ELEKTOR ACADEMY PRO

Tube Amplifier Circuits

From SRPP and Mu-Follower to OTL Designs

Peter Dieleman

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MEDIA & LEARNING

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Preface

In 2004 Elektor published my first book:
'Theorie en Praktijk van Buizenversterkers'.

The book was a success and soon it was translated into French and into German.
'Théorie & pratique des amplificateurs audio à tubes' was the French title.
The German name was 'Theorie und Praxis des Röhrenverstärkers'.

I wrote the book because in those days knowledge on tubes was not easily available.

In a German Elektuur book 'Audio en HiFi-buizen', the author Rainer zur Linde described an SRPP driver invented by K. Anzai in 1969. I asked myself why such an SRPP would be better than a classic anode resistance amplifier.
I started doing calculations on the design.
It was wrong. I found out about the most infamous mistake (the cathode elco).
I got interested and later on I learned that the design had three of the errors mentioned in this SRPP book in it.
Although the design was wrong, the idea was inspiring. I did research and one of the designs in my first book had such an SRRP but now without the errors.

In the following years I did more research on SRPPs but also on mu-followers and OTLs.

In 2009 Elektor published my second book on these matters.
It was immediately translated into German.

Today Elektor and I still get requests for a reprint. The books are out of stock.
Elektor decided no to do another reprint but instead to translate the book into English thus reaching a much larger readers community.

The result is this book. It has been revised a bit. The Dutch version contained a few little errors and my knowledge has grown in the past years.
I consider this version to be much better than the Dutch and the German ones.
It is consequent in style and much more accurate in the details.

I want to thank Jan Didden who inspired Elektor and me to accept the translation and the publishing job. I got in contact with him and he made me publish the article ‘Myths in Tube Circuit Design’ in the audioxpress magazine in May 2023.

I thank Menno van der Veen for his inspiring words and friendship during the past many years.

I thank Elektor’s Patrick Wielders for having transformed the manuscript into a good looking book.

Introduction

Tube amplifiers suffer from distortion.
Fortunately, there exist SRPP amplifiers, μ-followers, β-followers etcetera.
All these produce a minimal distortion even with output voltages of 50 to 100 V_t.

Often these designs are published with errors in them.
It shows to be easy to make a wrong design when we do not have a good understanding of the theory.

In the first section of this book we investigate the origin of the distortion and after that the design of an SRPP and of a μ-follower.

On the internet we can find the most exotic designs. Evaluating them teaches us that these designs often make things worse than they are by nature. In the chapter on wrong SRPPs and μ-followers we sometimes see bizarre but also misplaced designs where a simple, one triode amplifier would perform much better.

There exist push-pull end stages. These are investigated and the similarity with the SRPP are looked at. This is done especially with the theory behind the OTL based on the 'mother' of all OTLs, the Philips HF303.

Finally attention is given to the frequency characteristics and technical matters like the supply voltage and the power supply of the filaments.

In order to illustrate things there are a few designs that describe the discussed subjects.

This book describes much new theory that has not been published before.
Often it is an eye opener as it shows that most things have a beautiful and unexpected simplicity.

Section 1

Prior knowledge

1 Conventions and notations

In scientific publications it is customary that the author call himself 'the writer'. He also uses the word 'reader'.
I prefer the more charming 'I' and 'you'.
Conveying knowledge is a joint effort.
In this book I will use 'we have', 'we can see' etcetera.

In this book it is tried to consequently use a number of notations and conventions. These are described below.
Alle DC voltages(tensions), -currents and DC resistances are indicated with italic uppercase letters *U, I* and *R*.
Two examples: U_{ak}: the DC voltages between anode and cathode
R_a : the anode resistance

In English literature the power supply voltages is often called HT (**H**igh **T**ension) but in this book it is indicated by U_b. This comes from its European origin.

Resistances that are numbered are written as R4 etc.

A *resistance* is a component in a schematic. A *resistor* is something you can touch. It may get hot.
The same distinction is made for *capacities* versus condensers or *capacitors*.
A triode or a pentode again is a component in a schematic. A tube is the glass thing that will break when it falls out of your hands. It gets hot. A *tube* like an ECC83 or 12AX7 contains two *triodes*.
Compare self-inductions versus the physical coil.

A transformer often is called a trafo.

The value of a resistance is written as 6.8 kΩ. In schematics this often shows up like 6K8. This is an old Dutch Elektor habit.

The maximum value of the power the resistor must be able to withstand is indicated only when this is relevant.

