An investigation of the screen grid tap
A search for the hidden arguments

Rudolf Moers

GLOSSARY OF SYMBOLS

v_p	primary transformer AC voltage
i_p	primary transformer AC current
Z_p	primary transformer AC impedance
R_p	primary transformer DC resistance (copper)
v_s	secondary transformer AC voltage
i_s	secondary transformer AC current
Z_s	secondary transformer AC impedance
R_s	secondary transformer DC resistance (copper)
n	transformation ratio
x_{TURNS}	screen grid tap expressed as part of the turns
$x_{TURNS\text{-}\%}$	screen grid tap expressed as percentage of the turns in %
$x_{IMPEDANCE}$	screen grid tap expressed as part of the impedance
$x_{IMPEDANCE\text{-}\%}$	screen grid tap expressed as percentage of the impedance in %
V_b	supply DC voltage
V_{g1k}	control grid cathode DC voltage
$\Delta V_{g1k} = v_{g1kp}$	control grid cathode AC voltage amplitude (**p**eak value)
V_{g2k}	screen grid cathode DC voltage
$\Delta V_{g2k} = v_{g2kp}$	screen grid cathode AC voltage amplitude (**p**eak value)
V_{ak}	anode cathode DC voltage
$\Delta V_{ak} = v_{akp}$	anode cathode AC voltage amplitude (**p**eak value)
I_a	anode DC current
$\Delta I_a = i_{ap}$	anode AC current amplitude (**p**eak value)
I_{g2}	screen grid DC current
$\Delta I_{g2} = i_{g2p}$	screen grid AC current amplitude (**p**eak value)
S	static anode transconductance
S_d	dynamic anode transconductance
S_2	static screen grid transconductance
S_{2d}	dynamic screen grid transconductance
r_i	anode AC internal resistance (also called plate resistance)
r_a	anode AC external resistance (external AC load at the anode)

1 Introduction

My first article for Linear Audio, *The Ultra-Linear Power Amplifier*, was published in Volume 2 [6]. One of the sections of that article is called *Practical determination of the screen grid tap*. With my own discovered method I thought it was possible to determine the screen grid tap with the lowest THD. That was wrong. With my method I can achieve the most linear anode characteristic.
A lot of measurements which show the relation between THD and the screen grid tap, have learned me that the lowest THD is not achieved at the screen grid tap which gives the most linear anode characteristic only.
I also studied results of similar measurements done by great engineers like F. Langford-Smith and A.R. Chesterman [2], and D.T.N. Williamson and P.J. Walker [3].
A nice coincidence is that the article of F. Langford-Smith and A.R. Chesterman was published in the same month and year that I was born.

In this article I will lead you through my investigation and the hidden arguments why the lowest THD is achieved at a certain screen grid tap. I will repeat my method followed by another method according to an algorithm of the µTracer which was described in L|A-Volume 8 [5]. Each of these methods can derive the other one. Both methods can give a linear anode characteristic but not the lowest THD. I will treat measurements (push pull situation) done by the mentioned great engineers as well as my own measurements (single ended situation).

First a short review of the Ultra-Linear Power Amplifier (extensively covered in [7]).
Observe **figure 1**. With the triode connection, we see a gentle 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*-axis is shown along the primary winding of the output transformer. The transformer side connected to V_b is called $x = 0$. Because V_b is a short circuit for AC currents, we can say that $x = 0$ = grounded. The side of the transformer connected to the anode is called $x = 1$.
Scale *x* is divided homogeneously over the geographical position of the primary transformer winding.

What do we do, when we want a linear anode characteristic in the form $I_a = k_{ultralinear} \cdot V_{ak}$?
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*.
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 2**.

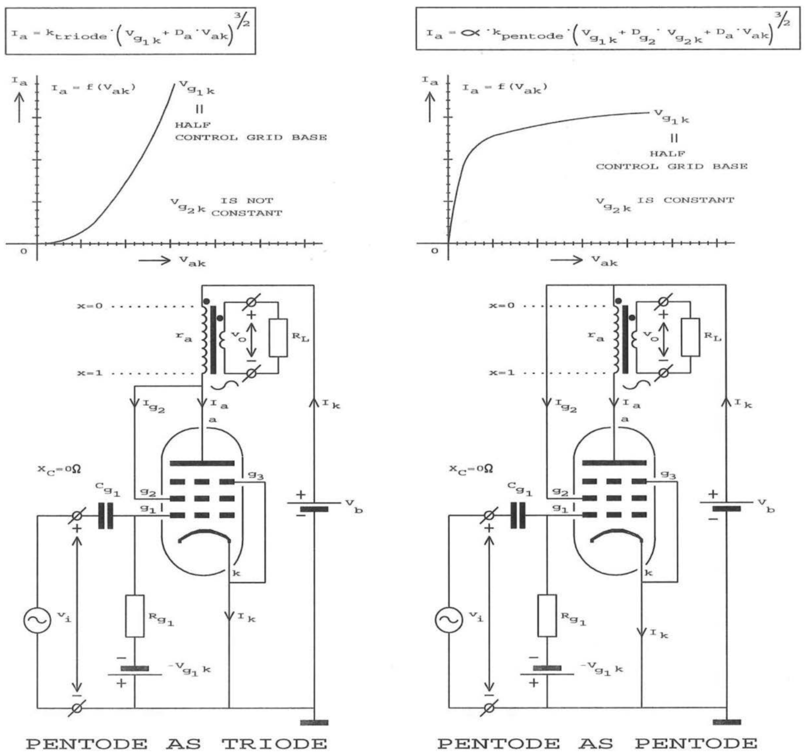


Figure 1 Pentode as triode and pentode as pentode in a power amplifier.

The part between the screen grid primary transformer tap *x* and V_b is called $x{\cdot}r_a$ and the part 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_{g2k} is a tap of anode cathode AC voltage v_{ak}. The screen grid cathode AC voltage v_{g2k} is superimposed on the screen grid cathode DC voltage V_{g2k}. $(V_{g2k} + v_{g2k})$ changes instantaneously and because of this, the attractive force on the electrons in the electron cloud around the cathode changes. The screen grid behaves slightly adversely as does the anode with triodes. However, with a less attractive force on the electron cloud than with real triodes.

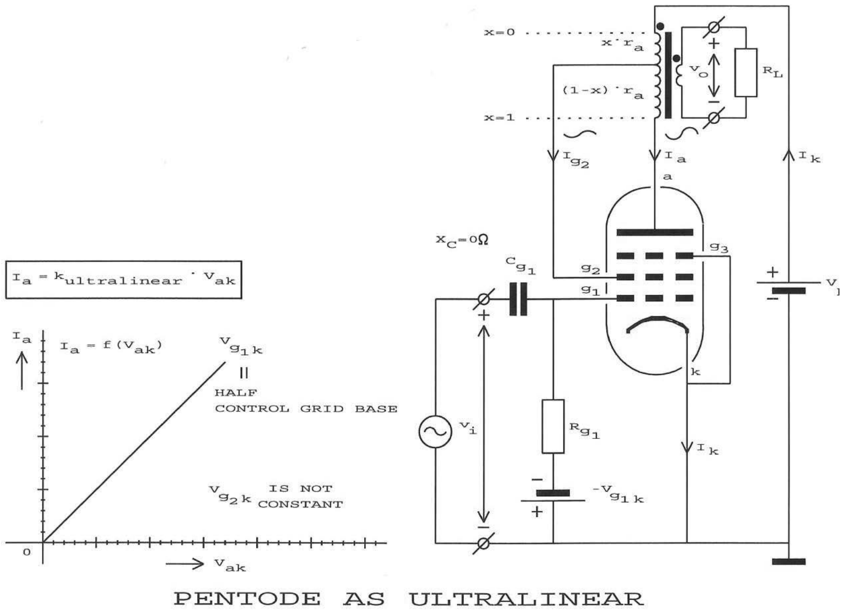


Figure 2 Pentode as ultra-linear power amplifier.

2 Definitions of the screen grid tap

After writing my book [7], and my article for Volume 2 [6], I still knew only one definition of the screen grid tap. Later, after reading [2], I learned that there are two definitions of the screen grid tap. It is important to distinguish them.

The transformation ratio is the ratio of the primary voltage and the secondary voltage: $n = \frac{v_P}{v_S}$

The transformation ratio is also the ratio of the secondary current and the primary current : $n = \frac{i_S}{i_P}$

The ratio of the transformation impedances: $\frac{Z_P}{Z_S} = \frac{\frac{v_P}{i_P}}{\frac{v_S}{i_S}} = \frac{v_P}{i_P} \cdot \frac{i_S}{v_S} = \frac{v_P}{v_S} \cdot \frac{i_S}{i_P} = n \cdot n = n^2 \Leftrightarrow n = \sqrt{\frac{Z_P}{Z_S}}$

Hence $\frac{v_P}{v_S} = \sqrt{\frac{Z_P}{Z_S}}$.

Now I give these ratios their own transformation ratio: $n_{TURNS} = \frac{v_P}{v_S}$ and $\sqrt{n_{IMPEDANCE}} = \sqrt{\frac{Z_P}{Z_S}}$

Hence $n_{TURNS} = \sqrt{n_{IMPEDANCE}}$.

Screen grid tap *x* is a fraction of *n* (meant is here number of windings) and $0.0 < x < 1.0$.

Hence $x \cdot n_{TURNS} = \sqrt{x \cdot n_{IMPEDANCE}}$

The next step is rather strange but I do this because x is a part of n_{TURNS} and a part of $n_{IMPEDANCE}$.

$x_{TURNS} = \sqrt{x_{IMPEDANCE}}$

To express x_{TURNS} in % I need to multiply this equation with 100, hence index $_{TURNS}$ becomes $_{TURNS-\%}$.

$$x_{TURNS-\%} = 100 \cdot \sqrt{x_{IMPEDANCE}} \quad \text{in \%}$$

$$x_{TURNS-\%} = \sqrt{100} \cdot \sqrt{100} \cdot \sqrt{x_{IMPEDANCE}} \quad \text{in \%}$$

$$x_{TURNS-\%} = \sqrt{100} \cdot \sqrt{100 \cdot x_{IMPEDANCE}} \quad \text{in \%}$$

$$x_{TURNS-\%} = 10 \cdot \sqrt{100 \cdot x_{IMPEDANCE}} \quad \text{in \%}$$

When I multiply $x_{IMPEDANCE}$ with 100, then index $_{IMPEDANCE}$ becomes $_{IMPEDANCE-\%}$.

Hence $x_{TURNS-\%} = 10 \cdot \sqrt{x_{IMPEDANCE-\%}}$ in %

This equation can be found, without derivation, in [2].

To do this calculation in an opposite way we achieve:

$$10 \cdot \sqrt{x_{IMPEDANCE-\%}} = x_{TURNS-\%} \quad \text{in \%}$$

$$\sqrt{x_{IMPEDANCE-\%}} = 0.1 \cdot x_{TURNS-\%} \quad \text{in \%}$$

$$x_{IMPEDANCE-\%} = 0.1^2 \cdot x^2_{TURNS-\%} \quad \text{in \%}$$

$$x_{IMPEDANCE-\%} = 0.01 \cdot x^2_{TURNS-\%} \quad \text{in \%}$$

$$x_{IMPEDANCE-\%} = \frac{x^2_{TURNS-\%}}{100} \quad \text{in \%}$$

When Hafler and Keroes, see reference [1], determined that $x_{IMPEDANCE-\%}$ =18.5% gives the lowest THD, then for those who "think in a screen grid tap in turns", the lowest THD is at $x_{TURNS-\%} = 10 \cdot \sqrt{x_{IMPEDANCE-\%}} = 10 \cdot \sqrt{18.5} = 10 \times 4.3 = 43\%$. Table 1 shows some values of $x_{TURN-\%}$ (percentage of the turns) and $x_{IMPEDANCE-\%}$ (percentage of the impedance).

Table 1

$x_{TURNS-\%}$ in %	$x_{IMPEDANCE-\%}$ in %
0	0
22.4	5
31.6	10
38.7	15
43	18.5
44.7	20
50	25
59.2	35
70.7	50
86.6	75
100	100

3 The AC method (Rudolf Moers)

Supply voltage V_b in figure 2 is a short circuit for AC currents. The amplitudes of anode cathode AC voltage v_{ak} and screen grid cathode AC voltage v_{g2k} start from point $V_{ak} = V_b$ on the V_{ak}-axis of **figure 3** (example of an anode characteristic). For AC currents and AC voltages this point is ground. With the assumption that $I_a \approx 10 \cdot I_{g2}$ one can state that $v_{g2k} = x_{TURNS} \cdot v_{ak}$ is valid. So stay at the right side of the knee of the anode characteristic. Further in working point W we can state that $\boldsymbol{V_{g2k} \approx V_{ak} \approx V_b}$ because

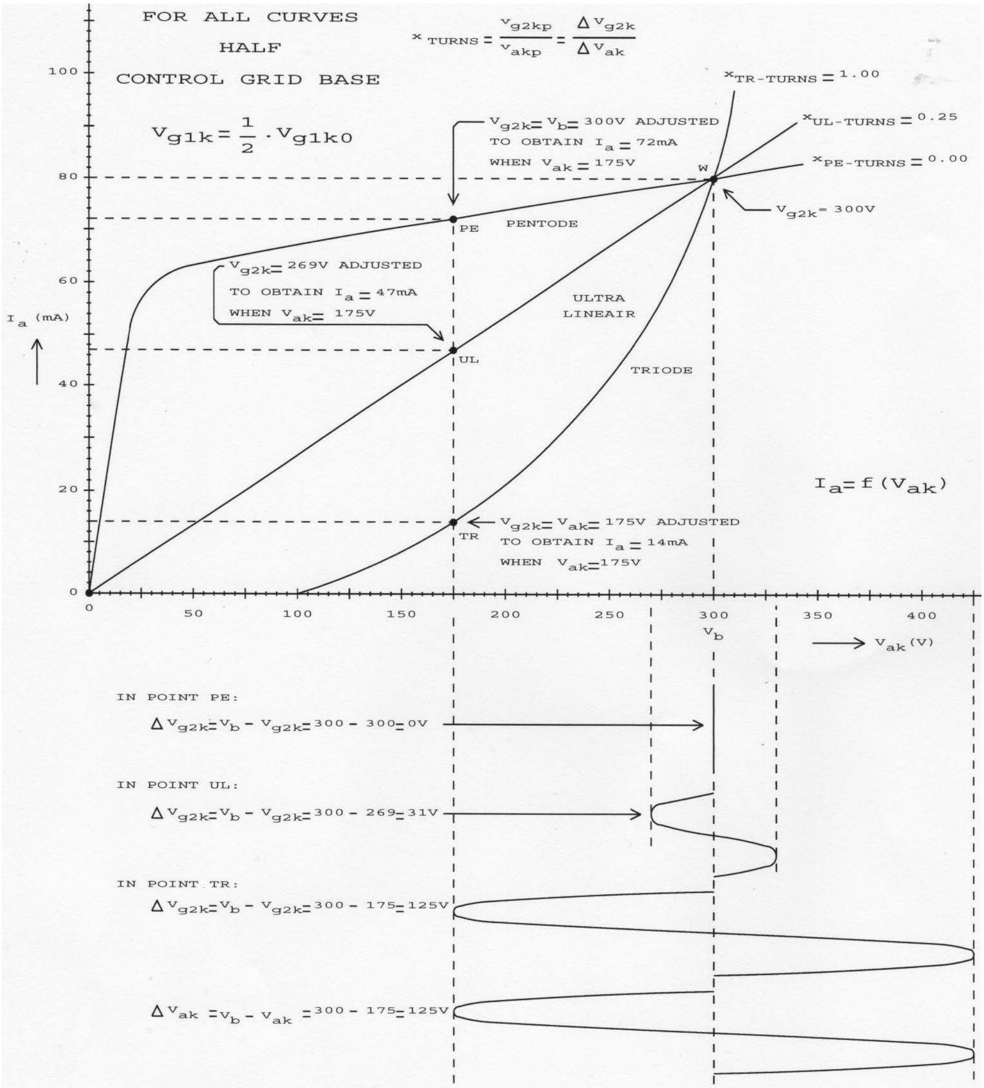


Figure 3. Explanation of the method to determine the screen grid tap x_{TURNS}

the DC voltage drop over the primary transformer winding can be neglected with respect to the anode AC external resistance r_a.
On line $x_{TR\text{-}TURNS}$ = 1.00 of the triode $V_{g2k} = V_{ak}$ is always valid. To get at V_{ak} = 175 V in point TR an anode DC current of I_a = 14 mA, we must adjust V_{g2k} = 175V. By "coincidence" that is also V_{ak}.
On line $x_{PE\text{-}TURNS}$ = 0.00 of the pentode $V_{g2k} = V_b$ = 300V is always valid. To get at V_{ak} = 175 V in point PE an anode DC current of I_a = 72 mA, we must adjust V_{g2k} = 300 V. By "coincidence" that is also V_b.
The curves V_{g1k} = ½ control grid base for the triode and the pentode cross at working point W 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 $x_{UL\ TURNS}$.

