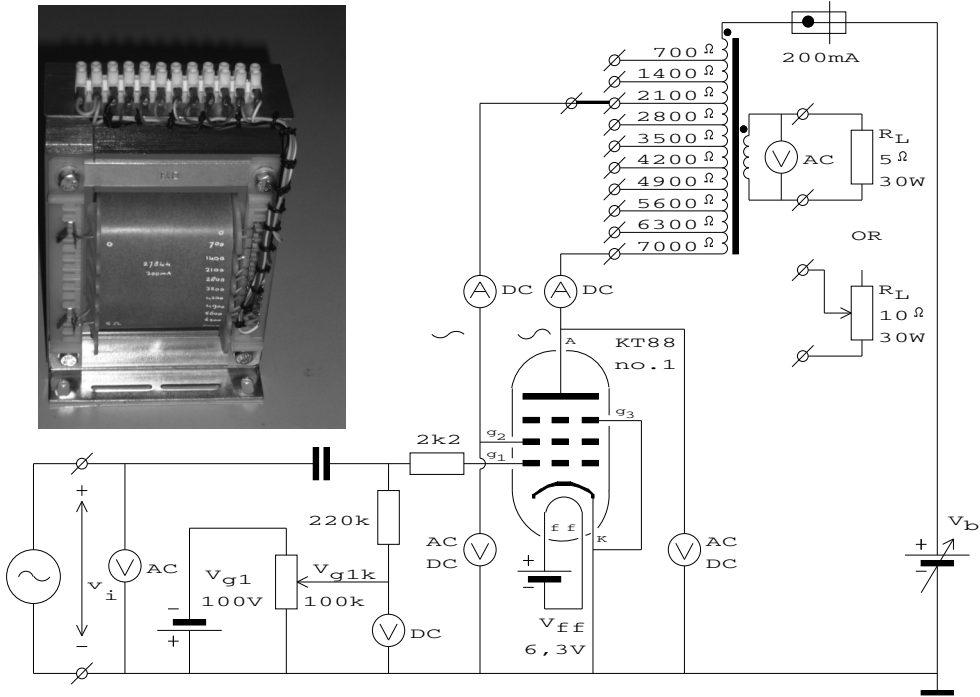


Figure 16. Test circuit to determine the dependence of the anode AC gain and the circuit AC output resistance on the screen grid tap x .

Note that if working point W changes slightly with other values of screen grid primary transformer tap x , we must change $V_{g1,kw}$ slightly to achieve the nominal setting. There is a voltage drop across the primary transformer winding of $(I_a + I_{g2}) \cdot (1 - x) \cdot R_p$ which depends on the screen grid primary transformer tap x . It varies and is approximately 10 V. At each value of x , the working point is adjusted as necessary.

Looking at the test circuit of figure 16 we would expect the following values of x at each tap:

$$x = \frac{0\Omega}{7000\Omega} = 0.0 ; x = \frac{700\Omega}{7000\Omega} = 0.1 ; x = \frac{1400\Omega}{7000\Omega} = 0.2 ; x = \frac{2100\Omega}{7000\Omega} = 0.3 ; \dots x = \frac{7000\Omega}{7000\Omega} = 1.0$$

We define $x_{measured} = \frac{\Delta V_{g2,k}}{\Delta V_{ak}} = \frac{V_{g2,k}}{V_{ak}}$ and measurements will determine whether $x = x_{measured}$.

How linearly are the taps divided over the primary transformer winding? What is the influence of I_{g2} and I_{g2} on the function of the tap? What is the influence of screen grid AC internal resistance r_{i2} on x ? We must realize that this test transformer is not designed and produced for ultra-linear applications, but it is available so let us try. Hence the introduction of quantity $x_{measured}$:

$$V_{g2,k} = x \cdot V_{ak} \rightarrow V_{g2,k} = x_{measured} \cdot V_{ak}$$

We start with anode AC gain $A_a = f(x_{measured})$.



You will observe that the output voltages and powers are rather low. Please do not judge that too harshly. In the other applications with KT88 pentodes, the supply voltage can be 400 V instead of 300 V. Realize that the delivered output power is proportional with (V_b^2/r_a) .

OK, here we go: anode AC external resistance $r_a = 7000 \Omega$. Fraction $R_i = V_{ak}/I_{aw} = 300 \text{ V}/80 \text{ mA} = 3750 \Omega$. That give us the fraction $r_a/R_i = 7000/3750 = 1.87$ and reference [1] shows that this value is very unfavorable to achieve large output power. But I promise you; all will eventually be well concerning the output power; please be patient.

We also need equation $A_a = \frac{v_{ak}}{v_{g1,k}} = - \frac{(S + x \cdot S_2) \cdot r_a}{1 + \left(\frac{x}{\mu_{g2,g1}} + \frac{1}{\mu} \right) \cdot (S + x \cdot S_2) \cdot r_a}$ and for x we substitute in $x_{measured}$.

We can get the following quantities from the datasheets of the KT88:

$S = 11.5 \text{ mA/V}$ and $r_i = 12 \text{ k}\Omega$ and $\mu_{g2,g1} = 8$. Unfortunately, S_2 is not given, but that is (not) to be expected from the current manufacturers of electron tubes. In the previous measurements, we have seen that at $V_{ak} = 300 \text{ V}$, $I_a \approx 10 \cdot I_{g2}$. So I make the assumption that $S = 10 \cdot S_2$ and that gives us $S_2 = 1.15 \text{ mA/V}$. We now have all the necessary quantities to substitute in the equation together with $x_{measured}$.

We start with $v_{g1,k} = 3.72 \text{ V}_{RMS} = 5.25 \text{ V}_p$, to avoid v_{ap} clipping at $x = x_{measured} = 0.0$.

Output power $p_a = \frac{v_{ak,RMS}^2}{r_a}$ and $p_{R_i} = \frac{v_{R_i,RMS}^2}{r_a}$ will be very poor, but as promised will be well in the end.