All AC voltages, -currents and -impedances are indicated with a lower case letter.
For AC voltages we use the letter *v*; not the lower case letter *u*.
The unity of course is volt or V for DC. For AC signals we use 'volts'.
Except in power supply circuits we never use the effective values like 20 V_{eff}.
It makes no sense to give a triode a grid signal of 10 V_{eff}. It is the peak- or top value that counts.

Where needed we use the top values indicate by V_t or V_{tt} although others may prefer V_p or V_{pp}. V_p is reserved for a pentode's V_{plate}.

In the theory of electrical networks the word *excitation* is used. It means offering a signal to a circuit.
We will use the more mondain word steering- or driving signal. A car has a steering wheel; a tube has a steering grid, also called control grid.

For AC currents we use the lower case letter *i*. Here also we use the top values only.

For AC resistances or impedances we use the lower case letter *r*.
In this book there is never a need for *complex* impedances like $R + j\omega L$.

Two AC resistances are of special importance. They are r_i and r_p.
The first one is the AC resistance that we see, looking into a circuit.
Usually this means the triode's internal resistance: $r_i = \frac{\Delta U_{ak}}{\Delta I_a}$

With r_p the same equation is meant, but then for a pentode. Here the letter p stands for the American word plate; the plate resistance.

In resistances and voltages, the cathode is not written with a 'c' but with a 'k' like in U_{ak}.

The value of electrolytic capacitors is given in µF. In the text they are called an *elco*. Both schematic elcos and physical elcos are called elcos.
The maximum allowed voltage is only given when relevant.

All other capacities are given in pF or nF.

When we use the word *grid* we mean a tube's G_1.
The grid DC voltages are always negative relative to the cathode voltages.
There exists the term NGV. This means **N**egative **G**rid **V**oltage.
We may have NGV = 4 V or U_{gk} = -4 V. Please note the minus sign.
In this book we never use positive grid voltages implying a grid current. These positive grid voltages are used in switching electronics and in radar designs.

In fact all the tube's voltages are relative to the one from the cathode.

The transconductance of a triode or pentode is indicated with a capital letter S.

We use the definition: $S = \frac{\Delta I_a}{\Delta U_{gk}}$

This is the situation without the presence of an anode resistance. It indicates the behavior of the ‘naked’ triode/pentode.

When discussing the transconductance of a triode/pentode in a circuit we use the lower case letter *s*, meaning the so called *dynamic* transconductance.

References are like [Dieleman]. They are mentioned in the reference chapter.

Calculating and calculations is about the derivation of equations.
I use compute, computing and computations when it’s about getting the numerical values.

2 Prior knowledge

To be able to understand the material in this book, knowledge of tubes and the circuits is necessary.
We could derive all this knowledge here but it can be found in several good books.
As a compromise, some results are presented here, where you find references to [Dieleman].
These books (Dutch, German and French) however are hard to get.

2.1 The 3/2 power law

The relation between the current through a diode and the voltage across it satisfy the so called Child-Langmuir equation.

$$I = \frac{4}{9}\varepsilon_0 \frac{A}{b^2}\sqrt{\frac{2q}{m_e}} \cdot U\sqrt{U} \quad \text{or} \quad I = p \cdot U^{\frac{3}{2}} \qquad (2.1)$$

In fact it is the Child equation which was extended many years later by Irving Langmuir. This Langmuir equation can be found in appendix C.

A is the cathode's surface and b is the distance between anode and cathode.
In (2.1) the letter p stands for the word *perveance*.
This perveance value usually is somewhat larger than 1 having the current I in mA and the voltage U in volts.
So for a current of I = 64 mA we need a tension/voltage of U_{ak} = 16 V.

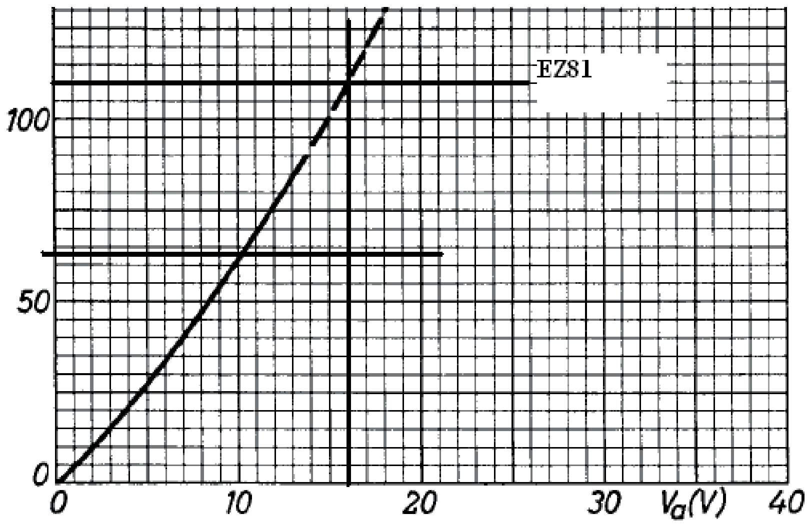

Figure 2.1 The U-I characteristics of an EZ81 rectifier tube

An EZ81 rectifier (see figure 2.1) ends up almost twice as large and has p ≈ 1.7.