In point UL at V_{ak} = 175 V, we can read I_a = 47 mA. Now we must offer a certain voltage of V_{g2k} to get an anode DC current of I_a = 47 mA at V_{ak} = 175 V. In this case V_{g2k} = 269 V.

The anode characteristics for triode and pentode in figure 3 can be measured with the test circuit of **figure 4**.

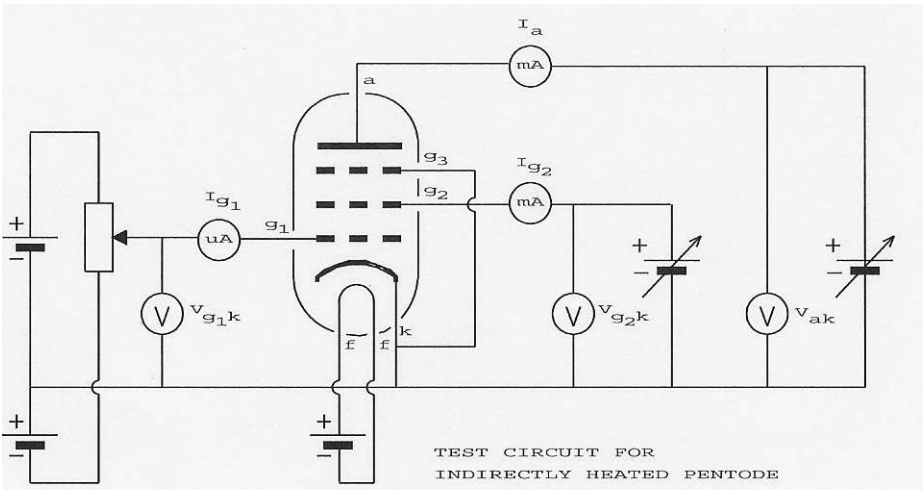


Figure 4 Test circuit for measuring all static pentode characteristics.

We can now determine screen grid primary transformer taps $x_{TR\text{-}TURNS}$, $x_{UL\text{-}TURNS}$ and $x_{PE\text{-}TURNS}$.

At point PE:

$v_{g2kp} = \Delta V_{g2k} = V_b - V_{g2k} = 300 - 300 = 0\ V$

$v_{akp} = \Delta V_{ak} = V_b - V_{ak} = 300 - 175 = 125\ V \rightarrow x_{PE-TURNS} = \frac{v_{g2kp}}{v_{akp}} = \frac{\Delta V_{g2k}}{\Delta V_{ak}} = \frac{0V}{125V} = 0.00$

At point UL:

$v_{g2kp} = \Delta V_{g2k} = V_b - V_{g2k} = 300 - 269 = 31$ V

$v_{akp} = \Delta V_{ak} = V_b - V_{ak} = 300 - 175 = 125$ V $\rightarrow$ $x_{UL-TURNS} = \frac{v_{g2kp}}{v_{akp}} = \frac{\Delta V_{g2k}}{\Delta V_{ak}} = \frac{31V}{125V} = 0.25$

At point TR:

$v_{g2kp} = \Delta V_{g2k} = V_b - V_{g2k} = 300 - 175 = 125$ V

$v_{akp} = \Delta V_{ak} = V_b - V_{ak} = 300 - 175 = 125$ V $\rightarrow$ $x_{TR-TURNS} = \frac{v_{g2kp}}{v_{akp}} = \frac{\Delta V_{g2k}}{\Delta V_{ak}} = \frac{125V}{125V} = 1.00$

If the explanation of this method is not 100 % clear, it will be soon because we now apply this method in practice. **Figure 5** shows the anode characteristics for three different values of screen grid primary transformer tap of specimen KT88-no.1.

<u>Line 1 is measured in advance</u> where the pentode is connected as a triode: $x_{TR-TURNS} = 1.00$.

<u>Line 2 is drawn afterwards</u> with a straight ruler, but we do not know yet that: $x_{UL-TURNS} = 0.25$.

<u>Line 3 is measured in advance</u> where the pentode is connected as a pentode: $x_{PE-TURNS} = 0.00$.

From all lines we can read I_a for each V_{ak}. We must now search for the necessary value of V_{g2k} at each point on these lines. <u>Therefore, we need the test circuit of figure 4 which I have used to measure lines 1 and 3.</u> At a certain anode cathode DC voltage V_{ak} and at a measured anode DC current I_a, the value of screen grid cathode DC voltage V_{g2k} which I have adjusted and measured to obtain I_a, must be subtracted from V_b = 300 V. Also V_{ak} must be subtracted from V_b = 300 V. That gives ΔV_{g2k} and ΔV_{ak} respectively.

Tables 2, 3 and 4 show the method of figures 3 and 5 explained in practice and deliver the evidence that for all measured values, the dots on the lines, the screen grid primary transformer tap is (almost) the same for each line.

Table 2 Measured values of **line 1**

V_{ak} (V) adjusted	I_a (mA) read on I_a-axis	V_{g2k} (V) adjusted to read I_a	ΔV_{ak} (V) [300V – V_{ak}]	ΔV_{g2k} (V) [300V – V_{g2k}]	$x_{TURNS} = \frac{\Delta V_{g2k}}{\Delta V_{ak}}$
0	0	0	300	300	1.00
25	0	25	275	275	1.00
50	0	50	250	250	1.00
75	0	75	225	225	1.00
100	0	100	200	200	1.00
125	0	125	175	175	1.00
150	0	150	150	150	1.00
175	2.6	175	125	125	1.00
200	8.5	200	100	100	1.00
225	19.2	225	75	75	1.00
250	35.6	250	50	50	1.00
275	55	275	25	25	1.00
300	79	300	0	0	unknown
325	110	325	Not further than point W	Not further than point W	Not further than point W
350	140	350			
375	170	375			
400	200	400			

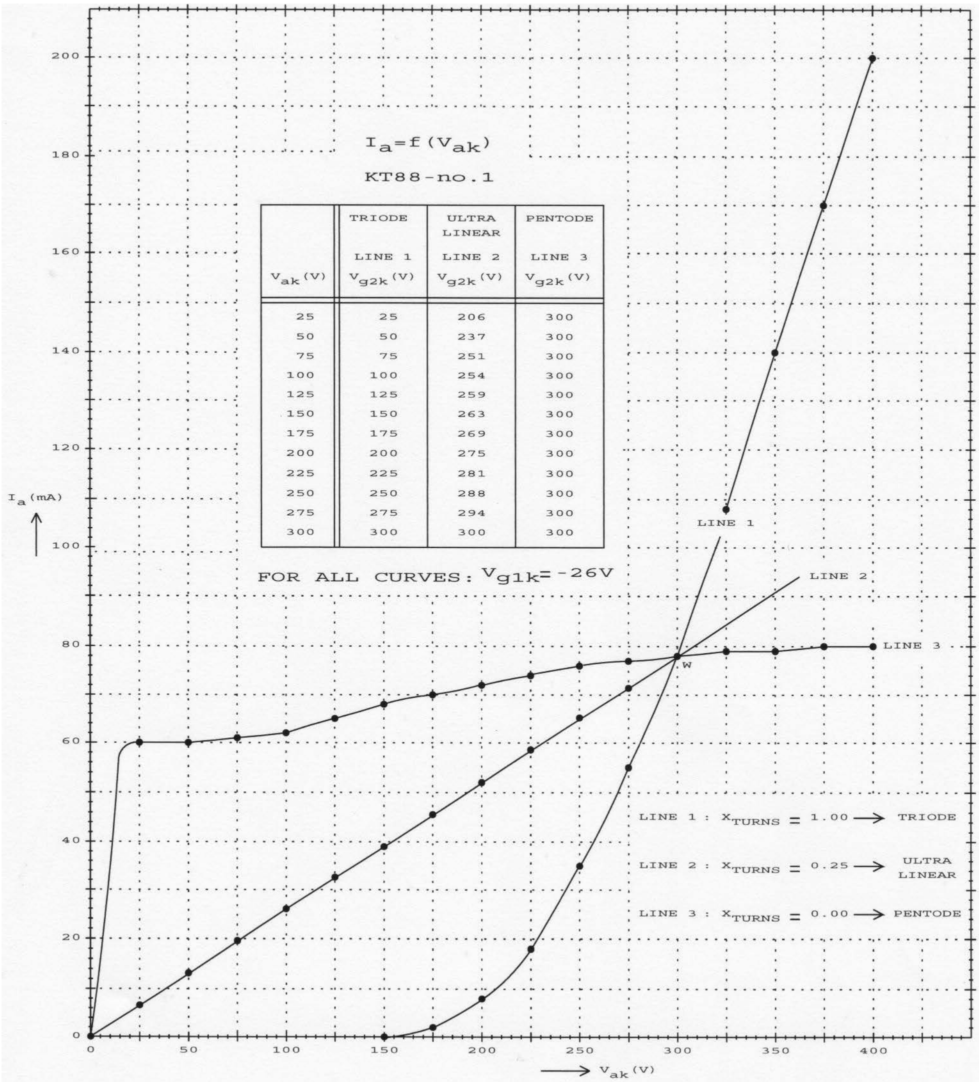
The adjustment of V_{g2k} happens automatically of course, because the screen grid is connected to the anode. The screen grid primary transformer tap x_{TURNS} = 1.00 but that will surprise nobody, so pentode connected as triode.

Table 3 Measured values of **line 2**					
V_{ak} (V) adjusted	I_a (mA) read on I_a-axis	V_{g2k} (V) adjusted to read I_a	ΔV_{ak} (V) [300V – V_{ak}]	ΔV_{g2k} (V) [300V – V_{g2k}]	$x_{TURNS} = \frac{\Delta V_{g2k}}{\Delta V_{ak}}$
0	0	unknown	300	unknown	unknown
25	6.5	206	275	94	0.34
50	13	237	250	63	0.25
75	19.5	251	225	49	0.22
100	26	254	200	46	0.23
125	32.5	259	175	41	0.23
150	39	263	150	37	0.25
175	45.5	269	125	31	0.25
200	52	275	100	25	0.25
225	58.5	281	75	19	0.25
250	65	288	50	12	0.24
275	71.5	294	25	6	0.24
300	78	300	0	0	unknown

The average value of all screen grid primary transformer taps x_{TURNS} is 0.25. This value is mentioned at line 2 of figure 5. For this specimen KT88-no.1 we have a straight line at $x_{TURNS} \approx 0.25$.

Table 4 Measured values of **line 3**					
V_{ak} (V) adjusted	I_a (mA) read on I_a-axis	V_{g2k} (V) adjusted to read I_a	ΔV_{ak} (V) [300V – V_{ak}]	ΔV_{g2k} (V) [300V – V_{g2k}]	$x_{TURNS} = \frac{\Delta V_{g2k}}{\Delta V_{ak}}$
0	1	300	300	0	0.00
25	60	300	275	0	0.00
50	60	300	250	0	0.00
75	61	300	225	0	0.00
100	63	300	200	0	0.00
125	65	300	175	0	0.00
150	68	300	150	0	0.00
175	70	300	125	0	0.00
200	72	300	100	0	0.00
225	74	300	75	0	0.00
250	75	300	50	0	0.00
275	76	300	25	0	0.00
300	77	300	0	0	unknown
325	78	300	No further than point W	No further than point W	No further than point W
350	79	300			
375	80	300			
400	80	300			

The adjustment of V_{g2k} happens automatically of course, because the screen grid is connected to V_b. The screen grid primary transformer tap x_{TURNS} = 0.00 but that will surprise nobody, so pentode connected as pentode.



	TRIODE	ULTRA LINEAR	PENTODE
	LINE 1	LINE 2	LINE 3
V_{ak} (V)	V_{g2k} (V)	V_{g2k} (V)	V_{g2k} (V)
25	25	206	300
50	50	237	300
75	75	251	300
100	100	254	300
125	125	259	300
150	150	263	300
175	175	269	300
200	200	275	300
225	225	281	300
250	250	288	300
275	275	294	300
300	300	300	300

Figure 5 Anode characteristic of KT88-no.1 for different values of screen grid primary transformer tap x_{TURNS}. The corresponding values of Vg2,k at each measured point are shown in the table.

With this method you can determine screen grid primary transformer tap x_{TURNS} or $x_{TURNS\text{-}\%}$ for each specimen pentode and from each curvature in $I_a = f(V_{ak})$.

What happens when one does not distinguish $x_{TURNS-\%}$ from $x_{IMPEDANCE-\%}$ is that one finds a screen grid tap value of 25% while Hafler and Keroes found in the past an optimal screen grid tap value of 18.5%.

4 The DC method (Ronald Dekker)

In L|A Volume 8 Morgan Jones reviewed a curve tracer for valves [5]. The review investigated the µTracer instrument offered as a bare board kit by its designer Ronald Dekker at http://www.dos4ever.com/uTracer3/uTracer3_pag0.html. I recommend the reader to visit that site. From the start page, select "downloads" and then select "user manual". You will find a table of contents. Select chapter 8, section 7: *Distributed loading* (*Ultra-Linear Mode*).

You will find a short explanation regarding the Ultra Linear circuit with a short history of Hafler and Keroes' work. Then you will see equation $V_s = V_a + (1-k) \bullet (V_{a,max} - V_a)$ which is "falling from the sky".

Ronald Dekker means with V_s, V_a, k and $V_{a,max}$ what I mean with V_{g2k}, V_{ak}, x_{TURNS} and supply DC voltage V_b respectively. Translated to my symbols we achieve $V_{g2k} = V_{ak} + (1-x_{TURNS}) \bullet (V_b-V_{ak})$.