The results of the measurements and calculations are shown in **table 7** and as expected, $x \neq x_{measured}$, because the taps are not perfectly linearly divided over the primary transformer winding. We will see later that with an actual toroidal-core transformer, $x = x_{measured}$.

x	$v_{g1,k}$ (VRMS)	$v_{g2,k}$ (VRMS)	v_{ak} (VRMS)	$x_{measured} = \frac{v_{g2,k}}{v_{ak}}$	p_a (W)	v_{RL} (VRMS)	p_{RL} (W)	$ A_a = \frac{v_{ak}}{v_{g1,k}}$	$ A_a $ with formula
0.0	3.72	0.0	158.0	0.00	3.60	4.01	3.20	42.4	50.6
0.1	3.72	19.2	60.8	0.32	0.53	1.51	0.45	16.3	16.8
0.2	3.72	21.3	47.7	0.45	0.33	1.22	0.29	12.8	13.3
0.3	3.72	22.3	40.7	0.55	0.24	1.01	0.20	10.9	11.3
0.4	3.72	23.2	36.1	0.64	0.19	0.92	0.16	9.7	10.1
0.5	3.72	23.6	33.4	0.71	0.16	0.83	0.14	9.0	9.3
0.6	3.72	23.9	30.9	0.77	0.14	0.78	0.12	8.3	8.7
0.7	3.72	23.2	28.9	0.84	0.12	0.73	0.11	7.8	8.1
0.8	3.72	24.2	27.3	0.89	0.11	0.69	0.10	7.3	7.7
0.9	3.72	24.6	26.1	0.94	0.10	0.65	0.09	7.0	7.3
1.0	3.72	25.0	25.0	1.00	0.09	0.62	0.08	6.6	7.0

Table 7. The results of measurements and calculations based on figure 16.

Figure 17 shows plots of the table 7 results of the ninth and tenth column as a function of the fifth column, or in other words the functions $A_{a,measured} = f(x_{measured})$ and $A_{a,calculated} = f(x_{measured})$ respectively. The agreement between theory and practice is good. Only at low values of $x_{measured}$ there are some differences.

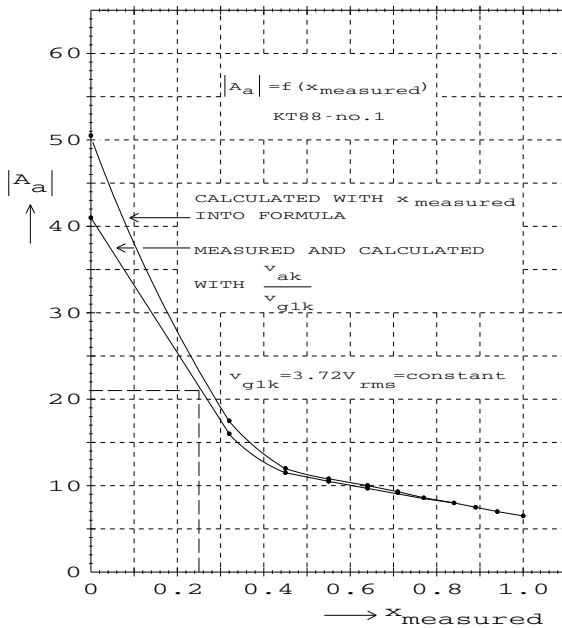


Figure 17. $p_a = f(x_{measured})$ for a constant $v_{gl,k}$, calculated and measured.

This test transformer has no taps at $0.00 < x < 0.10$ and $0.00 < x_{measured} < 0.32$. In the other ranges we see that the decrease in $|A_a|$ almost perfectly tracks the increase in x and $x_{measured}$. The larger x and $x_{measured}$, the greater the screen grid negative feedback and the decrease in $|A_a|$. A low anode gain delivers low values of v_{ak} and v_{RL} and thus, a low p_a and p_{RL} , see columns 6 and 8 of table 7. However, no one can stop us to leave the value $v_{gl,k} = 3.72V$ as it is for each value of x . The larger the value of x the more we move toward triode and the less the upper bend in transconductance characteristic $I_a = f(V_{gl,k})$. Hence, the control

grid base increases and can be used with a larger value of $v_{gl,k}$.

Figure 18 shows $p_a = f(x_{measured})$ for $v_{gl,k} = 3.72V$, the second column of table 7, and shows $p_a = f(x_{measured})$ with adjusted $v_{gl,k}$ which is as large as possible without causing non-linear distortion visible on the oscilloscope. The anode power then lies between 2.5 W and 5.5 W and that will provide reasonable sound levels. More power can be obtained by increasing $V_{akw} = V_b$ and I_{aw} , but I will not do that here. Of course, we must choose fraction r_a/R_i optimally, see reference [1]. As promised, those power numbers will all turn out to be fine.

The dashed lines in fig 17 show the gain for $x_{measured} = 0.25$ and that is the ultra-linear mode for this specimen KT88-no.1. See also line 3 of figure 14 and the seventh column of table 4.

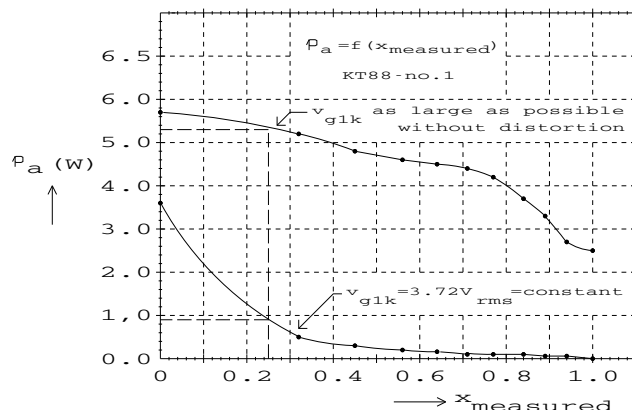


Figure 18. $p_a = f(x_{measured})$ for a constant $v_{gl,k}$ and for an adjusted $v_{gl,k}$.



We now continue with the circuit AC output resistance as a function of the actual screen grid primary transformer tap x , or $r_{out} = f(x_{measured})$.

In theory, we can apply Thevenin's $r_{out} = \left| \frac{v_{open}}{i_{shortcircuit}} \right|$ but in practice this is dangerous.

Shorting i_{RL} is permissible for a short time, but $V_{RL,open}$ is dangerous. When a secondary load on the output transformer is removed suddenly, an inductive high voltage may appear which can destroy the power tube. (This is the reason you should never disconnect the loudspeakers from the outputs of your electron tube amplifier when it is not switched off). We will determine r_{out} according to **figure 19**.