Popular tubes have different perveances. An ECC83 (12AX7) with U_{ak} = 150 V and U_{gk} = -2 V has a current of I_a = 3 mA, where a 6SN7 in contrast has a current of I_a = 12.5 mA.
We get a high perveance by using a large cathode. Please note that the cathode's temperature is not in the Child equation (the Child model is somewhat simple).
The perveance however is very dependent on the filament temperature.

This is a good reason to never neglect the correct value of this filament voltage.
The tubes characteristics are only valid when using the indicated voltage.
In appendix C the perveance is further investigated.

2.2 The characteristics of triodes and of pentodes

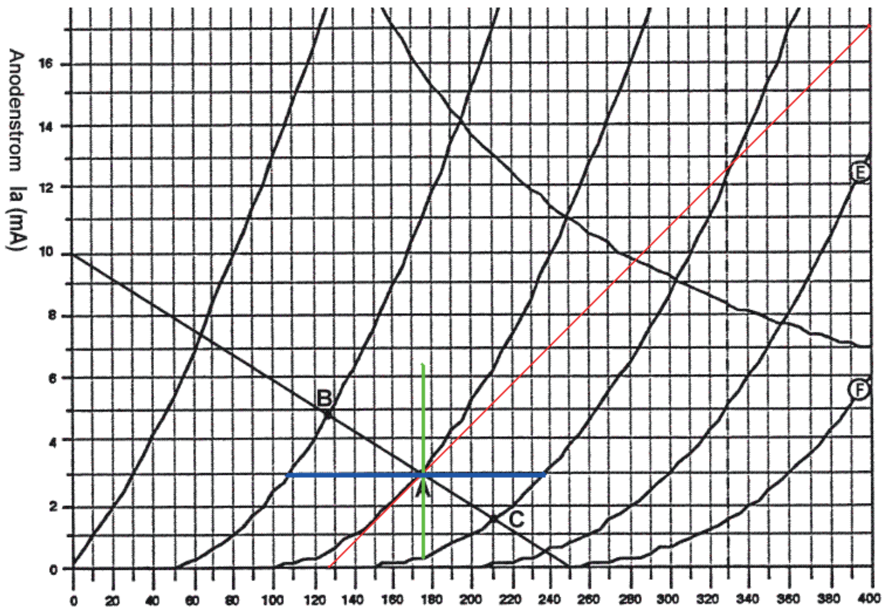

Figure 2.2 An ECC82 or 12AU7
It is a German graph; Anodenstrom means anode current

In the above figure 2.2 we see the characteristics of an ECC82.
For a number of negative grid voltages the current is shown depending on the anode voltage.

Curve E has U_{gk} = -16 V, curve F has -20 V. Each curve to the left every time has a 4 volts less U_{gk} voltage.
The curve through the position A has U_{gk} = -8 V.
The one in position C has -12 V and the one in position B has -4 V.
The leftmost curve has U_{gk} = 0 V. It goes through the zero point and it is in fact the characteristic of a diode like te one we saw for the EZ81.

The Child-Langmuir equation for a triode is $I = p \cdot (U_{gk} + \frac{U_{ak}}{\mu})^{\frac{3}{2}}$ (2.2)

From figure 2.2 we can conclude that with a grid voltage of U_{gk} = -8 V and an anode voltage of U_{ak} = 175 V, there is a current I_a = 3 mA; the position A.

The bold blue *horizontal* line through the point A gives us the amplification factor μ.
We select the point (-8; 175) on the 3 mA line.
When we now go one curve to the right we find a change of the grid voltage of 4 volts.
The corresponding anode voltage is 236 V; the point (-12; 236).
Would we go one curve to the left, we would get U_{ak} = 108 V.

So with a constant current of I_a = 3 mA we find a change of 236 – 108 = 128 V.
The ratio of these voltage changes is thus 128 / 8 = 16.
By definition this is the μ = 16, where the ECC82's specs say μ = 17.
Those specs do not always hold exactly.