Ronald does not distinguish $k = x_{TURNS-\%}$ from $x_{IMPEDANCE-\%}$ as he quotes the results of Hafler and Keroes. Scroll slightly further on this internet page until you observe **animated** anode characteristics and **animated** transconductance characteristics of pentodes EL84 and EL34. Very impressive. It looks like a movie. You will see a sequence of mentioned characteristics for each $0.0 \le k \le 1.0$ in steps of 0.1.

The algorithm of the DC method is Ronald's equation $V_s = V_a + (1-k) \bullet (V_{a,max} - V_a)$ or $V_{g2k} = V_{ak} + (1-x_{TURNS}) \bullet (V_b-V_{ak})$ in my notation but how does it work? Observe **figure 6**.

Initially I did not understand his equation because I was thinking too much that the primary transformer winding has a copper resistance that can be neglected with respect to the anode AC external resistance r_a. In that case we have hardly any DC voltage drop so $V_{ak} \approx V_{g2k} \approx V_b$. In figure 6 we see

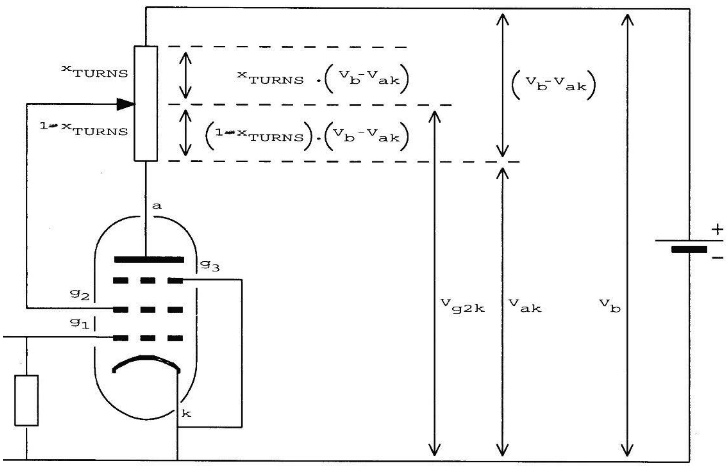


Figure 6 The UL circuit model that lead to $V_{g2k} = V_{ak} + (1-x_{TURNS}) \bullet (V_b-V_{ak})$.

a potmeter with different DC voltages. It is not really a physical potmeter, but a resistive model of the anode external impedance that makes it possible to see how V_{g2k} is expressed in x_{TURNS}, V_{ak} and V_b under the assumption that I_{g2} is negligible with respect to I_a. So, avoid the pentode knee in $I_a = f(V_{ak})$.

DC voltage across the potmeter is : $(V_b - V_{ak})$

DC voltage across the upper part of the potmeter is : $x_{TURNS} \cdot (V_b - V_{ak})$

DC voltage across the lower part of the potmeter is : $(1 - x_{TURNS}) \cdot (V_b - V_{ak})$

The screen grid cathode DC voltage according figure 6 is : $V_{g2k} = V_{ak} + (1 - x_{TURNS}) \cdot (V_b - V_{ak})$

With the next isolation steps we achieve x_{TURNS} : $V_{g2k} - V_{ak} = (1 - x_{TURNS}) \cdot (V_b - V_{ak})$

$$(1 - x_{TURNS}) = \frac{(V_{g2k} - V_{ak})}{(V_b - V_{ak})}$$

$$x_{TURNS} = 1 - \frac{(V_{g2k} - V_{ak})}{(V_b - V_{ak})}$$

Let's use $x_{TURNS} = 1 - \frac{(V_{g2k} - V_{ak})}{(V_b - V_{ak})}$ with the numbers of table 3 of the previous section (AC method).

Table 5 Measured values of **line 2**

V_{ak} (V) adjusted	$V_{g2,k}$ (V) adjusted to read I_a	$[V_{g2k} - V_{ak}]$ (V)	$[V_b - V_{ak}]$ (V) with $V_b = 300$V	$(1 - x_{TURNS})$	x_{TURNS}
0	unknown	unknown	300	unkown	unknown
25	206	181	275	0.66	0.34
50	237	187	250	0.77	0.24
75	251	176	225	0.80	0.21
100	254	154	200	0.78	0.22
125	259	134	175	0.78	0.22
150	263	113	150	0.77	0.24
175	269	94	125	0.77	0.24
200	275	75	100	0.77	0.24
225	281	56	75	0.79	0.23
250	288	38	50	0.80	0.21
275	294	19	25	0.76	0.24
300	300	0	0	unknown	unknown

The average value of all screen grid primary transformer taps x_{TURNS} is 0.24. The values of x_{TURNS} from table 3 (The AC method) and table 5 (The DC method) are similar. The next section will show why these results are similar.

5 The relationship between the AC method and the DC method

For the relationship between the AC method and DC method we start with Ronald's equation.

$$V_{g2k} = V_{ak} + (1 - x_{TURNS}) \cdot (V_b - V_{ak})$$ subtract V_{ak} at the left and right of the =-sign

$$V_{g2k} - V_{ak} = (1 - x_{TURNS}) \cdot (V_b - V_{ak})$$ $\Leftrightarrow$

$$V_{g2k} - V_{ak} = 1 \cdot (V_b - V_{ak}) - x_{TURNS} \cdot (V_b - V_{ak})$$ $\Leftrightarrow$

$$V_{g2k} - V_{ak} = V_b - V_{ak} - x_{TURNS} \cdot (V_b - V_{ak})$$ add V_{ak} at the left and right of the =-sign

$$V_{g2k} = V_b - x_{TURNS} \cdot (V_b - V_{ak})$$ subtract V_{g2k} at the left and right of the =-sign

$$0 = V_b - V_{g2,k} - x_{TURNS} \cdot (V_b - V_{ak})$$ add $x_{TURNS} \cdot (V_b - V_{ak})$ at the left and right of the =-sign

$$x_{TURNS} \cdot (V_b - V_{ak}) = V_b - V_{g2k}$$ $\Leftrightarrow$

$$x_{TURNS} = \frac{(V_b - V_{g2k})}{(V_b - V_{ak})} = \frac{\Delta V_{g2k}}{\Delta V_{ak}}$$ with the assumption that I_{g2} is negligible with respect to I_a

Hence the AC method and the DC method give the same results.

Ronald was glad that his equation gave the same results as my method. Both methods give a straight line in the anode characteristic for V_{g1k} is half of the control grid base. I told him that to achieve the screen grid tap for the lowest THD both our methods are wrong, but that his µTracer will help me to explain why.

6 The AC method applied for linear anode characteristics

Now I wanted to determine several screen grid taps for four linear anode characteristics, see **figure 7**. I started to draw the *lines* with a ruler on grid paper paper.

The first anode characteristic goes from origin 0 to working point W1 which is located at I_{ak}/V_{ak} = 72mA/300V. Increase is in steps of 6mA/25V à anode AC internal resistance $r_{i,W1}$ = 4167Ω.
The second anode characteristic goes from origin 0 to working point W2 which is located at I_{ak}/V_{ak} = 70mA/350V. Increase is in steps of 5mA/25V à anode AC internal resistance $r_{i,W2}$ = 5000Ω.
The third anode characteristic goes from origin 0 to working point W3 which is located at I_{ak}/V_{ak} = 64mA/400V. Increase is in steps of 4mA/25V à anode AC internal resistance $r_{i,W3}$ = 6250Ω.
The fourth anode characteristic goes from origin 0 to working point W4 which is located at I_{ak}/V_{ak} = 54mA/450V. Increase is in steps of 3mA/25V à anode AC internal resistance $r_{i,W4}$ = 8333Ω.

The points on the characteristic lines of figure 7 are real measurement. The anode DC currents I_a and anode cathode DC voltages V_{ak} were really present with the imposed screen grid cathode DC voltages V_{g2k}. All of this with control grid working point $V_{g1k,w}$ (middle of the control grid base) which is different for each line of figure 7. I then applied the AC method.

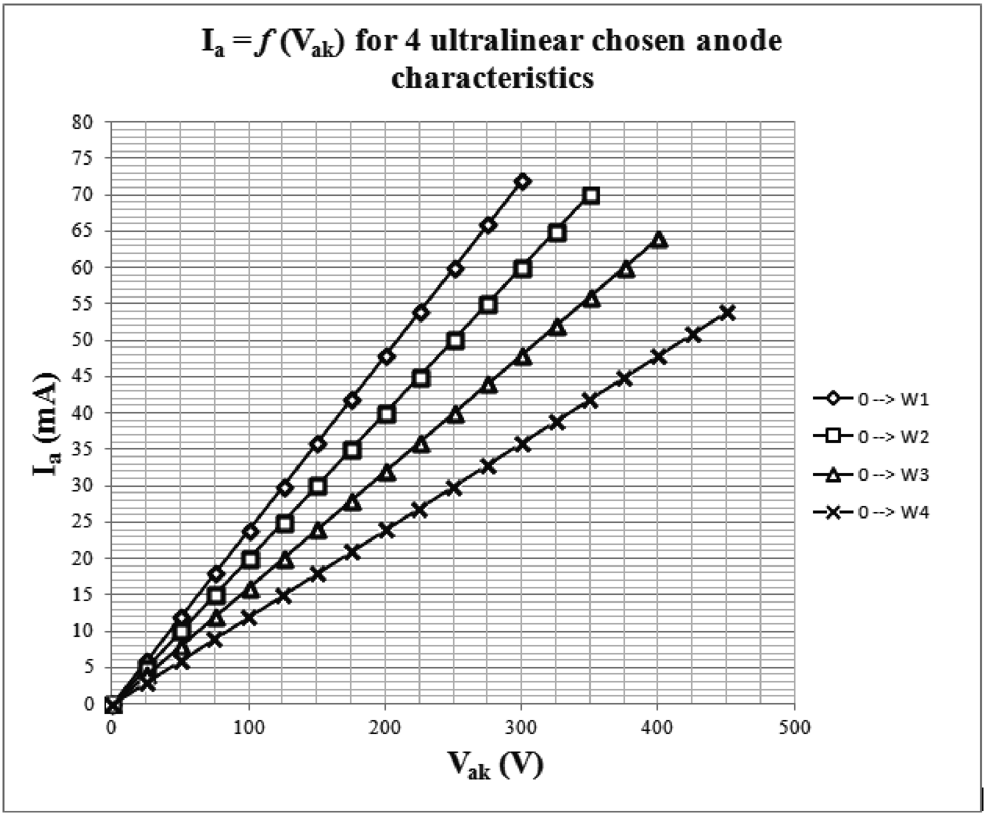


Figure 7 Four hand-drawn straight anode characteristic lines, later marked with measurements.

The chosen beam power tetrodes were:

1. Svetlana	KT88 no.1
2. Svetlana	KT88 no.2
3. JJ	KT88 no.1
4. JJ	KT88 no.2
5. Electro-Harmonix	KT88 no.1
6. Electro-Harmonix	KT88 no.2

Four linear anode characteristics times 6 beam power tetrodes result in 24 tables like table 3.
A lot of measurement and calculation work but without hard work no results. **Table 6** gives a resume.

Table 6						
	Svetlana 1	Svetlana 2	JJ-2	JJ-2	Electro-Harmonix 1	Electro-Harmonix 2
Line 0 − W1	$V_{g1k,w} = -27.3V$	$V_{g1k,w} = -27.7V$	$V_{g1k,w} = -25.8V$	$V_{g1k,w} = -26.0V$	$V_{g1k,w} = -27.6V$	$V_{g1k,w} = -26.6V$
	$x_{TURNS-AVERAGE} = 0.23$	$x_{TURNS-AVERAGE} = 0.21$	$x_{TURNS-AVERAGE} = 0.22$	$x_{TURNS-AVERAGE} = 0.24$	$x_{TURNS-AVERAGE} = 0.22$	$x_{TURNS-AVERAGE} = 0.19$
Line 0 −W2	$V_{g1k,w} = -34.5V$	$V_{g1k,w} = -34.8V$	$V_{g1k,w} = -32.3V$	$V_{g1k,w} = -32.6V$	$V_{g1k,w} = -34.5V$	$V_{g1k,w} = -33.5V$
	$x_{TURNS-AVERAGE} = 0.19$	$x_{TURNS-AVERAGE} = 0.20$	$x_{TURNS-AVERAGE} = 0.19$	$x_{TURNS-AVERAGE} = 0.21$	$x_{TURNS-AVERAGE} = 0.18$	$x_{TURNS-AVERAGE} = 0.14$
Line 0 −W3	$V_{g1k,w} = -42.0V$	$V_{g1k,w} = -42.5V$	$V_{g1k,w} = -39.6V$	$V_{g1k,w} = -40.0V$	$V_{g1k,w} = -42.2V$	$V_{g1k,w} = -41.2V$
	$x_{TURNS-AVERAGE} = 0.17$	$x_{TURNS-AVERAGE} = 0.16$	$x_{TURNS-AVERAGE} = 0.16$	$x_{TURNS-AVERAGE} = 0.17$	$x_{TURNS-AVERAGE} = 0.15$	$x_{TURNS-AVERAGE} = 0.13$
Line 0 −W4	$V_{g1k,w} = -51.0V$	$V_{g1k,w} = -51.4V$	$V_{g1k,w} = -47.6V$	$V_{g1k,w} = -48.2V$	$V_{g1k,w} = -50.9V$	$V_{g1k,w} = -49.7V$
	$x_{TURNS-AVERAGE} = 0.13$	$x_{TURNS-AVERAGE} = 0.13$	$x_{TURNS-AVERAGE} = 0.12$	$x_{TURNS-AVERAGE} = 0.12$	$x_{TURNS-AVERAGE} = 0.14$	$x_{TURNS-AVERAGE} = 0.13$

Some conclusions:

- Each line of $V_{g1k,w}$ is the same order of magnitude for each tetrode.
- The flatter the lines, the higher V_{ak} at a certain I_a, the more negative $V_{g1k,w}$.
- Each line of $x_{TURNS-AVERAGE}$ is the same order of magnitude for each tetrode.
- The flatter the lines, the higher V_{ak} at a certain I_a, the lower $x_{TURNS-AVERAGE}$.
- In these 24 measurements not once $x_{TURNS-AVERAGE} \approx 43\%$ or $x_{IMPEDANCE-AVERAGE} \approx 18.5\%$ appeared.

It seems that a linear anode characteristic alone is not enough to achieve the lowest THD, because measurements from the past gave result $x_{IMPEDANCE-\%} \approx 18.5\%$ for the lowest THD.
It's time to study these measurements from the past and, if possible, to repeat them.

7 THD measurement results from the past

Let's start with THD measurements from the past. **Figure 8** is a part of the first page of [2].
This Ultra Linear (UL) article in Radiotronics was followed by two others in June and July 1955 but these do not investigate the screen grid tap. This article treats subjects like the history of UL, a circuit description, linearity, efficiency and overload characteristics and distortion. **Figure 9** shows the test circuit. The oscillator harmonics were reduced by a filter followed by an amplifier with a lot of negative feedback. By this, THD at the control grids of the pentodes was less than 0.2%. The input transformer T_1 was made with a C core and has an inductance of 100H, with a step-up ratio of 1:2 primary to whole of secondary. The leakage inductance was 16mH primary to whole of secondary, and 36mH primary to half secondary.
A tapped inductor L_1 was used in preference to a transformer, tapped at 5%, 10%, 15%, 20%, 25%, 35%, 50% and 75% of the impedance ($x_{IMPEDANCE-\%}$). The anode to anode inductance was 350H at low level, 500H at 240V @ 50Hz with leakage inductance of 10mH from one half-winding to the other half.