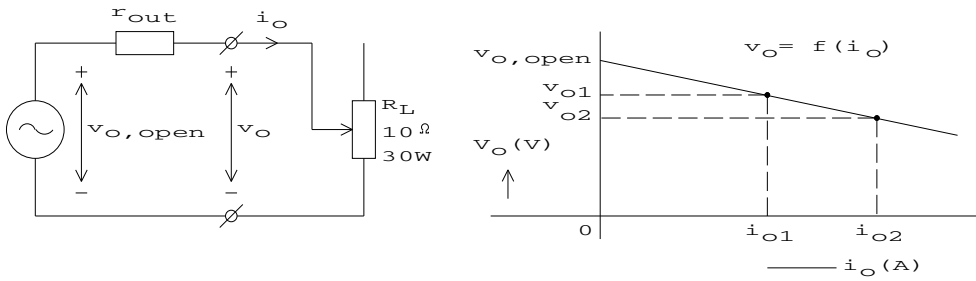


Figure 19. Voltage source model to determine circuit AC output resistance r_{out} .

The voltage source is the secondary side of the output transformer and we want to know the value of r_{out} . Use a wire-wound adjustable resistor of $10\Omega/30W$ as the load resistor R_L and set the slider at mid-position; now $R_L = 5\Omega$.

From figure 19 we can derive

$$: v_{o,open} = i_{o1} \cdot r_{out} + v_{o1}$$

$$v_{o,open} = i_{o2} \cdot r_{out} + v_{o2}$$

We now use the following equations:

$$i_{o1} \cdot r_{out} + v_{o1} = i_{o2} \cdot r_{out} + v_{o2} \quad \Leftrightarrow$$

$$(v_{o2} - v_{o1}) = (i_{o1} - i_{o2}) \cdot r_{out} \quad \Leftrightarrow$$

$$r_{out} = \frac{(v_{o2} - v_{o1})}{(i_{o1} - i_{o2})} \quad \Leftrightarrow$$

$$r_{out} = \frac{\Delta v_o}{\Delta i_o}$$

By adjusting the slider slightly clockwise or counterclockwise, we can create Δv_o and Δi_o and apply this for each value of x and $x_{measured}$. At larger values of x and $x_{measured}$, when the gain is low and thus the values of v_o and i_o are also low, we can increase $v_i = v_{g1,k}$ to achieve larger values of v_o and i_o .

If $v_o \approx 5V$ then $i_o \approx 1A$ because $R_L = 5\Omega$. These values are very easily measured with a voltmeter and a current probe. For each value of x and $x_{measured}$ we can make a table for v_{o1} , v_{o2} , i_{o1} , i_{o2} and r_{out} .



We also need equation $r_{out} = \left(\frac{n_s}{n_p}\right)^2 \cdot \frac{1}{(S + x \cdot S_2) \cdot \left(\frac{x}{\mu_{g2,g1}} + \frac{1}{\mu}\right)}$ and substitute $x_{average}$ for x .

The values of S , S_2 , μ and $\mu_{g2,g1}$ have already been determined. The square of the transformer winding ratio is of course $(n_s/n_p)^2$. When you look at the design impedances of the test transformer you get the square of the winding ratio as $5\Omega/7000\Omega = 1/1400$. To get the *actual* values, it is better to look at the measured values of v_{RL} at the primary side and v_{ak} at the secondary side, in table 7. When you calculate this fraction for each x and $x_{measured}$ you get $v_{RL}/v_{ak} = 0.025$ so the square of the winding ratio is $(v_{RL}/v_{ak})^2 = 1/1600$. All the 'ingredients' of this equation are now known and we will apply this eleven

times as we step x from 0.0 to 1.0 in 0.1 increments. We will put all results of $r_{out-calculated}$ and $r_{out-measured}$ in the same table as the measured values and then draw the graphs as shown in **figure 20**.

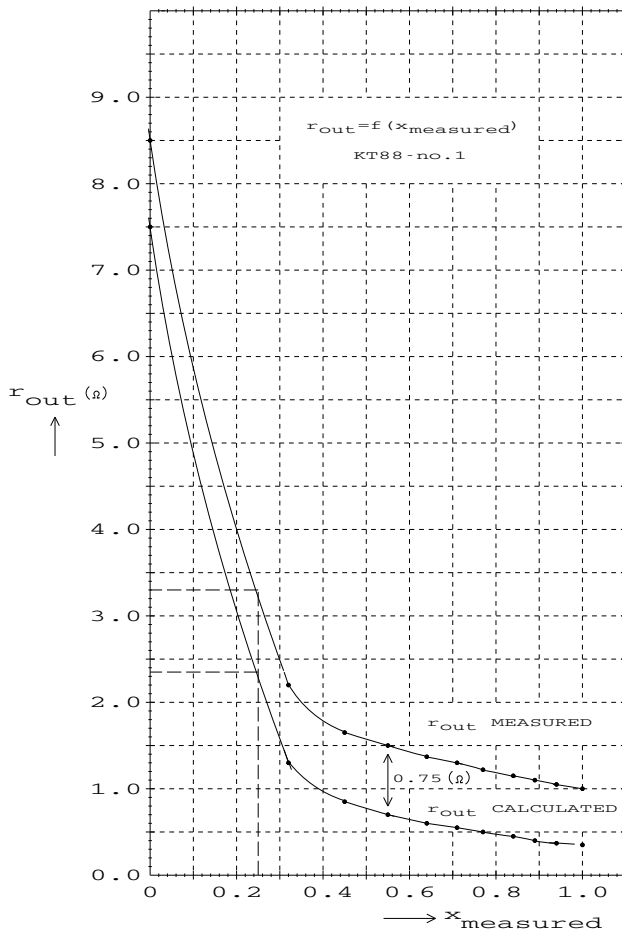


Figure 20. $r_{out} = f(x_{measured})$, calculated and measured.

The difference between $r_{out-calculated}$ and $r_{out-measured}$ for each $x_{measured}$ is approximately 0.75Ω , which is caused by the primary and secondary copper resistances of the test transformer and the wire/contact resistances of the test circuit. In the ultra-linear mode, for $x_{measured} = 0.25$, we find an output impedance of $r_{out-calculated} = 3.3 \Omega$ (dashed lines). Knowing the importance of r_{out} on the damping factor, audiophiles can be expected to hear the difference in sound character due to the differences in r_{out} caused by different $x_{measured}$ values.