The vertical green bold line through A is about the so called *transconductance*.
When, at 175 V in the point A, we go 2 volts upward the current gets I_a = 6.5 mA; an increase of 3.5 mA. When we go 4 volts downward we find a decrease of 2.5 mA. The total change of I_a is 6 mA.
The grid voltage had a change of 6 volts (4 downward and 2 upward).
Now the fraction of these changes by definition is the transconductance.
This is S = 6 / 6 = 1 mA / V. That is not much; most triodes have a larger transconductance.

The tangent in the point A goes horizontally over a distance of 400 – 12 = 273 V. Vertically there is a difference of 17 – 0 = 17 mA.
The internal resistance r_i therefore is 273 / 17 = 16.0625 kΩ.

Multiplying the transconductance and this r_i gives us 16.06. This must be equal to the value of μ.

This is the famous Barkhausen equation $\mu = S \cdot r_i$ (2.3)

Please be aware that a different quiescent position has different r_i and S values.
With small signals we will find the same value for μ.
This μ should be a *constant*; it is about constant.
There is a special chapter 3 about this.

Warning:
At point A in figure 2.2 we see a DC grid voltage of U_{gk} = -8 V. This means that the input signal must have a maximum value of 8 V_t. When we exceed this amplitude there will be a so called *grid current* onset. Where grid current is common in impulse circuits and radar electronics, we never do this in audio amplifiers as it gives an enormous distortion.

In fact there is only *grid room* for 7.5 V_t. This a bit lower value is caused by the existence of the so called *electrons space charge*.
It is approximately 0.5 V in ECC8x tubes.
For an explanation see appendix C on the extended tube model.

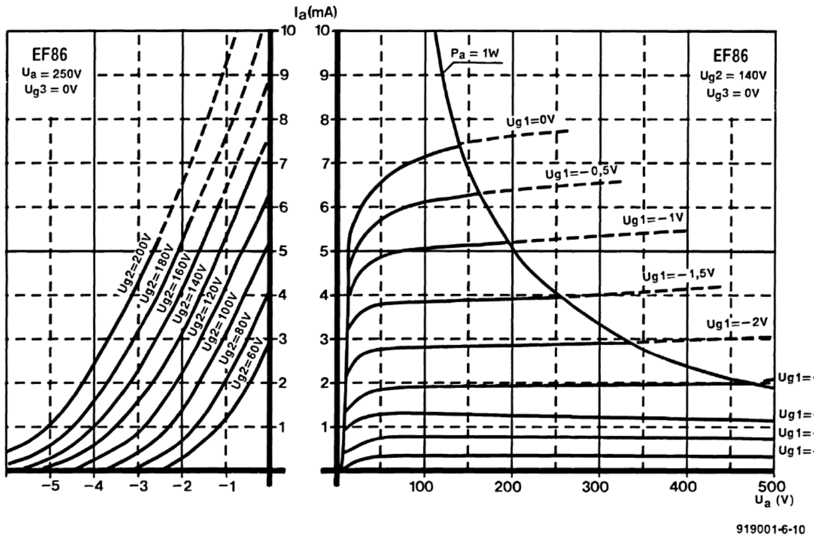

Figure 2.3 The characteristics of the EF86 small signal pentode

The EF86 is a small signal pentode that is often used in audio pre-amplifiers. The U_{g1} = -3 V curve bends downward in the right part of the right graph. The graph's curve most likely is wrong[1].

On the left we see the graphs where the negative grid voltages and the corresponding anode currents are drawn. All of this with a fixed anode voltage of 250 V. You are lucky when this is the anode voltage of your wish. Such a high anode voltage is unusual for an EF86. These left graphs are not used frequently.

[1] In the heroic days, when lacking graphic tools and equipment, these graphs were made by gluing small rubber wires onto a piece of white paper. They were then photographed. The -3 V wire probably was glued somewhat wrong. What we have here is a curiosity.

For a set of G_1 voltages the graphs are drawn in the right part of figure 2.3. From this group of curves we can learn much about the transconductance and the amplification and even about the distortion.

In the right graphs we see the typical shape of pentode curves with the sharp bending at voltages less than 50 V. All graphs are taken using a fixed U_{g2} voltage of 140 V.

More to the right we can see that increasing the anode voltages gives almost no extra current.
In other words the pentode has a high r_p. A value of 1 to 2 MΩ is easily found.
In comparison, the r_i of an end triode is 1 kΩ and it is 10 kΩ to 60 kΩ for a small signal triode.