RADIOTRONICS

Registered at the General Post Office, Sydney, for transmission by post as a periodical. Single Copy, One Shilling

Volume 20 **May 1955** **Number 5**

ULTRA LINEAR AMPLIFIERS

First article of a series by F. LANGFORD-SMITH

and A. R. CHESTERMAN

This first article gives a general introduction to the subject, with its history, some of its characteristics, and then an investigation into the effects of the tapping point on the power output and distortion. The effects of high resistive loads are also investigated.

1. Name

The name has been the subject of much controversy. "Tapped Transformer" and "Triode Tetrode" operation have been suggested in England, while "Partial Triode Operation" has been used in the Radiotron Designer's Handbook (Ref. 1). None of these seem to have taken on, so that we are left with the title "Ultra Linear", which will be used throughout this article in its abbreviated form, UL.

sufficiently detailed to satisfy an amplifier designer. The present article is the first of a series to meet this need.

3. Description

A typical circuit diagram is shown in Fig. 1. It differs from pentode operation by the screens being connected to tapping points T, T, on the transformer primary. It is always advisable to fit screen suppressors R3 and R4 and usually also condensers C1 and C2 between the plates and the transformer end of the screen suppressors, to eliminate a form of instability. Typical values are 0.001 or 0.002 μF and 47 to 220 ohms. Grid stopper resistors (10K) are also desirable.

In this article, "pentode operation" is to be taken as including beam tetrode operation.

Figure 8 First page of [2]. By coincidence, date May 1955 was the month and year that your author was born.

The total copper resistance was 440Ω. The large number of taps gave a tendency towards instability, which was avoided by use of stopper resistors on control grid, screen grid and anode and the 1nF capacitors between the screen grid and the anode. Several load resistors simulate the anode AC external resistance r_a. The pentodes were KT66 and for more details of the measurements, please read the article.

Figure 10 shows the output power and THD as function of $x_{IMPEDANCE\text{-}\%}$ for a certain test.
THD lines (3) and (4) correspondence with power lines (1) and (2) respectively. The lowest THD is achieved at $x_{IMPEDANCE\text{-}\%}$ is 15% and 20% respectively. One can see that the anode AC resistance and control grid cathode DC voltage V_{g1k} have influence on the results too. **Figure 11** shows more results with $x_{IMPEDANCE\text{-}\%}$ = 20% for the lowest THD. For completeness see **figure 12** from Hafler and Keroes

(who, by the way, in contrast to what is shown in the figure, were not the inventors of this; that was Alan Blumlein).

These measurements where applied in push pull configuration. For very good matched power pentodes the even harmonics are cancelled and the odd harmonics are doubled. But whether such a matching is also valid for several values of $x_{TURNS\text{-}\%}$ or $x_{IMPEDANCE\text{-}\%}$ is open to discussion. I don't think it is.

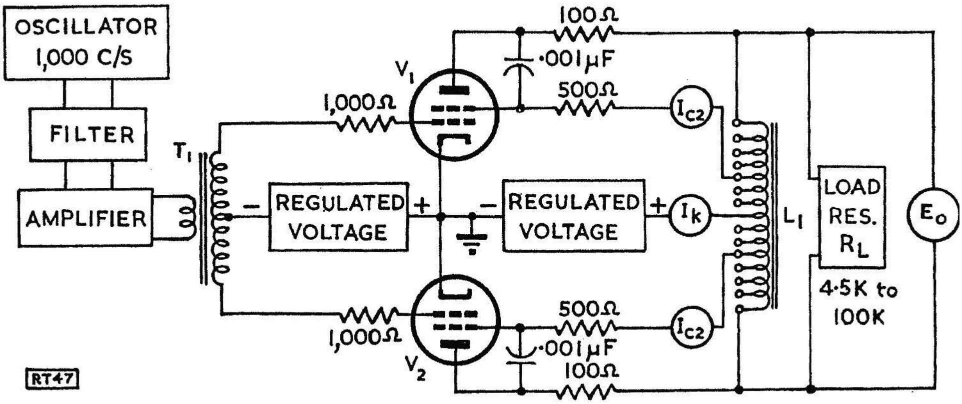


Figure 9 Circuit used for deriving test results published in Radiotronics Volume 20 (figure 8).

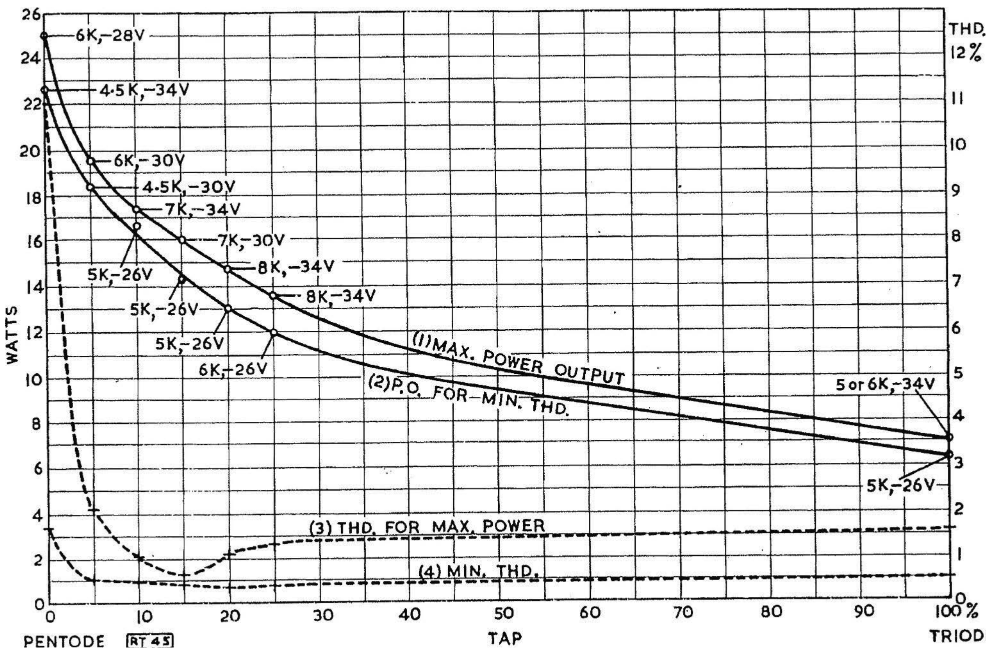


Figure 10 The output power and THD as function of $x_{IMPEDANCE\text{-}\%}$.

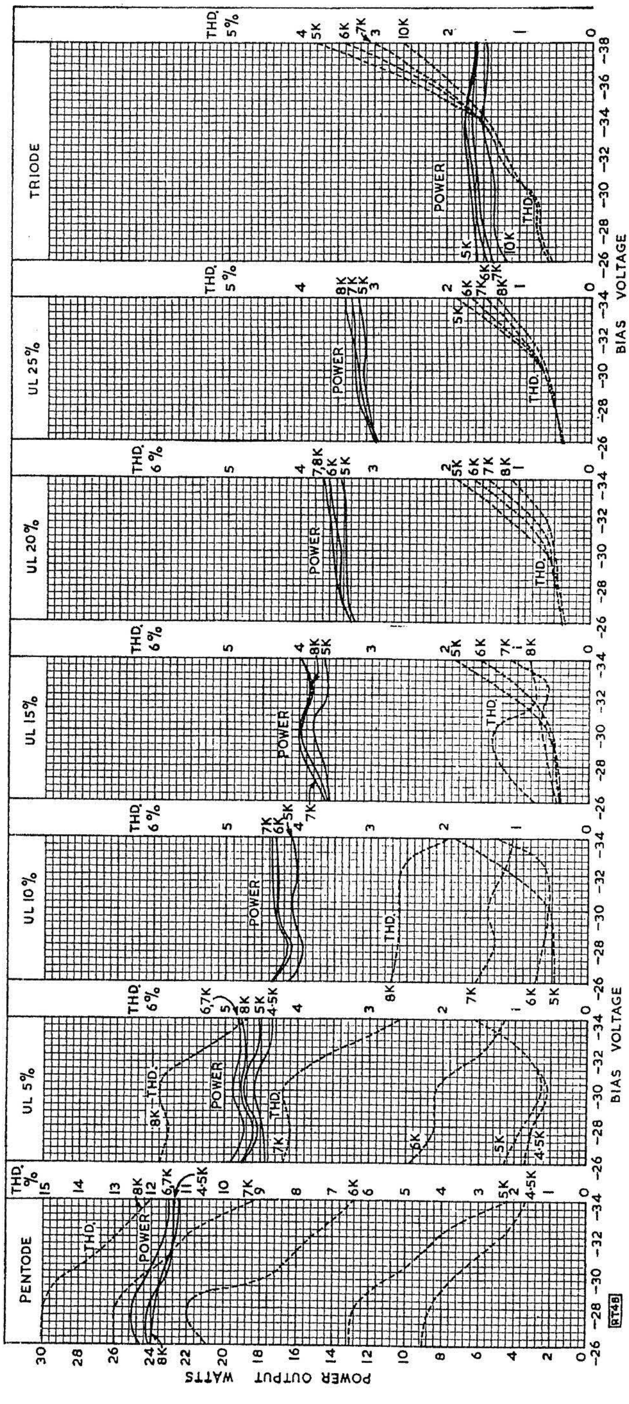


Figure 11 Power output and THD versus V_{g1k} for selected values of anode AC resistances.

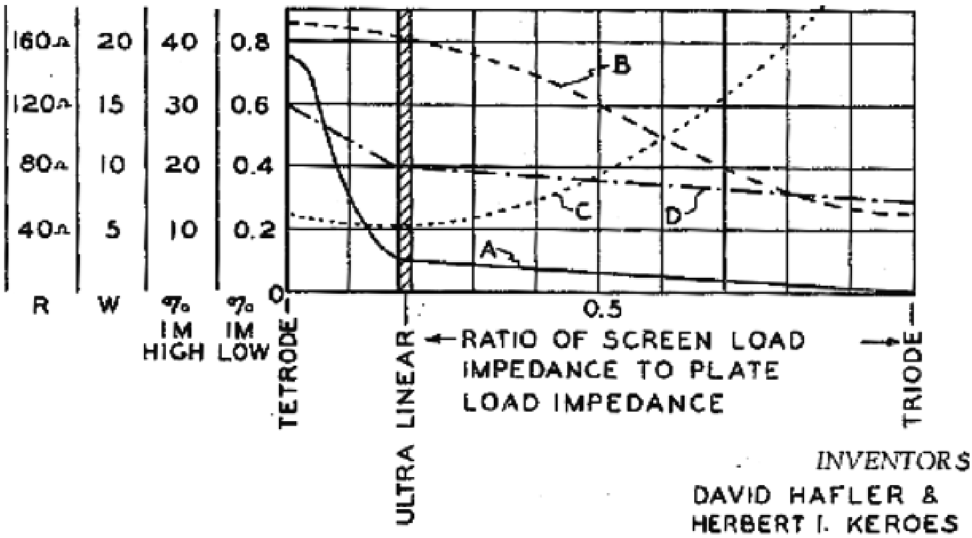


Figure 12 Results by Hafler and Keroes.

8 More recent THD measurement results

Figure 13 shows the test circuit. What immediately strikes us is the output transformer with the 10 taps. Once, before I had ever heard about the ultra-linear power amplifier, I did an investigation of 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 anode AC internal resistance $r_i = 700\ \Omega$, then it does not seem strange that the taps of the primary transformer winding (r_a) of figure 13 are a multiple of 700 Ω. Although this investigation is very interesting, it is out of the scope of this article. See chapter 4 of reference [7] for that investigation.

For those who want to do the same experiments as I did, you can order this test output transformer at the Dutch transformer manufacturer AE-europe. The type of this output transformer is 27844 and its maximum DC current is 200 mA, but do not expect enough bandwidth and other qualities. But it is sufficient for power (and later also for UL) investigations at mid-audio frequencies.

If working point W moves slightly due to another screen grid primary transformer tap x_{TURNS}, we then must change $V_{g1k,w}$ slightly to achieve the desired adjustment. There is a voltage drop across the primary transformer winding of $(I_a+I_{g2})\cdot x_{TURNS}\cdot R_p+I_a\cdot(1-x_{TURNS})\cdot R_p$ which depends on the screen grid primary transformer tap x_{TURNS}. It varies and is approximately 10 V. At each value of x_{TURNS}, the working point needs to be adjusted again.
Looking at the test circuit of figure 13 we would expect the following values of x_{TURNS}:

$$x_{TURNS} = \frac{0\ \Omega}{7000\ \Omega} = 0.0\ ;\ x_{TURNS} = \frac{700\ \Omega}{7000\ \Omega} = 0.1\ ;\ x_{TURNS} = \frac{1400\ \Omega}{7000\ \Omega} = 0.2\ ;\ .\ .\ .\ .\ x_{TURNS} = \frac{7000\ \Omega}{7000\ \Omega} = 1.0$$

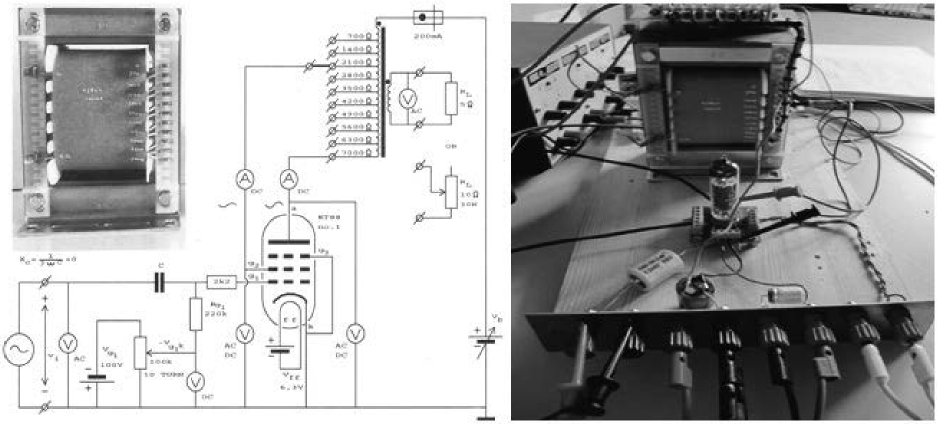


Figure 13 Test circuit to determine the dependence of the anode AC amplification and the circuit AC output resistance as function of the screen grid tap x_{TURNS} (copied from [6]).

We define $x_{TURNS\text{-}MEASURED} = \frac{\Delta V_{g2k}}{\Delta V_{ak}} = \frac{v_{g2kp}}{v_{akp}}$ and measurements with this test circuit have shown that $x_{TURNS} \neq x_{TURNS\text{-}MEASURED}$

How homogeneously 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? We must realize that this test transformer is not designed and produced for ultra-linear applications, but it is available so let us try.