At last, we can conclude that the network analysis of section 4 matches reality!



7 Practical comparison of a triode, ultra-linear and pentode power amplifier

In this section we will compare the output power and efficiency, the frequency behavior and the non-linear distortion of an existing electron tube amplifier which we can make to work as a triode, ultra-linear or pentode amplifier by changing some jumpers. The schematic, from reference [4], is shown in **figure 21**.

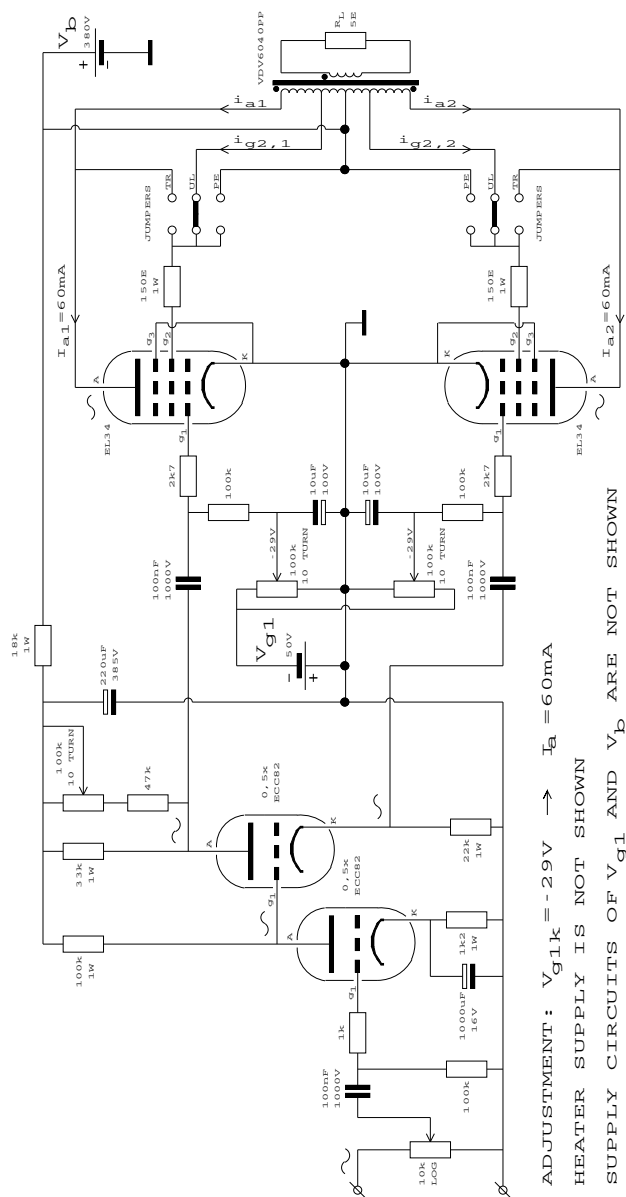


Figure 21. Circuit of one mono block of my first amplifier, the design is from reference [4].

**First I will start with the comparison of output power and efficiency.**

For each mentioned configuration the working point is set to $I_{av} = 60$ mA at $v_{g1,kp} = 0$ V.

In reference [4] 13 W is promised for the triode, 33 W for ultra-linear and 40 W for pentode. Tests after construction showed some distortion at those levels so I decreased these powers to 12 W for triode, 23 W for ultra-linear and 25 W for pentode. With these values there were no non-linear distortions visible on the oscilloscope screen and these powers are very large for use in a living room. Despite the “easy EL34” and the “standard circuit”, the sound quality is fantastic.

Figure 22 shows output power and efficiency as function of the control grid cathode AC peak voltage $v_{g1,kp}$ for the mono block of figure 21. The vertical axes show, on a common scale:

Input power	-	P_{in}
Anode dissipation	-	P_a
Delivered anode power	-	p_a
Anode efficiency	-	η_{anode}

The reason that P_{in} increases slowly is because I_a increases from 60 mA to 72 mA, to 80 mA and to 86 mA in the configurations triode, ultra-linear and pentode respectively. The working point moves from class A to class AB. The differences in output power between the triode and ultra-linear modes are relatively large. The differences in output power between the ultra-linear and pentode configurations are very small, as I have noted before.

Furthermore, you can see the differences in control grid base for the triode, ultra-linear and pentode configurations. The value of maximum $v_{g1,kp}$ to obtain maximum delivered anode power p_a is different. In order to be able to use the same preamp again in all cases, I used a “select-jumper” in series with the slider of the volume potentiometer. With three different values of resistors in series with the slider I could select three different input voltage levels.

Next, I continue with the comparison of the frequency behavior.

Figures 23 through 25 show the amplitude-frequency characteristic and the phase-frequency characteristic for triode, ultra-linear and pentode configuration respectively. During the measurements, the input of the amplifier was terminated by a resistor of 600 Ω and the input signal offered was 775 mV_{RMS} = 0 dB, thus 1 mW input power.

The AC output voltage was measured across the load resistor of 5 Ω and thus, the output power can be calculated by the equations shown below. The powers which are then obtained are less than the powers of figure 22 because the input signal is now limited to 775 mV_{RMS} = 0 dB, 1 mW input power. When you increase the input level to 1.6 V_{RMS}, the power levels of figure 22 can be reached easily. When we want these maximum power levels at 0 dB at the input, the voltage gain of the preamplifier and the phase shifter must be increased.