2.3 The tube's replacement model

Below we see the network substitution schematic of a triode with an anode resistance R_a connected. There is nothing connected to the grid. As known this control grid has an infinite high input resistance.

The anode current has two components. The left one is the contribution of the current source. This contribution is $S \cdot v_g$.
The second (the right one's) contribution is of the AC current caused by the changing anode voltage.
This contributing current goes through the resistance r_i.

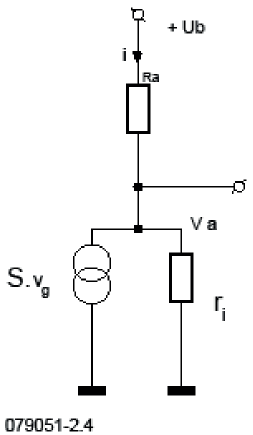

Figure 2.4 The triode's substitution model

The definition of transconductance is $S = \frac{\Delta I_a}{\Delta U_{gk}}$ (2.4)

The definition of the internal resistance is $r_i = \frac{\Delta U_{ak}}{\Delta I_a}$ (2.5)

Multiplying S and r_i again gives the classis Barkhausen equation:

$\mu = S \cdot r_i$. (2.3)

The definition of the amplification factor is $\mu = \frac{\Delta U_{ak}}{\Delta U_{gk}}$ (2.6)

2.4 Amplifications and impedances

We start with the elementary schematic below:

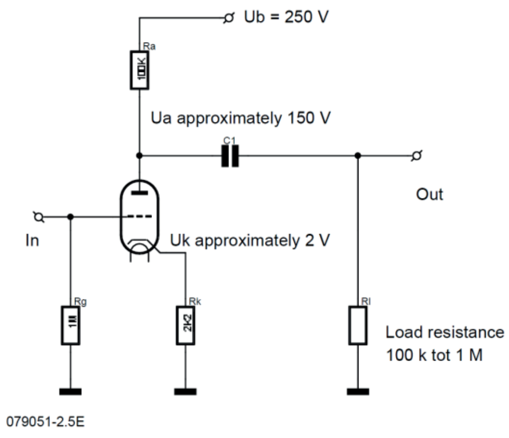

Figure 2.5 A non-decoupled resistance amplifier

For this circuit we have an amplification

$$Amp = \mu \cdot \frac{r_a}{r_a + r_i + (\mu{+}1) \cdot r_k} = \mu \cdot \frac{r_a}{r_a + r_i + \hat{u} \cdot r_k} \quad (2.7)$$

For short in this book we write **û** instead of (μ+1). This is just for brevity.

In this equation r_a is the switching in parallel of the anode resistance R_a and the load resistance R_{load}.
Usually the influence of the latter is small as it is a resistance of 1 MΩ (say), where R_a = 100 kΩ.
For an end triode we often have a smaller value like 270 kΩ.

Decoupling the cathode resistance in (2.7) with an elco, r_k gets the value 0.
So often the amplification reduces to:

$$Amp = \mu \cdot \frac{r_a}{r_a + r_i} \quad \text{or even to } Amp = \mu \cdot \frac{R_a}{R_a + r_i} \qquad (2.8)$$

Typical values are: ECC81 (12AU7), μ = 60, R_a = 100 kΩ and r_i = 15 kΩ.
For the amplification we then find Amp = 52 times. Amp is always less than μ.

2.5 Output impedance

Looking inward from above into the anode we see an output resistance of

$$r_u = r_i + \hat{u} \cdot r_k \qquad (2.9)$$

When decoupling the cathode resistance, this reduces to $r_u = r_i$, what could be expected looking at the triode's substitute model.

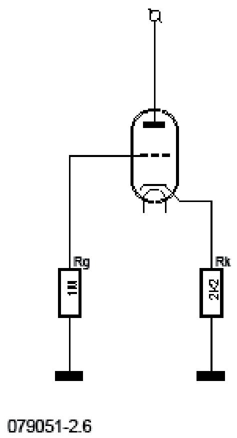

Figure 2.6 Output resistance seen at the anode.

Looking at figure 2.7 below, we could also look upward into the triode from the cathode.