Table 7 shows the real $x_{TURNS\text{-}MEASURED} = \frac{\Delta V_{g2k}}{\Delta V_{ak}} = \frac{v_{g2kp}}{v_{akp}}$ with use of measured values of v_{g2kp} and v_{akp}.

Because my results of $x_{TURNS\text{-}\%} \approx$ 12% .... 24% in sections 3, 4 and 6 and the result of $x_{IMPEDANCE\text{-}\%} \approx$ 20% ⇔ $x_{TURNS\text{-}\%} \approx$ 43% in section 7 are so different, I selected the x_{TURNS} of the 3rd column of table 7. The taps are used in opposite order as shown in figure 13. The values in the range 0.06 < $x_{TURNS\text{-}MEASURED}$ < 0.46 of the 3rd column are the most interesting for investigation.

The 2nd column doesn't have enough values of x_{TURNS} which cover the "THD-disagreement" and the values of the 1st column of table 7 are desired but not easily producible by the manufacturer of the transformer with all these taps.

Be aware that Messrs. F. Langford-Smith and A.R. Chesterman have used a push pull choke with taps, see figure 9, instead of a push pull transformer with symmetrical taps at both sides.

Table 7		
Desired x_{TURNS}	Real $x_{TURNS-MEASURED}$ when primary winding connection 0 Ω to supply V_b connection 7000 Ω to anode a	Real $x_{TURNS-MEASURED}$ when primary winding connection 7000 Ω to supply V_b connection 0 Ω to anode a
0.0	0.00	0.00
0.1	0.31	0.06
0.2	0.44	0.11
0.3	0.54	0.17
0.4	0.64	0.23
0.5	0.70	0.30
0.6	0.77	0.36
0.7	0.83	0.46
0.8	0.89	0.56
0.9	0.94	0.69
1.0	1.00	1.00

The output power is determined by measuring the RMS voltage over R_L = 5Ω/80W followed by the following calculation: $p_{R_L} = \frac{V^2_{R_L,RMS}}{R_L}$ · To achieve 1W, 2W, 3W, 4W and 5W, measure across R_L the voltages 2.24V_{RMS}, 3.16V_{RMS}, 3.87V_{RMS}, 4.47V_{RMS} and 5.00V_{RMS} respectively, set by input voltage v_i at 1 kHz, see figure 13. The harmonics are measured with USB scope HS3.

The electron tubes I have used are:

- A specimen EL84 (EL84-no.1) with working point $V_{ak,w}$ = 300V, $I_{a,w}$ =40mA, $I_{g2,w}$ ≈5mA, $V_{g1k,w}$ ≈ −9.1V, supply V_b≈305V and $V_{ak,w} \approx V_{g2k,w}$.
- A specimen EL34 (EL34-no.1) with working point $V_{ak,w}$ =300V, $I_{a,w}$ =80mA, $I_{g2,w}$ ≈10mA, $V_{g1k,w}$ ≈−16.1V, supply V_b≈305V and $V_{ak,w} \approx V_{g2k,w}$.
- A specimen KT88 (KT88-no.1) with working point $V_{ak,w}$ =300V, $I_{a,w}$ =80mA, $I_{g2,w}$ ≈ 8mA, $V_{g1k,w}$ ≈−26.4V, supply V_b≈305V and $V_{ak,w} \approx V_{g2k,w}$.

Although I measured harmonics d_2, d_3, d_4 and d_5, in the next **figures 14, 15 and 16** I will limit myself to show only THD as function of output power 1W, 2W, 3W, 4W and 5W.

What immediate strikes us in figures 14, 15 and 16, is that the THD measurements stop before reaching the value $x_{TURNS-MEASURED}$= 1.0 for powers 3W, 3W and 4W respectively. For a single ended power stage it is difficult to achieve 5W output power in (almost) triode configuration ($x_{TURNS-MEASURED} \rightarrow$ 1.0) when $V_{ak,w} \approx V_b$ is just 300V. Especially for an EL84 with $I_{a,w}$ = 40mA at $V_{ak,w} \approx V_b$ is 300V it is hard to achieve 3W or more.

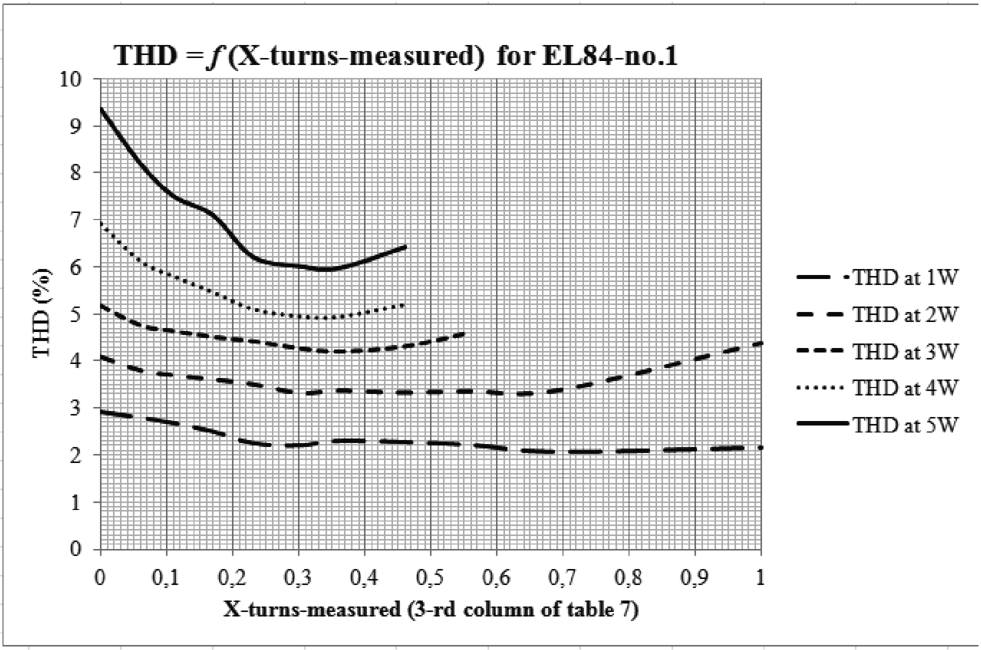


Figure 14 THD = f ($x_{TURNS-MEASURED}$) for specimen EL84-no.1.

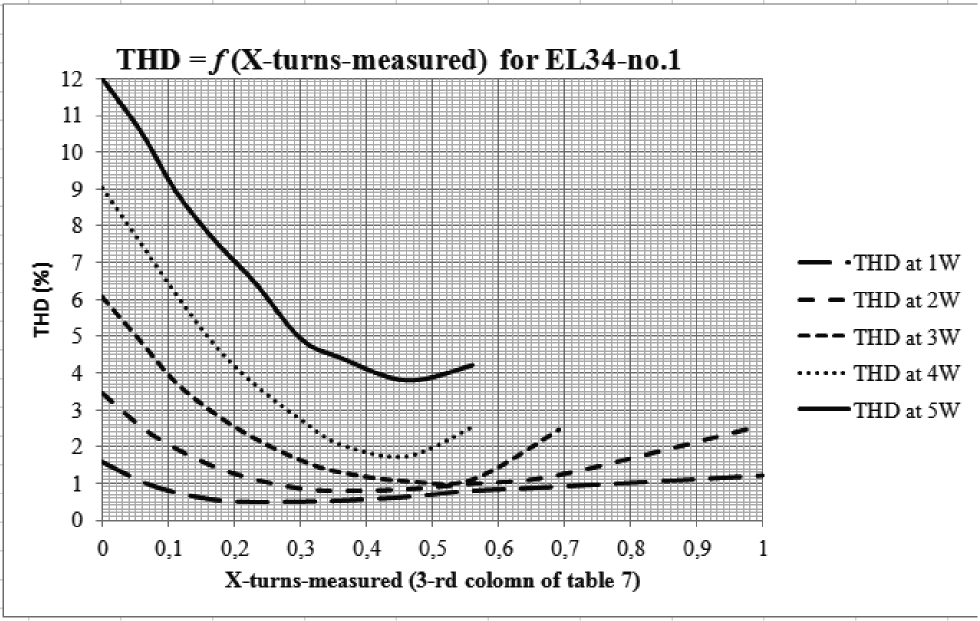


Figure 15 THD = f ($x_{TURNS-MEASURED}$) for specimen EL34-no.1.

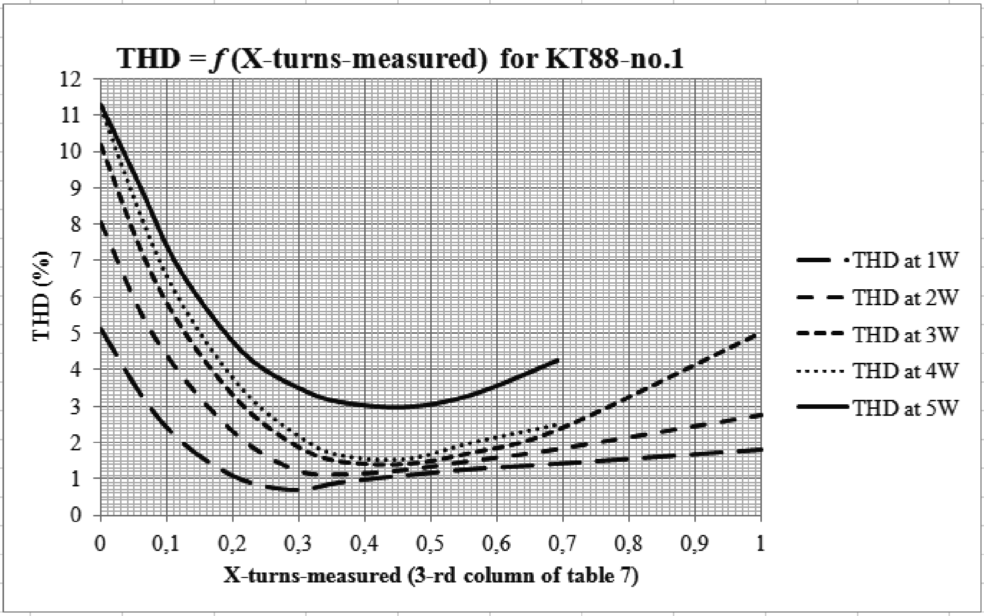


Figure 16 THD = f ($x_{TURNS\text{-}MEASURED}$) for specimen KT88-no.1.

Further conclusions:

- For small output powers (like 1W) the lowest THD is at $x_{TURNS\text{-}MEASURED} \approx 0.3$.
- For the other output powers the lowest THD is at $0.35 < x_{TURNS\text{-}MEASURED} < 0.45$.
- The lowest THD at $0.35 < x_{TURNS\text{-}MEASURED} < 0.45$ is similar for single ended and for push pull output stages (compare the THD results with THD results of the previous section).
- These recent THD measurements give the same results as THD measurements from the past.
- The AC method and DC method do not result in a screen grid tap which gives the lowest THD.
- Why the AC method and DC method do not result in a screen grid tap which gives the lowest THD will be investigate in the next sections.

Figure 17 is a part of the first page of [4] and shows that in the past some have tried to get better understanding of the behavior of the "ultra-linear" circuit.

Figure 18 is a part of the last page of reference [4] and shows a call for more understanding.

Tetrodes with Screen Feedback

FURTHER LIGHT ON THE SO-CALLED "ULTRA-LINEAR" CIRCUIT

AFTER a period of caution, amounting in some quarters to undisguised scepticism, the "ultra-linear" output stage[1, 2, 3, 4] is undoubtedly here to stay. It was unfortunate, though, that Hafler and Keroes in popularizing this circuit for audio amplifiers should have chosen a term which, if it means anything, suggests that the transfer characteristic has been bent "beyond the straight" and is therefore still curved!

Several alternative descriptions have been suggested, the most plausible being "triode-tetrode" operation. This hardly does justice to the circuit, since, although at the extreme limits of the screen tapping (Fig. 1) the valve is undoubtedly operating either as a triode or a tetrode, the intermediate tapping points do not give a progressive transition, so far as distortion is concerned, from one set of characteristics to the other. When the screen tapping point is properly adjusted the transfer characteristic is more nearly linear and distortion is less than that of either the tetrode *or the triode* connection. Obviously some factor is at work which is not present in either of the limiting conditions and "triode-tetrode" is misleadingly simple. If it is called the "UL" circuit the special nature of its performance is underlined, and we do not have to grit our teeth over that "beyond the linear."

The UL nomenclature is, incidentally, adopted by F. Langford-Smith and A. R. Chesterman who have recently[5] carried out an exhaustive experimental investigation of the push-pull circuit (Fig. 2). The results of their measurements with KT66s are given in Fig. 3 and it will be noted that they have taken the trouble to adjust the load resistance and bias for the best performance at each tapping point. This

Figure 17 First page of reference [4].

reduced the much stronger third harmonic. In practice, judging from the subjective quality from UL amplifiers we have heard, this effect, if present, is negligibly small; but it would repay investigation (assuming that distortion measurements of sufficient precision are forthcoming) if only to throw more light on the fundamental processes of UL operation.

Acknowledgment. Figs. 2, 3 and 4 are based on Figs. 6, 2 and 5 respectively of *Radiotronics* (Australia), Vol. 20, No. 5, May, 1955.

Figure 18 Last page of reference [4].

9 The animated UL anode and static transconductance characteristics

As noted before, go to http://www.dos4ever.com/uTracer3/uTracer3_pag0.html, Manual, chapter 8, section 7: Distributed loading (Ultra-Linear Mode); and continue down to the animated anode and transconductance characteristics of pentodes EL84 and EL34. Notice the sequence of mentioned characteristics for each $0.0 \le k \le 1.0$ in steps of 0.1 with $k = x_{TURNS}$.

This "movie" goes rather fast so I measured all these graphs separately for specimen of EL84, EL34 and KT88. The applied values for $k = x_{TURNS}$ I have chosen are the numbers from the 3th column of table 7. That gives the possibility to compare the results of figures 14 thru 16 with the linearity of the anode characteristics (and later the linearity of the dynamic transconductance characteristics).

Figures 19 thru 21 give a first impression of some UL anode characteristics of the mentioned pentodes with a $k = x_{TURNS}$ of 0.23, 0.30 and 0.36 respectively. Why the horizontal scale is $0V < V_{ak} < 600V$ while the graphs go no further than $V_{ak} = 300V$ will be explained in the next section. The shown load line (anode AC external resistance r_a) is 7000Ω which is the transformer impedance (with all these taps).

Load line for EL84-no.1 goes through working point $V_{ak,w}$ = 300V, $I_{a,w}$ =40mA and $V_{g1k,w} \approx -9.1$V.
Load line for EL34-no.1 goes through working point $V_{ak,w}$ = 300V, $I_{a,w}$ =80mA and $V_{g1k,w} \approx -16.1$V.
Load line for KT88-no.1 goes through working point $V_{ak,w}$ = 300V, $I_{a,w}$ =80mA and $V_{g1k,w} \approx -26.4$V.

The anode characteristics for all these tubes, for each value of $k = x_{TURNS}$ (values from the output transformer), are shown expanded in **appendices 13.A, 13.C and 13.E** respectively. There you can observe that in a wide middle range of $k = x_{TURNS}$ the anode characteristics are rather linear. It's not easy to distinguish in that wide middle range which "curve" is more linear and more parallel to another.