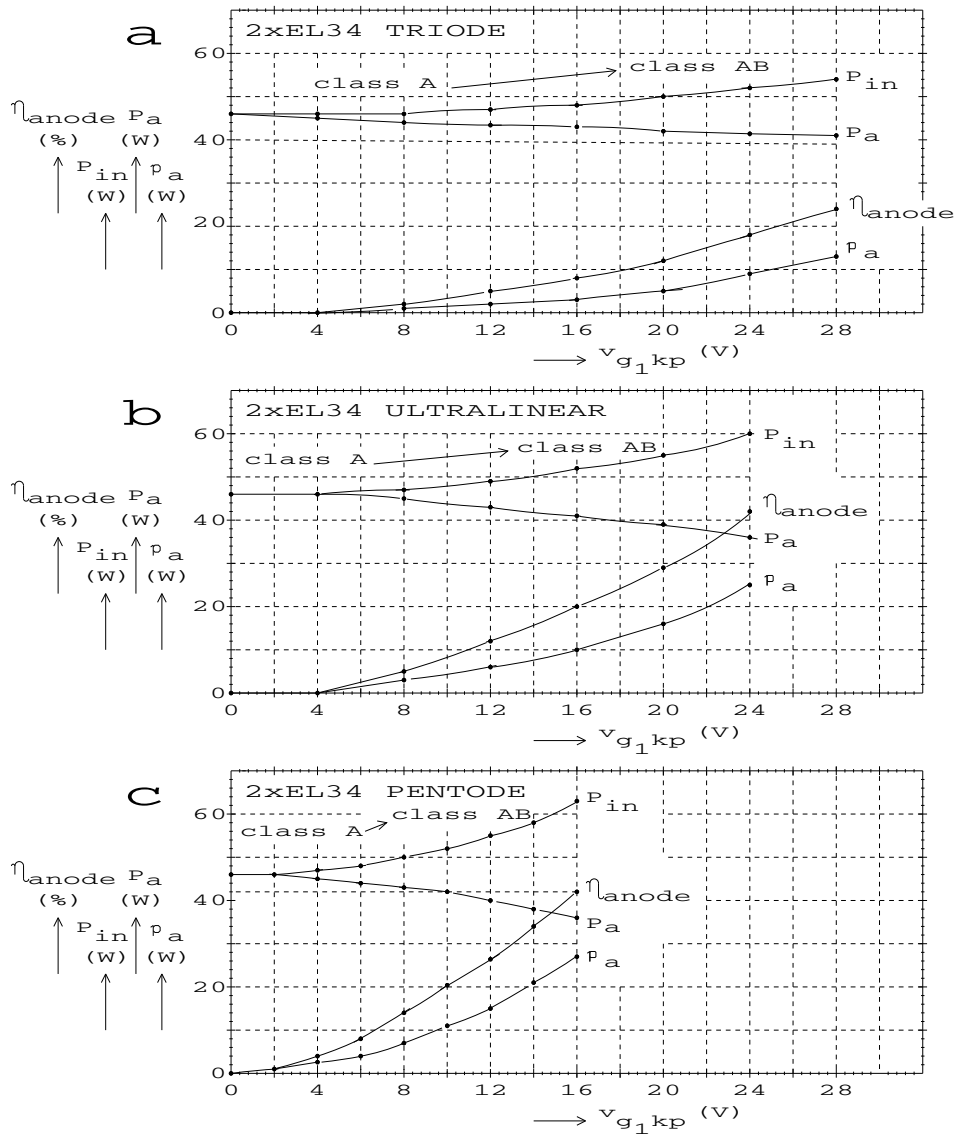


Figure 22. The output power, dissipation and the efficiency of the mono block of figure 22. Top to bottom: triode, ultra-linear and pentode mode.



$$\text{Power gain : } A_p = 10 \cdot 10 \log \frac{P_{out}}{P_{in}} = 10 \cdot 10 \log \frac{\left(\frac{v^2 R_L}{R_L} \right)}{0.001}$$

$$\text{Voltage gain: } A_v = 20 \cdot 10 \log \frac{v_{out}}{v_{in}} = 20 \cdot 10 \log \frac{v_{R_L}}{0.775}$$

Comparison of figures 23 through 25 shows that the crossover points at the lower end of the audio spectrum are almost the same for triode, ultra-linear and pentode mode. At the upper end of the audio spectrum, the crossover points are significantly different. The bandwidth increases from triode, via ultra-linear to pentode. We could believe that the larger $C_{a,g1}$ and the *Miller-effect* would have a large negative effect for triodes, but triodes have a low-value anode AC internal resistance r_i . Pentodes have a very low $C_{a,g1}$, but their anode AC internal resistances r_i are very high. The balance with the quantities $C_{a,g1}$ plus Miller-effect versus r_i tips towards triodes. Regarding the ultra-linear configuration, the bandwidth lies between those of triodes and pentodes. Furthermore, expect no slopes of 6 dB/octave or 20 dB/decade because this complete amplifier circuit with its several stages is a "patchwork" of separate amplitude-frequency characteristics and phase-frequency characteristics.

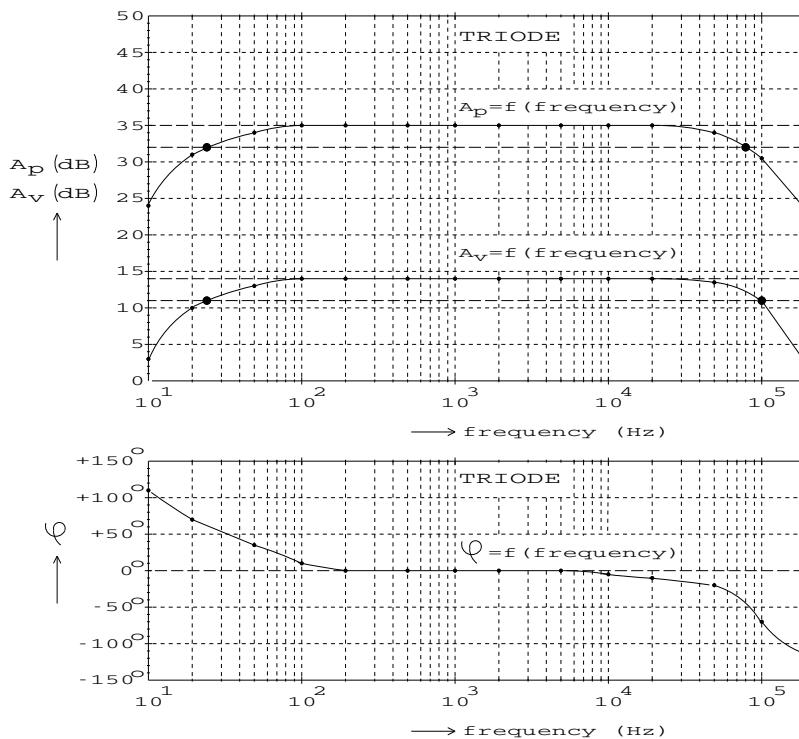


Figure 23. Measured frequency response of the mono block of figure 21 in triode configuration.