We then see an AC resistance of $r_u = \frac{r_a + r_i}{\hat{u}}$ (2.10)

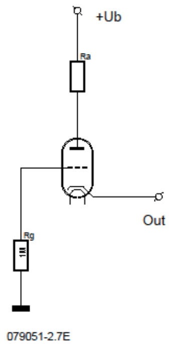

Figure 2.7 The output resistance seen from the cathode

The output resistance then is:

$$r_u = \frac{r_i}{\hat{u}} = \frac{r_i}{\mu + 1} \approx \frac{r_i}{\mu} = \frac{1}{S} \qquad (2.11)$$

Even for an ECC83 with its small transconductance of 1.2 mA / V, this results in a value less than 1 kΩ which is very small in the world of tubes.

2.6 Operation points of end triodes

A triode in a balanced end stage in class A is said to have an optimal so-called *match* when $r_a = 2 * r_i$ and thus in a balanced stage $r_{aa} = 4 * r_i$. (2.12)
r_a and r_{aa} here are the transformers primary impedances.
The theory can be found in [Dieleman] or in one of the better and complete books.
The theory in the next paragraphs corresponds to a **model**. Please note that this model is not sound. It is useful for making quick estimates. The only correct conclusions can be drawn looking at the graphs/characteristics.

The efficiency in class A is only 25 %. This is the main objection against the usage of triodes in an end stage.

The maximum AC anode *voltage* is half the one from U_{ak}.
The maximum value of the AC anode *current* equals the quiescent I_a.

Most designers strive to have a perfect match. It is not so that we always want this.

The efficiency in general is: $W_a = ½\ P_a \bullet (1 - 2 \cdot \frac{P_a \cdot r_i}{U_{ak}^{\ 2}})$ (2.13)

This equation is quite unknown. P_a is the triode's dissipation.

Equation (2.12) is a special case of (2.13).

So the triode's efficiency also has a maximum of 50 %, just like the one from a pentode. This is in contrast to what is often published.
We reach this maximum by taking a high value of U_{ak} and a triode with a low r_i at the same time.
Switching two triodes in parallel to get half the value of r_i does not solve a thing because the value of P_a between the two parentheses also doubles.
The product of P_a and r_i remains the same.
We really need a triode that has a low r_i by design.

$$v_i = \frac{3 \cdot U_{ak}}{4\ \mu} \qquad (2.14)$$

For an EL84 (6BQ5) with U_{ak} = 250 V and μ = 19 this gets v_i = 10 V_t.
For an EL34 with U_{ak} = 250 V and μ ≈ 10 we get v_i = 19 V_t.

The cathode resistance of an matching triode circuit has a value of:

$$R_k = {}^3/_S \qquad (2.15)$$

For an EL84 we then get 270 Ω.

As said, this model is not sound. In reality we often find r_a = 3 * r_i.

2.7 Efficiency

An end stage absorbs energy from the power supply. Only a small fraction of it is transported to the loudspeakers. The rest is wasted as heat in the tubes.
The efficiency much depends on the so called class.
There is class A, B and AB and on the other hand there is the choice between a triode or a pentode.

In [Dieleman] these efficiency percentages are derived completely.
In this paragraph the essences are presented.

2.7.1 The pentode in class A

We start with a pentode because that is easiest.

First, we look at the real characteristics of an EL84 pentode.
Look at the year in the upper right corner; it may be older than you are 😊.

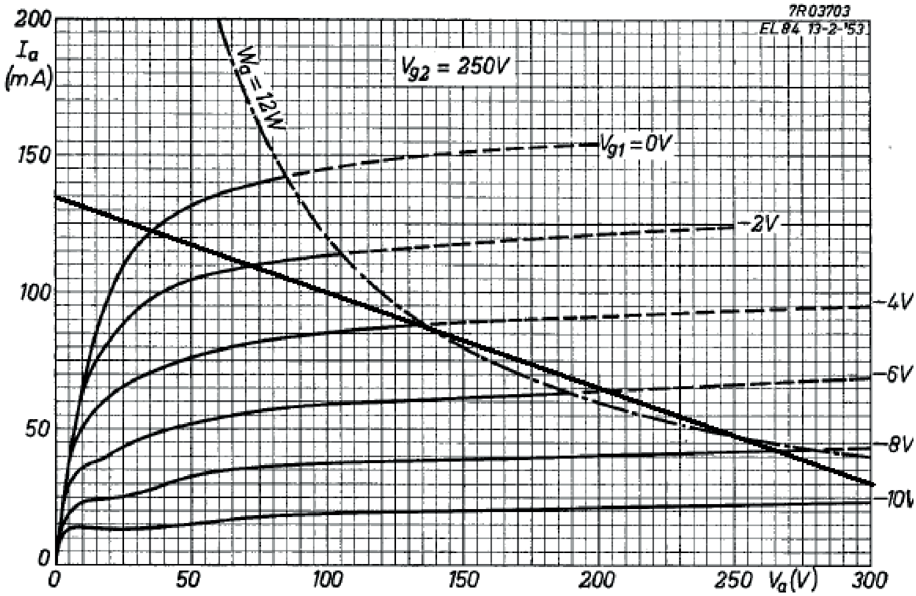

Figure 2.8 The EL84 pentode

Please note that the *dissipation hyperbolic* has the name W_a. In this book the *dissipation* has the name W_a where the *output power* to the loudspeakers is called P_a.