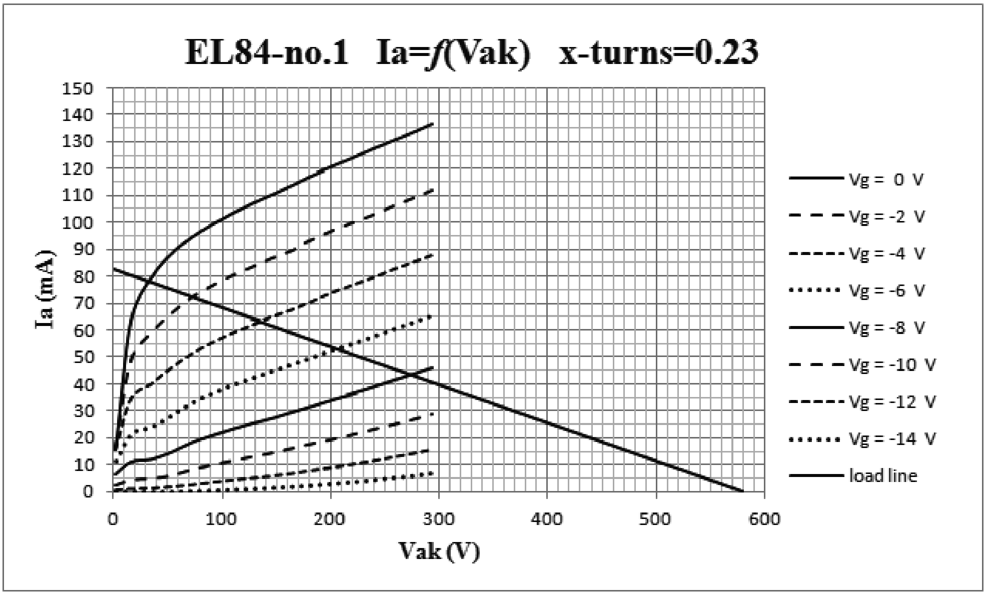


Figure 19 Anode characteristic for EL84-no.1 at x_{TURNS} = 0.23.

Let's investigate which pentode characteristic is so much curved that it will cause distortion, see **Figure 22.**

In figure 22a both anode and transconductance characteristics are linear. Therefor a perfect sine signal v_{g1k} will cause a perfect sine wave signal i_a which will cause a perfect sine signal V_{ak}.

In figure 22b the transconductance characteristic is linear and the anode characteristic is curved. Therefor a perfect sine signal v_{g1k} will cause a perfect sine wave signal i_a which will cause a distorted signal V_{ak}.

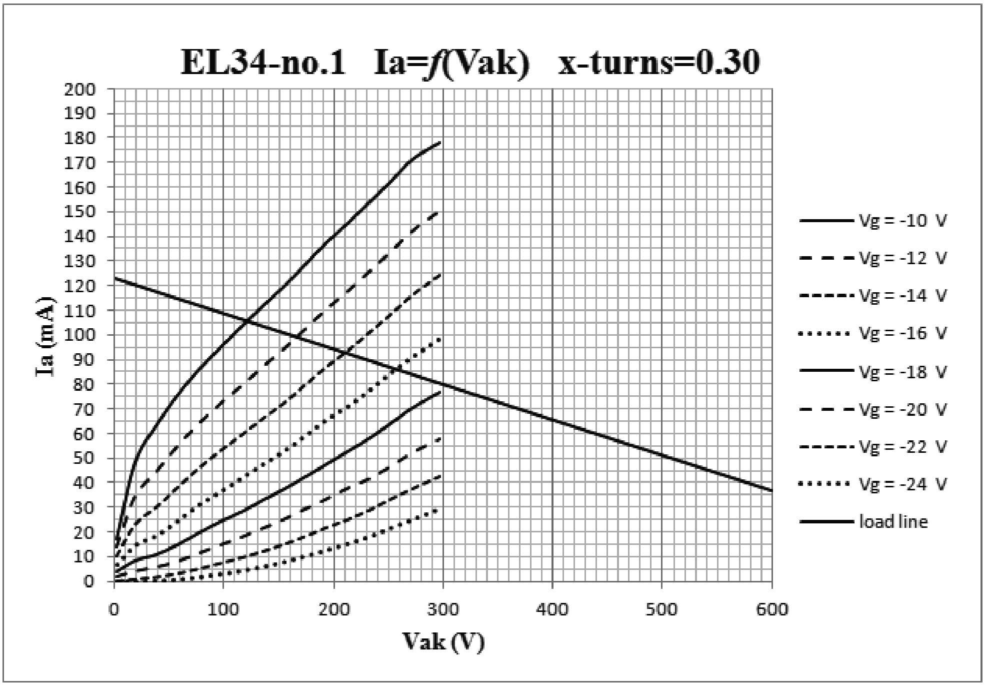


Figure 20 Anode characteristic for EL34-no.1 at $x_{TURNS} = 0.30$.

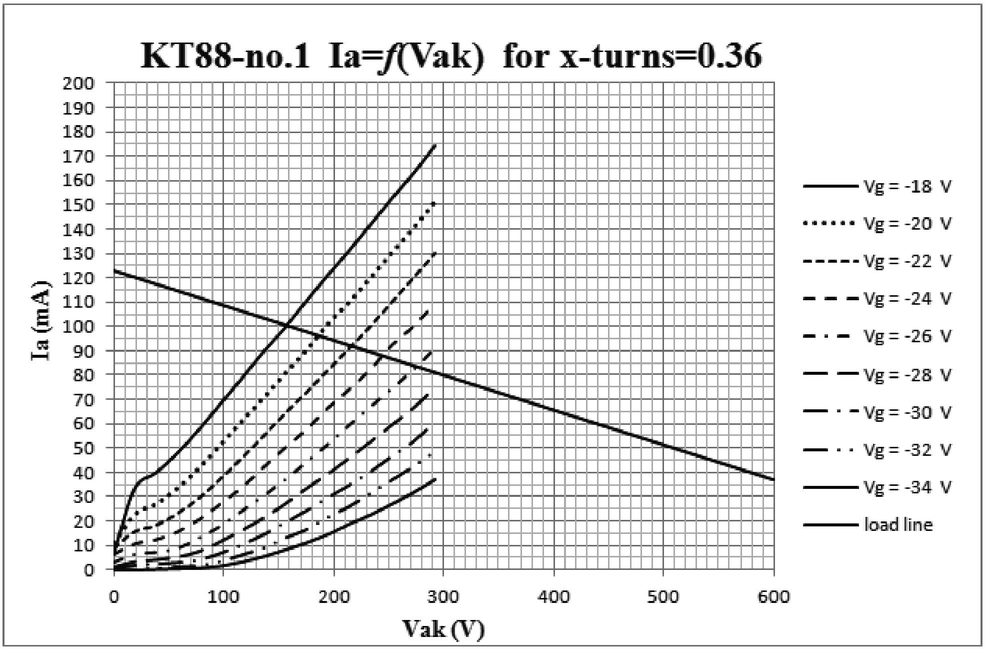


Figure 21 Anode characteristic for KT88-no.1 at $x_{TURNS} = 0.36$.

In figure 22c the transconductance characteristic is curved and the anode characteristic is linear. Therefor a perfect sine signal v_{g1k} will cause a distorted signal i_a which will cause a distorted signal V_{ak}.

When both anode and transconductance characteristics are curved, i_a and v_{ak} are also distorted. Be aware that all transconductance characteristics of figure 22 are **static** transconductances.

Except for small signal pentodes, manufacturers give (almost) never transconductance characteristics for power pentodes or power tetrodes. I don't like that but I must accept it. It is possible to construct a transconductance characteristic from an anode characteristic with V_{g1k}-curves. It is also possible to construct an anode characteristic from a transconductance characteristic with V_{ak}-curves. Chapter 4 of reference [7] but also other text books explain how this can be achieved. All transconductance characteristics discussed so far are **static transconductances** because they are measured in static conditions. When you put a load line through the working point of an anode characteristic then you can construct **dynamic transconductances**. **Figures 23 and 24** show how to construction dynamic transconductances for a triode and pentode respectively.

The construction of dynamic transconductances is as follows. Draw the load line of the anode impedance through the working point in the anode characteristic. This load line crosses the V_{g1k}-curves of the anode characteristic. Draw horizontal lines from the points of intersection between the load line and the V_{g1k}-curves to the I_a-axis. Read the values of anode DC current I_a which belong to a certain V_{g1k}-curve. When you have I_a and V_{g1k} value pairs, you can create curve $I_a = f\,(V_{g1k})$ which is called the **dynamic** transconductance because a load line has been used.
Normally dynamic transconducances are more linear than static transconductances.
The difference between the static and dynamic transconductance is larger for power triodes than for power pentodes because triodes have a significant lower anode AC internal resistances r_i while the anode AC external resistance r_a is a few kΩ with transformer load. Let's look closer to the relationship of the static and dynamic transconductance. See **figure 25**.

For $R_a = 0$ the anode current is: $i_a = S \cdot v_{g1k}$
For $R_a > 0$ the anode current is: $i_a = S_d \cdot v_{g1k}$

The current source equivalent diagram of figure 25 delivers $i_a = S \cdot v_{g1k} + \dfrac{v_{ak}}{r_i}$ and $v_{ak} = -i_a \cdot R_a$

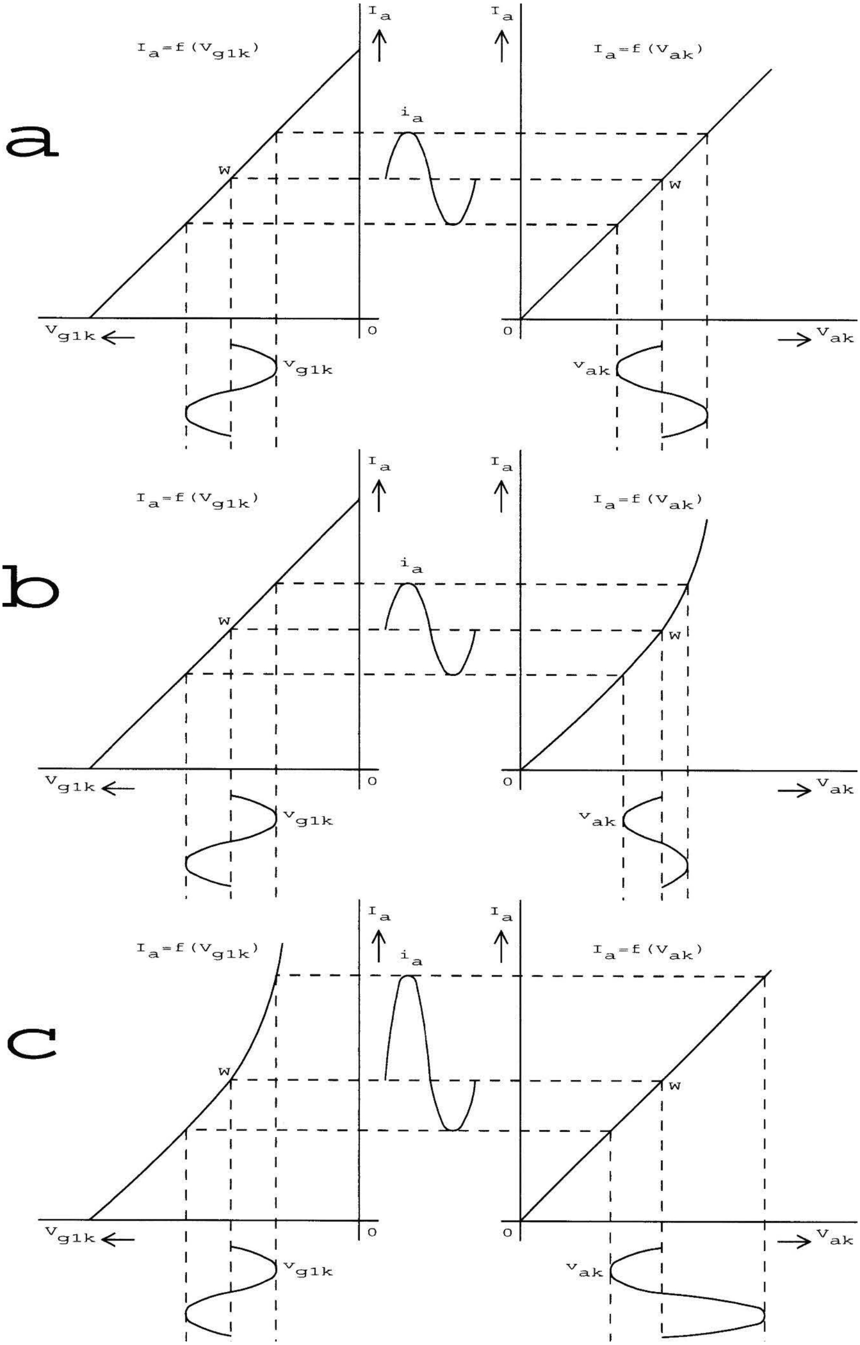


Figure 22 Curved and straight anode and (static) transconductance characteristics.

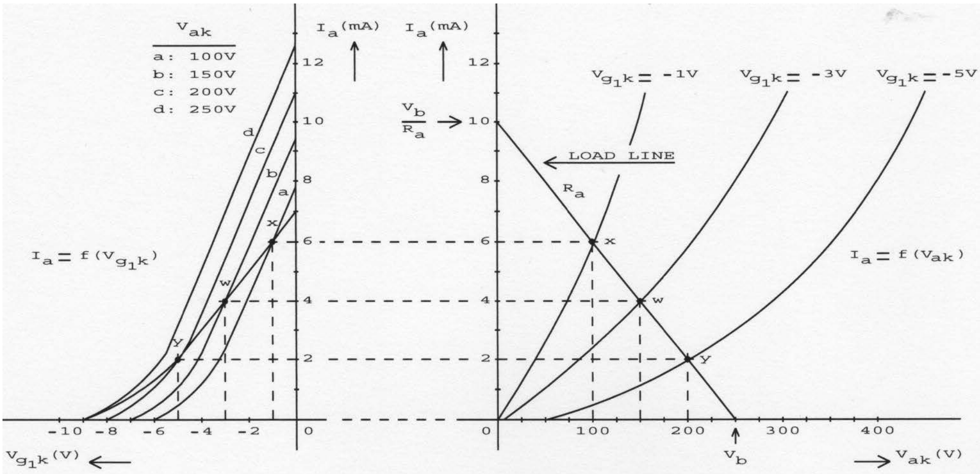


Figure 23 Dynamic transconductance (line x-w-y) in $I_a = f(V_{g1k})$ for a triode.