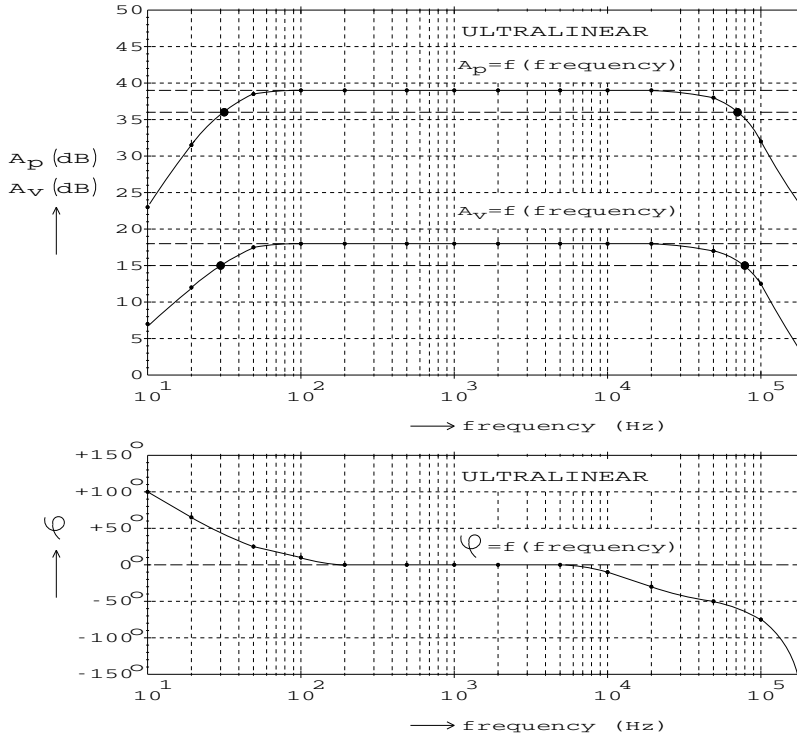


Figure 24. Measured frequency response of the amplifier of figure 21 in ultra-linear configuration.

We see that in figures 23 through 25 the power bandwidth is slightly smaller than the voltage bandwidth; this can be understood from the following calculations:

$$A_p = 10 \cdot 10 \log \left(\frac{P_{5\Omega}}{P_{600\Omega}} \right) = 10 \times 10 \log \left(\frac{v_{R_L}^2 / 5}{0.001} \right) = 10 \times 10 \log \left(\frac{v_{R_L}^2}{0.005} \right) = 10 \times 10 \log \left(\frac{v_{R_L}}{\sqrt{0.005}} \right)^2 = 20 \times 10 \log \left(\frac{v_{R_L}}{0.0707} \right)$$

$$A_p = 20 \times 10 \log \left(\frac{v_{R_L}}{0.0707 \times 0.1} \right) = 20 \times 10 \log \left(\frac{v_{R_L}}{0.0707} \times 10 \right) = 20 \times 10 \log \left(\frac{v_{R_L}}{0.0707} \right) + 20 \times 10 \log 10 \quad \Leftrightarrow$$

The power gain factor is: $A_p = 20 \cdot 10 \log \frac{v_{R_L}}{0.0707} + 20$

The voltage gain factor is: $A_v = 20 \cdot 10 \log \frac{v_{R_L}}{0.775}$

Imagine 10 V_{RMS} is measured across load resistance R_L of the pentode amplifier, see figure 25.

$$A_p = 20 \cdot 10 \log \frac{v_{R_L}}{0.0707} + 20 = 20 \times 10 \log \frac{10}{0.0707} + 20 = 20 \times 10 \log 14.1 + 20 = 23 + 20 \quad \Leftrightarrow \quad A_p = 43 \text{ dB}$$

$$A_v = 20 \cdot 10 \log \frac{v_{R_L}}{0.775} = 20 \times 10 \log \frac{10}{0.775} = 20 \times 10 \log 12.9 \quad \Leftrightarrow \quad A_v = 22 \text{ dB}$$

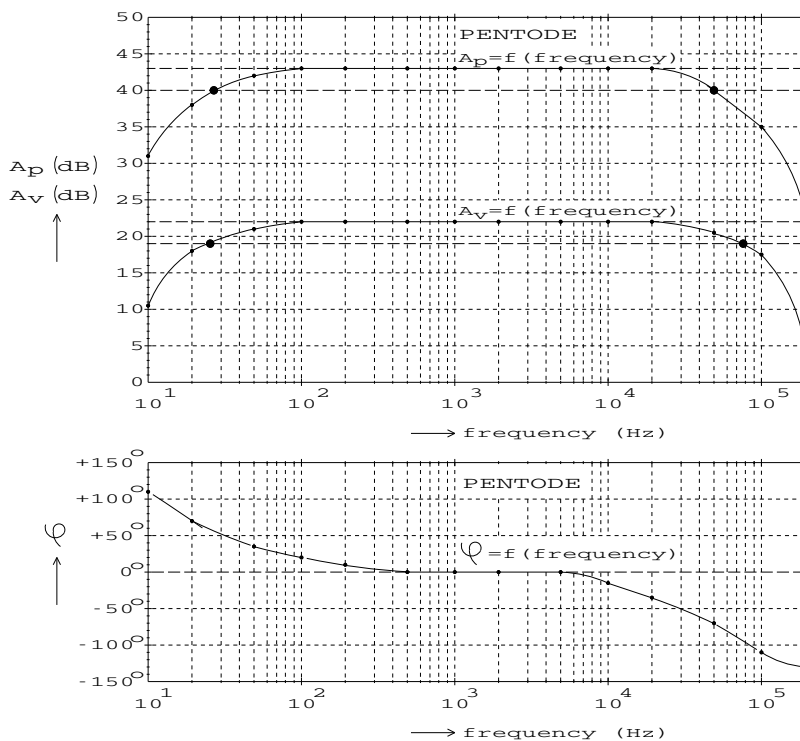


Figure 25. Measured frequency response of the amplifier of figure 21 in pentode configuration.