With curves like the ones in figure 2.8 the calculation of the efficiency cannot be done. We therefore idealize them getting the model below.

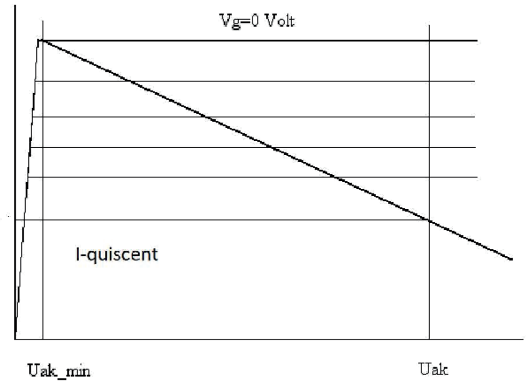

Figure 2.9 Idealized pentode curves

The sharp bending of the curves lies at U_{ak_min} which is almost 0 V and the curves are horizontal which means that we suppose an infinite r_p.

In quiescent mode there is an anode voltage U_{ak} and a current $I_{quiescent}$.
The consumed power given by the power supply therefore is:

$$P_b = U_{ak} \cdot I_{quiescent} \qquad (2.16)$$

The calculations are done for a class A pentode.
The *current* can drop to 0 and increase to twice the value of $I_{quiescent}$.
The anode *voltage* of a pentode can drop to almost 0 V.

This corresponds to a loudspeaker(transformer) power of:

$$W_a \approx ½ \cdot U_{ak} \cdot I_{quiescent}. \qquad (2.17)$$

The factor ½ result from working with top values in stead of effective values.

The efficiency is computed by dividing (2.17) and (2.16) so this has a maximum of ½. In reality it is somewhat less because the anode voltage cannot drop to zero. The real efficiency is about 40 %.
In this computation we also neglect the G_2 power loss and the filament heating power.

In practice the quiescent mode is taken somewhat below the dissipation hyperbolic. We would not risk destroying the tube by overheating it.

The load line intersects the curve for U_{gk} = 0 V where the bending of the curve is at its maximum.
In figure 2.8 this means the point U_{ak} = 250 V with I_a = 46 mA.
The line exceeds the hyperbolic which means that the above values are a bit too large.
To have a reliable and robust design we take a somewhat smaller quiescent current and/or a bit more flat load line.

2.7.2 The triode in class A

The model calculations for a triode are much more difficult. See [Dieleman].
In this chapter the calculations are made such as to let them look acceptable.

Firstly, again the real characteristics of an EL84, wired as if it were a triode.
This is done by connecting G_2 to the anode.

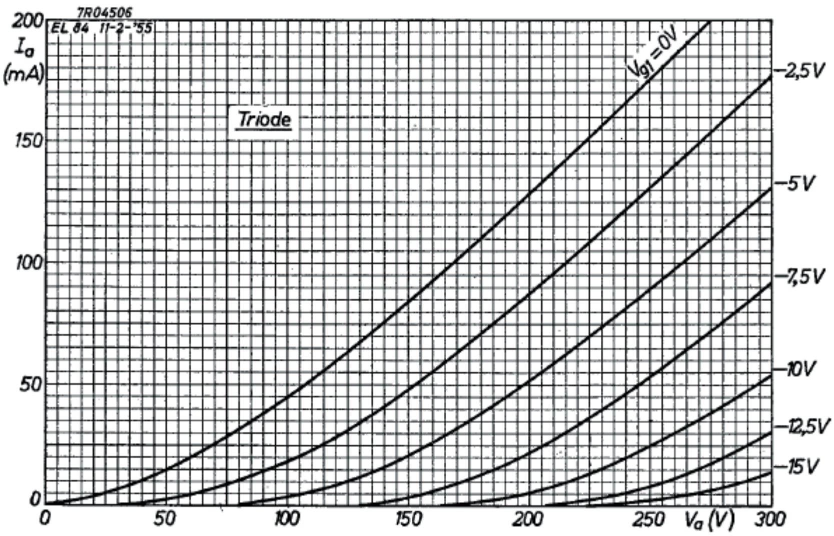

Figure 2.10 The characteristics of an EL84 triode

To ease the calculations, once more we use the idealized curves below.