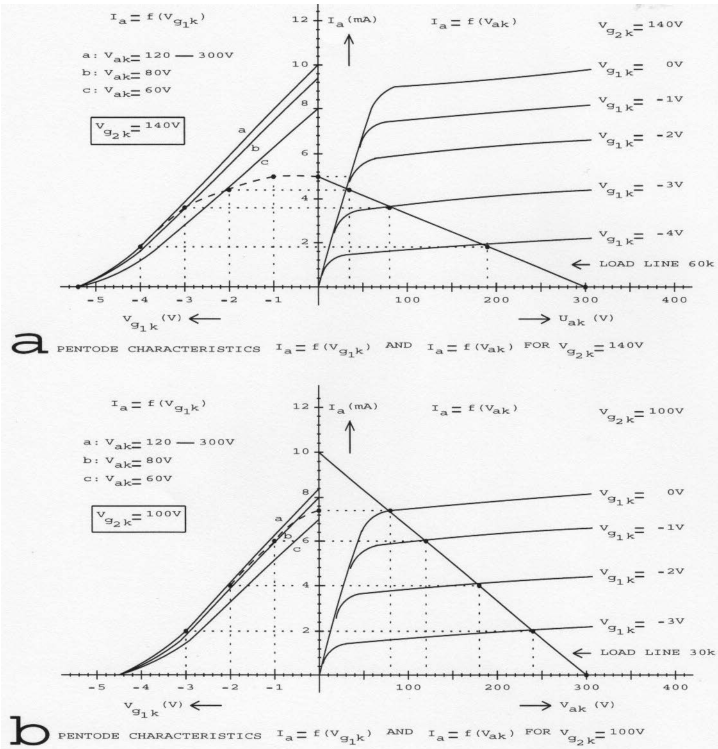


Figure 24 Dynamic transconductance (dashed line) in $I_a = f(V_{g1k})$ for a pentode.

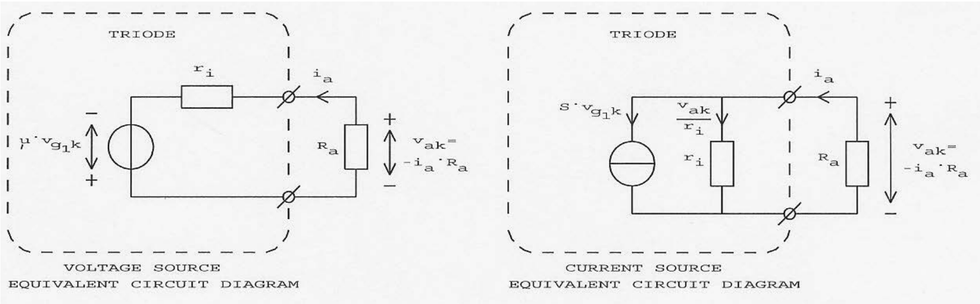


Figure 25 Voltage source and current source equivalent circuit diagram of a triode with anode resistor.

Combined we achieve: $i_a = S \cdot v_{g1k} - \frac{i_a \cdot R_a}{r_i} \quad \Leftrightarrow$

$$i_a + \frac{i_a \cdot R_a}{r_i} = S \cdot v_{g1k} \quad \Leftrightarrow$$

$$i_a \cdot \left(1 + \frac{R_a}{r_i}\right) = S \cdot v_{g1k} \quad \Leftrightarrow$$

$$i_a \cdot \left(\frac{r_i}{r_i} + \frac{R_a}{r_i}\right) = S \cdot v_{g1k} \quad \Leftrightarrow$$

$$i_a \cdot \left(\frac{r_i + R_a}{r_i}\right) = S \cdot v_{g1k} \quad \Leftrightarrow$$

$$i_a = S \cdot v_{g1k} \cdot \frac{r_i}{r_i + R_a}$$ with anode resistor load

$$i_a = S_d \cdot v_{g1k}$$ with anode resistor load

$$S_d \cdot v_{g1k} = S \cdot v_{g1k} \cdot \frac{r_i}{r_i + R_a}$$ divide all by v_{g1k} results in

$$S_d = S \cdot \frac{r_i}{r_i + R_a}$$ with anode resistor load

$$S_d = S \cdot \frac{r_i}{r_i + r_a}$$ with anode transformer load

The measurement results of the UL anode characteristics for a specimen of EL84, EL34 and KT88 are shown in appendices 13.A, 13.C and 13.E. There you can see that for several values of $k = x_{TURNS}$ the anode characteristics are quite linear. It is difficult to distinguish differences in their linearity.
But how linear are the dynamic transconductances for different values of $k = x_{TURNS}$?
That's the subject of the next section.

10 The forgotten dynamic transconductance

Figure 3 shows that working point W on the V_{ak}-axis of the anode characteristic lies at supply voltage V_b = 300V. The external anode load, not shown in figure 3, is a resistive AC load like a transformer with its secondary connected to a resistor load. We neglect a few volts voltage drop caused by the anode and screen grid DC currents through the transformer copper resistance.
The positive part of sine wave v_{ak} moves between V_b = 300V and V_{ak} = 425V → $+\Delta V_{ak}$ = 125V
The negative part of sine wave v_{ak} moves between V_b = 300V and V_{ak} = 175V → $-\Delta V_{ak}$ = 125V
The pentode, UL and triode curves of figure 3 do not go beyond 350V. In figure 3 an AC load line (not shown here) through working point W would start at I_a = 160 mA and terminate at V_{ak} = 600V.

The anode characteristics of figure 19 thru 21 do not go beyond 300V while the AC load lines and $+\Delta V_{ak}$ occupy the region between V_b = 300V and V_{ak} = 600V. Ronald's µTracer can measure anode characteristic up to 400V but we need to limit at V_b = 300V. **Figure 26** will show why.

In figure 26 at V_b = 300V we have the anode region $0 < V_{ak} < 300V$ for $-\Delta V_{ak}$ and the anode region $300 < V_{ak} < 600V$ for $+\Delta V_{ak}$. However in region $300 < V_{ak} < 600V$ we have no measured anode characteristic. **Figure 27** is a copy of figure 26 with extensions of the anode characteristic in the region $300 < V_{ak} < 600V$. I have drawn these extensions by hand with extrapolation. I admit that this is a weak part of my investigation. The anode characteristics in region $0 < V_{ak} < 300V$ are measured exactly and in region $300 < V_{ak} < 600V$ the anode characteristics are rather well extrapolated but not 100% exactly. However, figure 27 makes it possible to create a complete dynamic transconductance.

Is there a better way to determine a dynamic transconductance? **Figure 28** shows a part of the data sheets of a KT88 from Svetlana, the UL anode characteristic at $x_{TURNS\text{-}\%}$ = 40%. This figure shows two horizontal axes, a V_{ak}-axis and a V_{g2k}-axis. These axes are correct. You can determine a certain ΔV_{ak} with a corrsponding ΔV_{g2k}. Divide everywhere ΔV_{g2k} by a corresponding ΔV_{ak} and you achieve 0.4 = 40%. However this anode characteristic is rather useless when you want to design a UL power amplifier stage. There is just one point where the values of $V_{ak} \approx V_{g2k} \approx$ a certain V_b and that is at approximately 420V. This value forces an anode current of approximately 290mA when you extrapolate the curve V_{g1k} = −25V. No KT88 can handle the anode dissipation caused by these values. And be aware that the small copper resistance of the output transformer causes less voltage drop and by this $V_{ak} \approx V_{g2k} \approx V_b$.

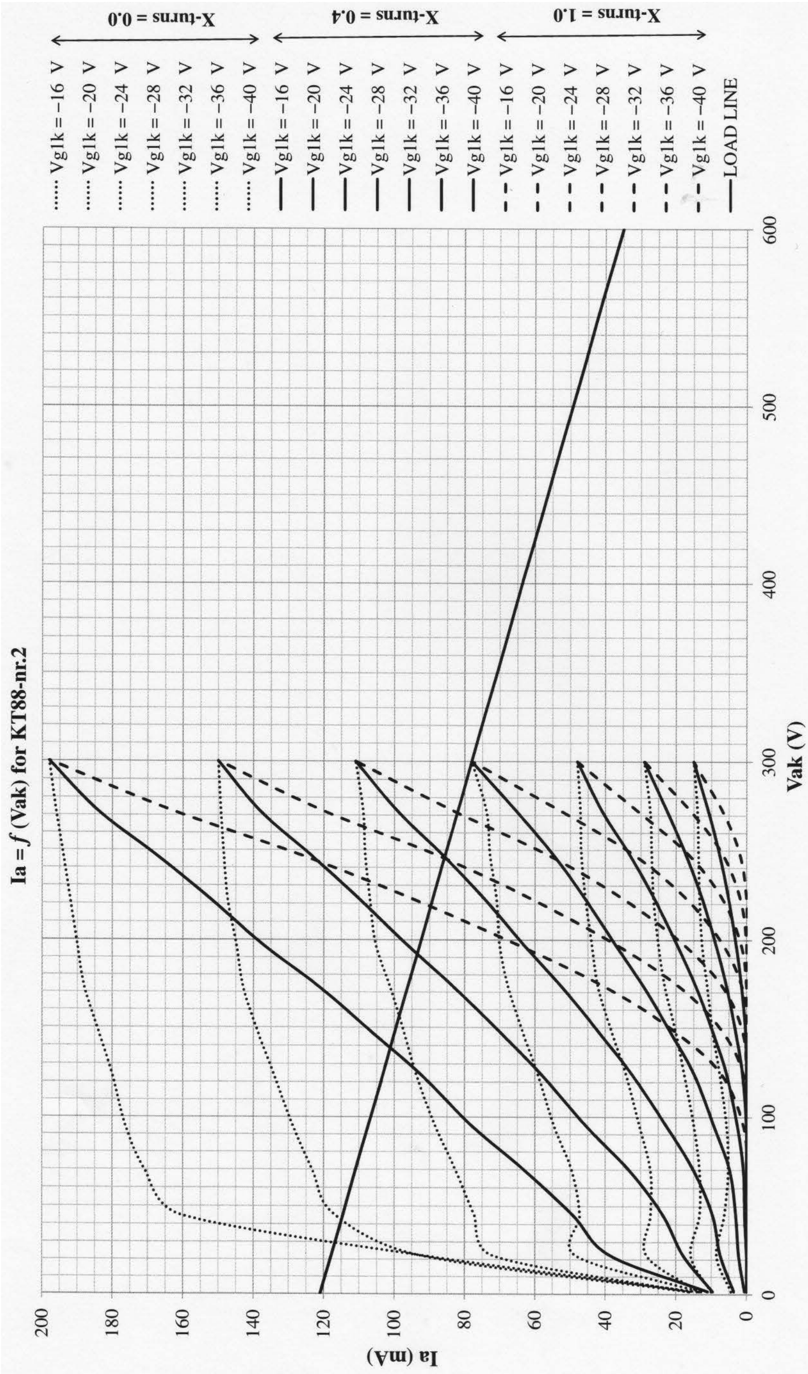


Figure 26 Anode characteristic of KT88-nr.2 for $x_{TURNS} = 0.0$ (pentode), $= x_{TURNS}$ 0.4 (UL) and $x_{TURNS} = 1.0$ (triode) for -16V < V_{g1k} < 40V. Measured without extrapolation.

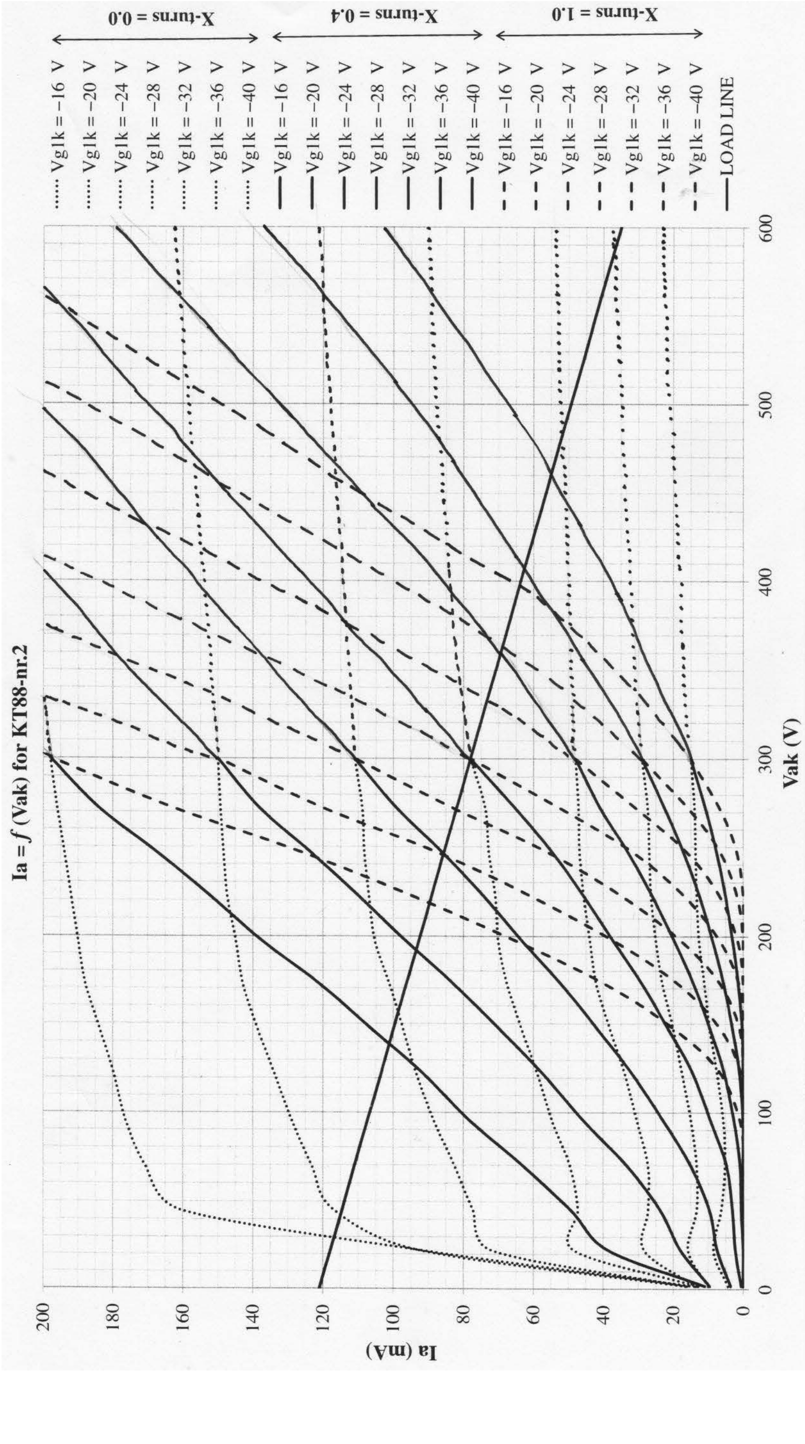


Figure 27 Anode characteristic of KT88-nr.2 for $x_{TURNS} = 0.0$ (pentode), $x_{TURNS} = 0.4$ (UL) and $x_{TURNS} = 1.0$ (triode) for $-16V < V_{g1k} < 40V$. Measured with extrapolation.