The difference between A_p and A_v is 21 dB and you can see that in figure 25. The slopes are different because $\log 14.1$ of A_p is not equal to $\log 12.9$ of A_v .

Lastly, I will compare non-linear distortions, see figure 26.

- If we accept just visible distortions on the oscilloscope, we can take the maximum power shown as delivered by the anode, p_a , multiplied by the transformer efficiency of about 93 %.

Configuration TRIODE:

- The triode amplifier generates mainly even harmonics (2nd) and that meets theory.
- A push pull power amplifier should eliminate the even harmonics, but not in the actual case of this amplifier. This is because although the anode DC currents are equal, the power tubes (and their parameters) are not identical.
- The figures for the distortion are not so bad, but opinions about this differ.
- This triode amplifier sounds very good, even at full-power drive. Of course, this is my personal opinion.

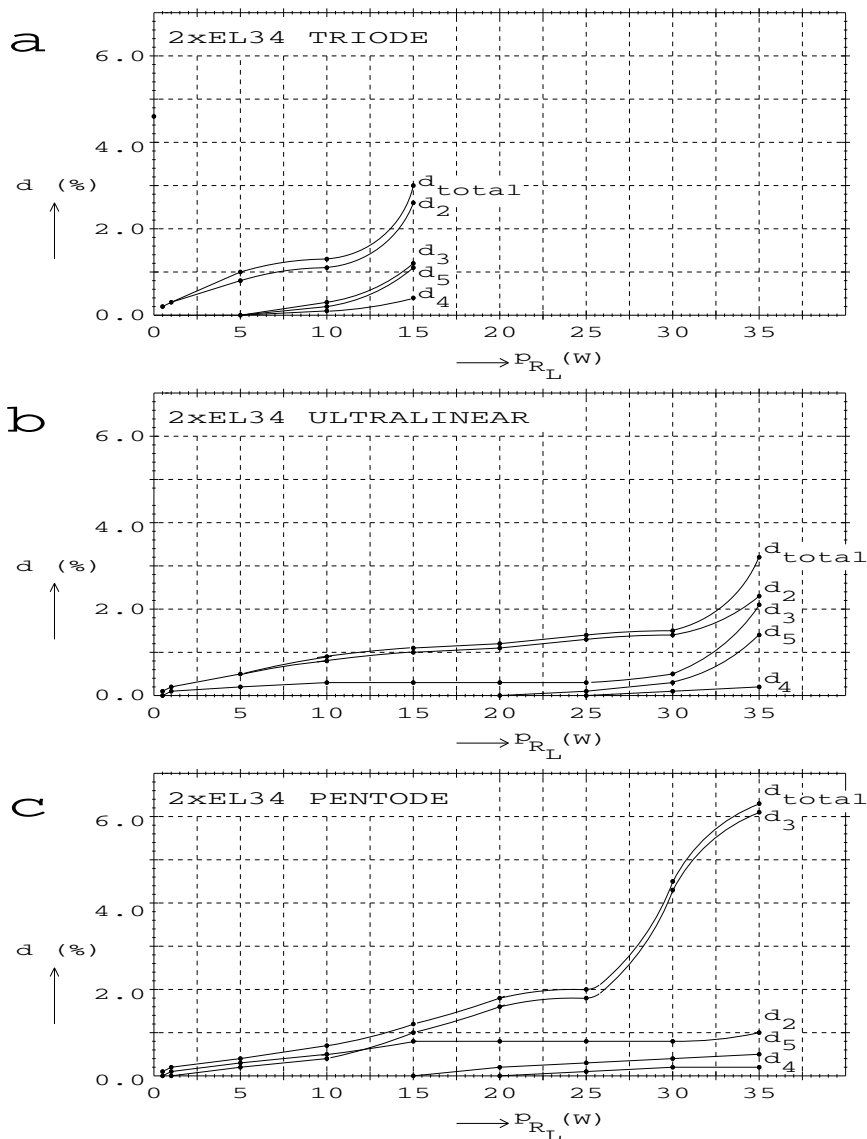


Figure 26. The harmonic distortions d_2 , d_3 , d_4 , d_5 and d_{total} (= THD) as function of output power P_{RL} of the circuit of figure 21 in the configurations triode, ultra-linear and pentode.

Configuration ULTRA-LINEAR:

- The ultra-linear amplifier has almost the same figures for distortion as the triode configuration. This is with a delivered anode power of 35 W, double the power of the triode configuration. Personally, I find this a very good result, but your opinion is possibly different.



- The maximum power is almost the same as that of the pentode configuration, but with half the distortion figures of the pentode configuration.
- Up to 30 W delivered anode power, this configuration leans slightly toward the triode configuration due to the even harmonics (2nd). Above this 30 W, the configuration leans more to the pentode configuration with its strongly increasing 3rd and 5th harmonics. Due to this, d_{total} increases strongly
- 20 W anode power gives a lot of sound volume and with 1 % distortion this is quite good.
- This ultra-linear amplifier sounds very good, also even at full-power drive. Of course, this is again, my personal opinion.

Configuration PENTODE:

- The pentode amplifier is known for its odd harmonics (3rd) and these are not (partially) cancelled by the push-pull configuration. The 2nd harmonic is half that of the ultra-linear configuration and is cancelled better by the push pull configuration. This is a pentode property. It seems that the pentode characteristics of these specimens of the EL34 tube are more equal than those of the triode characteristics of these same specimens.
- The pentode has too much distortion at maximum delivered anode power, but 25 W with $d_{total} = 2\%$ is not bad.
- My listening opinion says that at full-power drive this pentode amplifier does not sound very good, but at 25 W output power, your author cannot hear any disturbances.

8 Contribution of the anode AC current and screen grid AC current to ultra-linear power

In the network analyses of section 4 we have seen equation: $\frac{v_{ak}}{r_a} = -(i_a + x \cdot i_{g2}) = i_{total}$

As explained previously, i_{total} is a fictive AC current flowing through the anode AC external resistance r_a without screen grid primary transformer tap x . It delivers the same power as the real existing anode AC current i_a and the real existing screen grid AC current i_{g2} in their relationship $(i_a + x \cdot i_{g2})$. They deliver power to anode AC external resistance r_a with a screen grid primary transformer tap x .