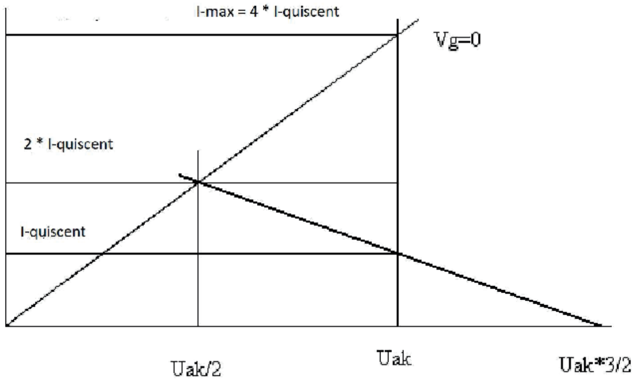

Figure 2.11 Idealized triode curves

The real calculations are quit elaborate. Here is the easier recipe.
Choose an U_{ak} and then divide the maximum dissipation value W_a by this U_{ak} and we get the current $I_{quiescent}$.
The maximum triode current is reached when U_{gk} = 0 V. We choose twice the value of the quiescent current. In class A the current can now drop to zero when the G_1 signal is negative and increase to twice the value of $I_{quiescent}$ with a positive G_1 signal .
The left point of the load line is now known.
The anode voltage there has half the chosen value of U_{ak}.
We can now draw the complete load line. It intersects the I = 0 horizontal where U_{ak} happens to be 3/2 times the chosen value of U_{ak}.
This 3/2 has nothing to do with the same factor in the Child equation.

The anode voltage has a top value of $v_a \approx ½ \cdot U_{ak}$. (2.18)

The current has a top value of $I_{quiescent}$.
The loudspeaker (transformer) power W_a now is:

$$W_a \approx ½ \cdot (½ \cdot U_{ak}) \cdot (I_{quiescent}) = ¼ \cdot U_{ak} \cdot I_{quiescent} \quad (2.19)$$

The consumed power again is $P_b = U_{ak} \cdot I_{quiescent}$ (2.20)

The efficiency now is ¼. That is not much but this what it is using a triode according to the model.

Taking the pentode's G_2 power into account[2] makes the comparison a bit less embarrassing.

From figure 2.10 we can conclude that we can drive the triode further to the direction U_g = 0 V when we have a triode with a low r_i. The curve gets more vertical. In general the equation below holds:

$$W_a = ½\ P_a \bullet (1 - 2 \cdot \frac{P_a \cdot r_i}{U_{ak}^2}) \qquad (2.13)(2.21)$$

We can rewrite this equation towards the one for efficiency

$$\nu = \frac{W_a}{P_a} = ½ \bullet (1 - 2 \cdot \frac{P_a \cdot r_i}{U_{ak}^2}) \qquad (2.22)$$

We can see that the efficiency ν (the Greek letter called nu; it is not the letter 'v') has a maximum of 50 % when the parenthesized part has a value of 1, or when the right term is at its minimum. We get this, so to speak, with a low value of r_i.

We may also take a large value for U_{ak}. This can easily be seen. Suppose we have U_{ak} = 170 V where we can make the anode voltage drop to 70 V.
We have an anode signal of 100 V_t.

The power supply then produces $P_b = 170 \cdot I_{quiescent}$ (2.23)

The loudspeaker power then is $W_a \approx ½ \cdot 100 \cdot I_{quiescent}$. (2.24)

The efficiency is 50 / 170 = 29 %.

Now we repeat the calculations with U_b = 370 V. We now can get a signal of 300 volts.

The power supply produces $P_b = 370 \cdot I_{quiescent}$

The loudspeaker power then is $W_a \approx ½ \cdot 300 \cdot I_{quiescent}$ (2.25)

[2] These calculation are from the time when the pentode's advantages were demonstrated. Manufacturers did not always hesitate and did some exaggeration.

The efficiency now is 150 / 370 = 40 %.

Always beware not to exceed the tubes maximum dissipation.

The efficiency overview in class A is:

- triode 25 – 30 %
- pentode 40 – 45 %

Please note that a pentode in class B can return as much as almost 75 %.

The warning was given before: the model is not that sound.
Use it as a first indication. Use the characteristics to get the real and correct values. The graphs always give these correct values.