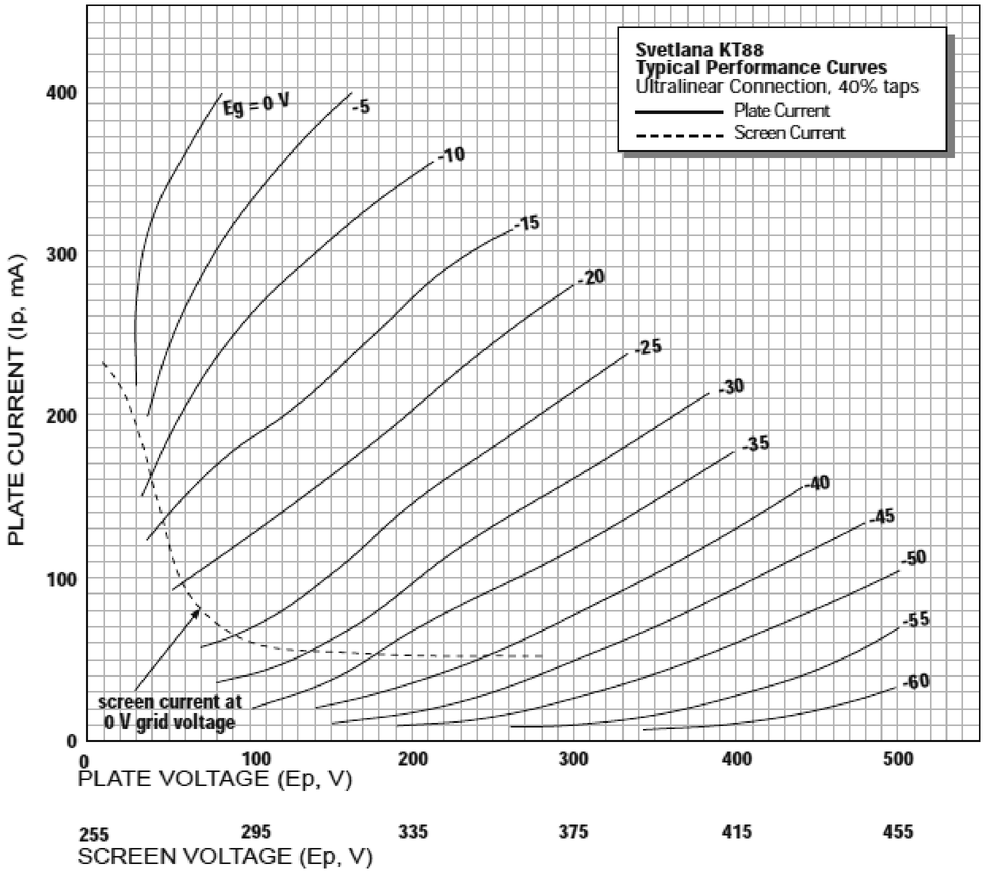


Figure 28 UL anode characteristic of KT88 from Svetlana datasheets.

Figure 29 shows an escape from this problem. There exist output transformers with a separate screen grid winding at the primary transformer side. By this you can give V_{g2k} its own value but still $V_{ak} \approx V_b$.

Figures 30 thru 32 show the transconductances determined for all values of x_{TURN} in one transconductance characteristic $I_a = f\,(V_{g1k})$ for EL84-no.1, EL34-no.1 and KT88-no.1 respectively.
The shown values x_{TURN} in these figures are from column 3 of table 7.

What immediately strikes us is that all dynamic transconductances cross in a single point. It will be no surprise that this is the working point. Which dynamic transconductance S_d is the most linear one (at which x_{TURN}) is difficult to distinguish in these figures. In **appendices 13.B, 13.D and 13.F** you can see the dynamic transconductances separately for all values of x_{TURN} and for each pentode. The only thing you need to do is put a ruler near each dynamic transconductance. Then you find the most linear one.

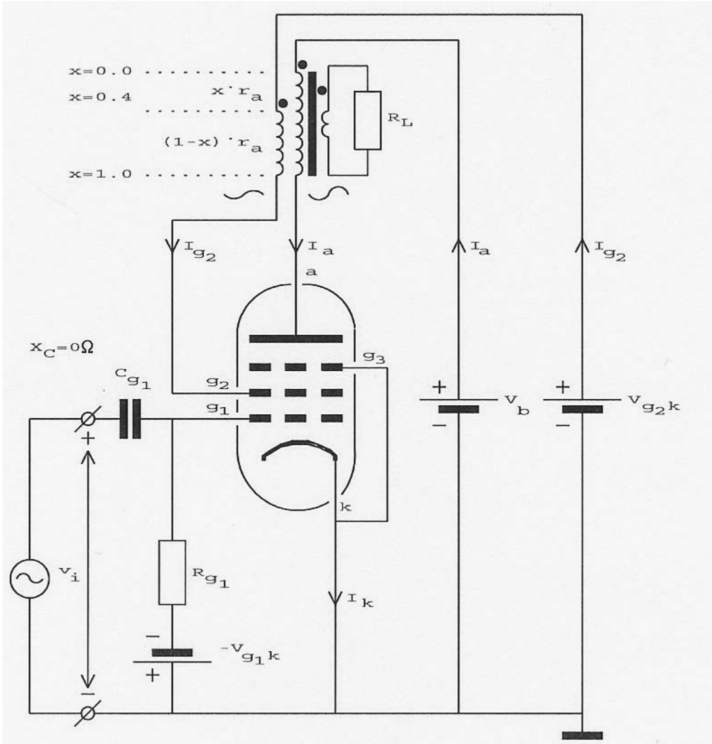


Figure 29 Separate screen grid winding at the primary transformer side.

I have already done this and the result will be no surprise.
For EL84-no.1 the most linear dynamic transconductance is at $x_{TURN} = 0.36 \rightarrow x_{TURN\text{-}\%} = 36\%$
For EL34-no.1 the most linear dynamic transconductance is at $x_{TURN} = 0.46 \rightarrow x_{TURN\text{-}\%} = 46\%$
For KT88-no.1 the most linear dynamic transconductance is at $x_{TURN} = 0.46 \rightarrow x_{TURN\text{-}\%} = 46\%$

11 Summary

In appendices 13.A, 13.C and 13.E, one can see that the difference in linearity of the anode characteristic (with x_{TURNS} values from column 3 of table 7) is hard to distinguish for values of x_{TURNS} between 0.23 and 0.56. I admit that the curves at the right side of V_{ak} = 300V are the result of extrapolation which may not be as accurate as measurements. In appendices 13.B, 13.D and 13.F, one can see that the difference in linearity of the dynamic transconductance characteristic (with values from column 3 of table 7) is hard to distinguish for values of x_{TURNS} between 0.30 and 0.46.
Of course, the mentioned extrapolations have influence on the accuracy of the determined dynamic transconductances.

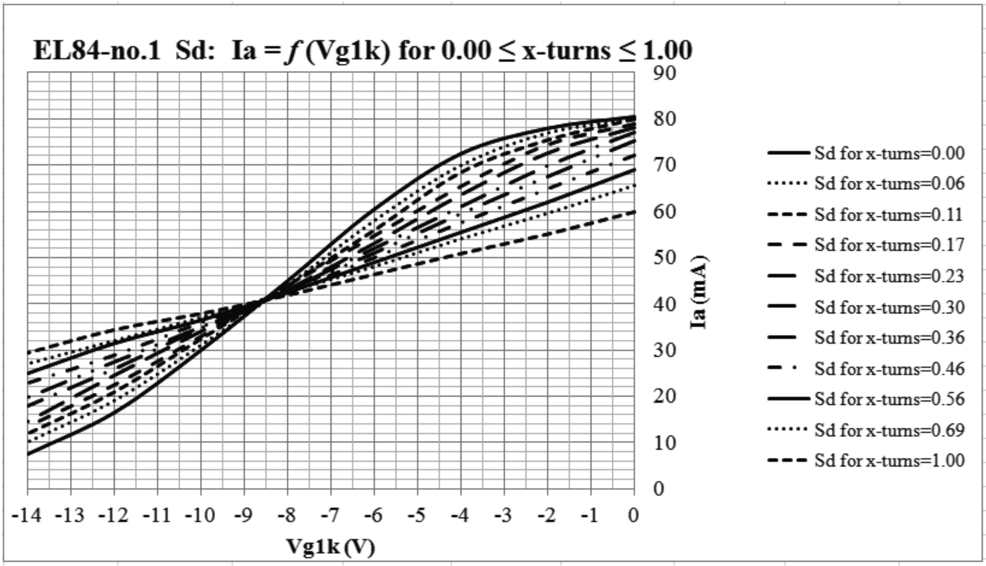


Figure 30 EL84-no.1 dynamic transconductance S_d : $I_a = f\,(V_{g1k})$ for $0.00 \leq x_{TURNS} \leq 1.00$.

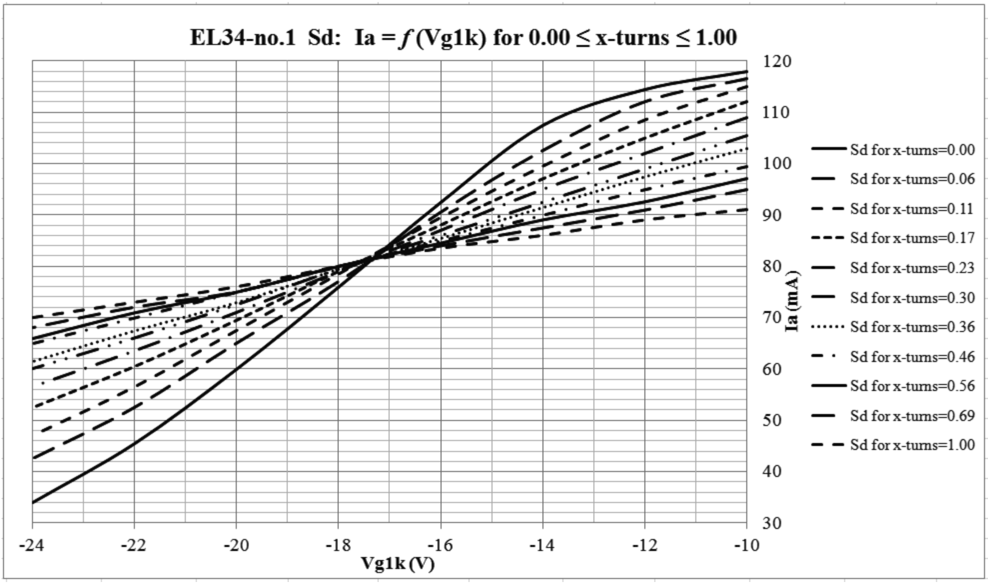


Figure 31 EL34-no.1 dynamic transconductance S_d : $I_a = f\,(V_{g1k})$ for $0.00 \leq x_{TURNS} \leq 1.00$.

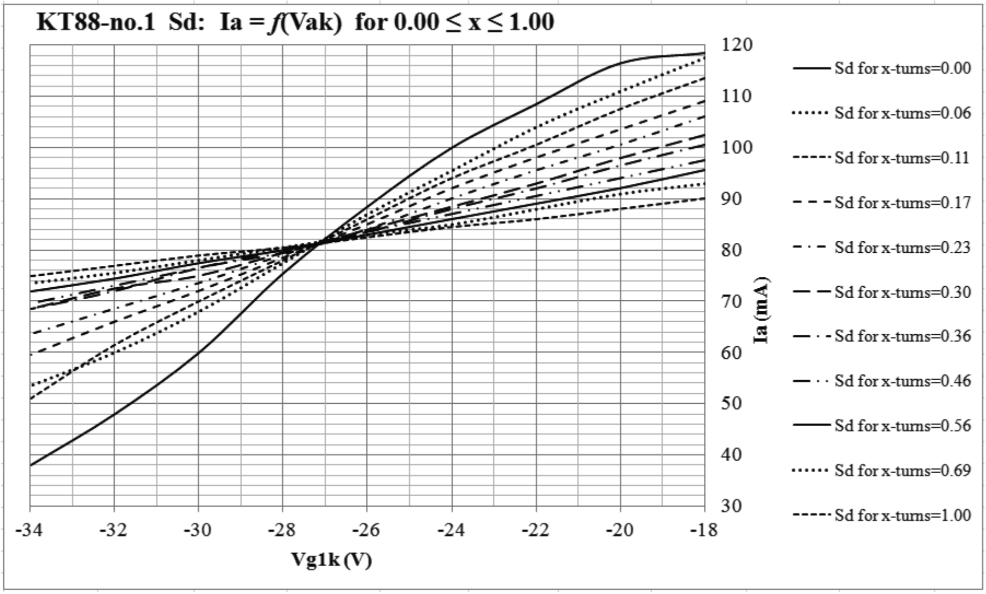


Figure 32 KT88-no.1 dynamic transconductance S_d : $I_a = f\ (V_{g1k})$ for $0.00 \leq x_{TURNS} \leq 1.00$.

The overall most linear of the anode characteristics and the most linear of the dynamic transconductance characteristics lies at 35% $< x_{TURNS\text{-}\%} <$ 45% or 12.25% $< x_{IMPEDANCE\text{-}\%} <$ 20.25%.
THD measurements from the past and recent measurements substantiate these results. I did not find a more optimal $x_{TURNS\text{-}\%}$ or $x_{IMPEDANCE\text{-}\%}$ for the lowest THD but it was fun to do this investigation.
I believe I have found a technical explanation of the THD behavior due to the position of the screen grid tap on the primary winding of the output transformer (load line) which also determines the dynamic transconductance. Despite the notable mechanical differences between EL84, EL34, KT88 and other power pentodes, and by this the notable differences of their internal electrical fields, the lowest THD will be achieved at $x_{TURNS\text{-}\%} \approx$ 43% or $x_{IMPEDANCE\text{-}\%} \approx$ 18.5%. The interesting question why electrons behave in these electric fields in such a way that the currents, cause by these electrons, give the lowest THD at $x_{TURNS\text{-}\%} \approx$ 43% or $x_{IMPEDANCE\text{-}\%} \approx$ 18.5% may be answered by physicists.

12 References

[1] David Hafler and Herbert Keroes — An Ultra-Linear Amplifier
Article in Audio Engineering, November 1951

[2] F. Langford-Smith and A.R. Chesterman — Ultra Linear Amplifiers
Radiotronics, volume 20, number 5, May 1955

[3] D.T.N. Williamson and P.J. Walker — Amplifiers and Superlatives
Article in Wireless World, September 1952

[4] By the Wireless World staff — Tetrodes with Screen Feedback
Further light on the so-called "ultra-linear" circuit
Article in Wireless World, January 1956

[5] Morgan Jones — The µTracer V.3.10 – a curve tracer for valves
Article in Linear Audio Volume 8, September 2014
ISBN 978-949092-909-1

[6] Rudolf Moers — The Ultra-Linear Power Amplifier
An adventure between triode and pentode
Article in Linear Audio Volume 2, September 2011
ISBN 978-9-490929-008

[7] Rudolf Moers — Fundamental Amplifier Techniques with Electron Tubes, Elektor, May 2010, ISBN 978-0-905705-934

13 Appendices (can be found on http://linearaudio.net/downloads)

Note: the screen grid taps x_{TURNS} referred to in these appendices are the values from column 3 of table 7.

A Measured with the µTracer and extrapolated anode characteristics of EL84 for several screen grid taps.

B Constructed dynamic transconductance characteristics of EL84 for several screen grid taps.

C Measured with the µTracer and extrapolated anode characteristics of EL34 for several screen grid taps.

D Constructed dynamic transconductance characteristics of EL34 for several screen grid taps.

E Measured with the µTracer and extrapolated anode characteristics of KT88 for several screen grid taps.

F Constructed dynamic transconductance characteristics of KT88 for several screen grid taps.