We will now study these real existing anode AC current i_a and the real existing screen grid AC current i_{g2} in their relationship $(i_a + x \cdot i_{g2})$. Therefore, we use the test amplifier of the previous section (fig 21) where we select the ultra-linear mode. We use two current probes to achieve an oscilloscope picture for the currents. The results are shown in **figure 27**.

When you connect these current probes to both a DC and an AC voltmeter, you then can measure the currents i_{a1} , i_{a2} , $i_{g2,1}$, $i_{g2,2}$, i_{a1} , i_{a2} , $i_{g2,1}$ and $i_{g2,2}$ respectively. These currents are also mentioned in the schematic of figure 21. We will do the calculations with the AC currents. For the VDV6040PP output transformer, $r_{aa} = 6000 \Omega$ and $x = 0.40$. **Table 8** shows $x = x_{measured}$. In contrast to the test transformer, this one has a real screen grid primary transformer tap.

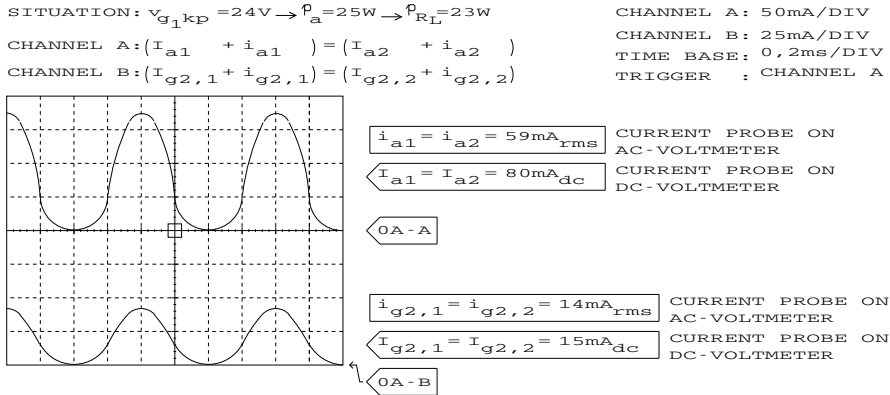


Figure 27. Anode currents and screen grid currents for the ultra-linear power amplifier

$v_{ak} (V_{RMS})$	$v_{g2,k} (V_{RMS})$	$x_{measured} = \frac{v_{g2,k}}{v_{ak}}$	given x of power transformer VDV6040PP
31,1	12,5	0,402	0,4
100,0	40,1	0,401	0,4
193,6	78,0	0,403	0,4

Table 8. Actual anode- and screen grid voltages and $x_{measured}$ for nominal $x=0.4$

The measured values are also shown in figure 27 where $v_{ak} = 193.6 V$ and $v_{g2,k} = 78.0 V$:

- $i_{a1} = i_{a2} = i_a = 59 mA_{RMS}$
- $I_{a1} = I_{a2} = I_a = 80 mA_{DC}$
- $i_{g2,1} = i_{g2,2} = i_{g2} = 14 mA_{RMS}$
- $I_{g2,1} = I_{g2,2} = I_{g2} = 15 mA_{DC}$

If we substitute these measured values of i_a and i_{g2} in the equation for i_{total} we get the measured fictive AC current:

$$i_{total} = i_{a,measured} + x \cdot i_{g2,measured} = 59 + 0.4 \times 14 = 59 + 5.6 \Leftrightarrow$$

$$i_{total} = 64.6 mA_{RMS}$$

We can also read anode power p_a for full-power drive ultra-linear from figure 22: **$p_a = 25 W$**

For each power pentode this is: $p_{a-EL34} = 12.5 W$

Also $p_{a-EL34} = i_{total}^2 \cdot r_a$ and $r_a = \frac{1}{2} \cdot r_{aa} = \frac{1}{2} \times 6000 \Omega = 3000 \Omega$

$$12.5 = i_{total}^2 \times 3000 \Leftrightarrow$$

$$i_{total} = \sqrt{\frac{12.5}{3000}} = \sqrt{4.1667 \times 10^{-3}} = 0.0645 A_{RMS} \Leftrightarrow$$

$$i_{total} = 64.5 mA_{RMS}$$



Calculated differently : $p_{a-EL34} = \frac{v_{ak}^2}{r_a}$

Substitute $12.5 = \frac{v_{ak}^2}{3000} \Leftrightarrow v_{ak} = \sqrt{12.5 \times 3000} = \sqrt{37500} = 193.6 V_{RMS}$

Apply equation : $i_{total} = i_{a,measured} + x \cdot i_{g2,measured} = \frac{v_{ak}}{r_a}$

Substitute : $i_{total} = \frac{193.6 V_{RMS}}{3000 \Omega} = 0.0645 A_{RMS}$
 $i_{total} = 64.5 \text{ mA}_{RMS}$

I'm sure you will allow me to neglect the difference of 0.1 mA_{RMS}.

The effect of this fictive i_{total} is an anode power of 12.5 W for one power pentode.

The effect of $(i_{a,measured} + 0.4 \times i_{g2,measured})$ is also an anode power of 12.5 W for one power pentode.

Thus, a piece of network analysis has been proven: *quod erat demonstrandum*

References

- [1] *Fundamental Amplifier Techniques with Electron Tubes*; 1st edition 2010; Rudolf Moers; Published by Elektor International Media BV; ISBN 978-0-905705-93-4
- [2] *An Ultra-Linear Amplifier*; David Hafler and Herbert I. Keroes; article in Audio Engineering; November 1951
- [3] *Radio Technique part 1*; 2nd edition 1959; A.J. Sietsma; Published by H. Stam, Haarlem
- [4] *Modern High-End Valve Amplifiers based on toroidal output transformers*; 1st edition; Menno van der Veen; Published by Elektor International Media BV; ISBN 0-905705-63-7
- [5] *Lehrbuch der Elektronenröhren und ihrer technischen anwendungen*; 8th edition 1928; Dr. H. Barkhausen; Published by S. Hirzel Verlag Leipzig
- [6] www.svetlana-tubes.com
- [7] www.triodefestival.net → ETF2007 → Tube Curves Tracer