Theory and Practise of Wide Bandwidth Toroidal Output Transformers

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THEORY AND PRACTISE OF WIDE BANDWIDTH TOROIDAL OUTPUT TRANSFORMERS

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The frequency range and time behaviour of output transformers, used in tube amplifiers, are determined by the transformer parameters and the impedances of the source and the load. A general theory will be discussed on how to calculate the frequency range and time behaviour of output transformers in conjunction with output tubes and loads. A new Frequency Decade Factor will be introduced and compared to the well known transformer Quality Factor, taking the influences of different source and load impedances into account. A new toroidal output transformer with a -3dB bandwidth from .3Hz to 250kHz will be discussed.

1-1 TUBE AMPLIFIERS ARE BACK IN BUSINESS AGAIN

Nowadays tube amplifiers are again attracting the attention of audiophiles (lit.1,2,3,4). During the development and the widespread introduction of semiconductor amplifiers over the last few decades, the tube amplifier never fully disappeared, but moved to the background. In spite of the good qualities of the semiconductor amplifiers, many companies have started designing tube amplifiers again because of the inherent warmth, the soft sound characteristics and the growing interest of potential customers.

Almost every month, new tube amplifiers appear on the hifi market (see for instance lit.4). Most of these amplifiers use Output Transformers to optimize the matching of the low speaker impedance (below 10 Ohms) to the output tube impedances (generally above 1000 Ohms).

Although output transformerless amplifiers (OTL) are possible with tubes (lit.5) most designers use output transformers.

1-2 AIM OF THE PREPRINT

In this preprint the relationship between output transformers and power tubes will be investigated and a new wide bandwidth toroidal output transformer will be discussed. We will pay special attention to the frequency range of the output transformer in conjunction with the power tubes. For this reason new factors will be introduced e.g: the **T**uning **F**actor (**TF**) and the **F**requency **D**ecade **F**actor (**FDF**). We will not pay any attention to the schematics of the amplifier or how the power tubes are driven or the frequency range of the amplifier section in front of the output transformer. We will assume that any frequency limitations will be caused by the combination of output transformer, power tubes and speakerload. For examples of schematics and discussions about tube amplifiers as a whole, see lit.1,2,3,5,6,10.

1-3 THE POWER TUBE AS A VOLTAGE SOURCE ?

For this discussion it is a good idea to replace the output tube(s) by a simplified equivalent diagram. Figure 1-1 shows the $\mathbf{I_a}$-$\mathbf{V_{ak}}$-$\mathbf{V_{gk}}$ characteristics of a well known power tube (EL34 or 6CA7) in Penthode mode. Whether two tubes are used (balanced configuration) or one tube is used (single ended configuration), the tube(s) are setup in a certain operating point (point A in figure 1-1). In this operating point the tube(s) can be replaced by an equivalent voltage source with an alternating voltage, $\mathbf{V_p}$,and a generator resistance, $\mathbf{R_g}$, in series. For a single ended configuration, $\mathbf{R_g}$ equals the plate resistance $\mathbf{r_i}$ of the tube. For a balanced configuration in class A, $\mathbf{R_g}$ equals 2*$\mathbf{r_i}$. When two tubes are used as cathode followers, $\mathbf{R_g}$ equals 2*1/**s** (lit.7). We could have also considered the tube as being a current source with $\mathbf{R_g}$ in parallel. However to simplify our calculations we will use the voltage source model, with the knowledge that both models will lead to the same results.

1-4 IMPEDANCE MATCHING

The tubes are loaded by the primary impedance of the transformer, $\mathbf{R_{aa}}$, which is mainly caused by the speaker impedance $\mathbf{Z_L}$ that is transformed back into the primary side of the output transformer. This transformer load is drawn in figure 1-1 as well and indicated by $\mathbf{R_{aa}}$. If the transformer is constructed with $\mathbf{N_p}$ primary turns and $\mathbf{N_s}$ secondary turns, the turns ratio **T** is given by:

$$T = \frac{N_s}{N_p} \qquad (1-1)$$

The relationship between $\mathbf{R_{aa}}$ and $\mathbf{Z_L}$ can then be given by:

$$R_{aa} = \frac{Z_L}{T^2} \qquad (1-2)$$

For maximum power transfer from the output tubes to the speaker, the total resistance of the tubes ($\mathbf{R_g}$) should to be the same as $\mathbf{R_{aa}}$ However this arangement is not always chosen. Therefore we define the load ratio (β) as:

$$\beta = \frac{R_g}{R_{aa}} \qquad (1-3)$$

In most of the tube amplifiers the value of β is greater than 1. In triode amplifiers β is almost equal or smaller than 1.

1-5 THE EQUIVALENT CIRCUIT OF THE TRANSFORMER

Many equivalent circuits are available for transformers. A survey is given in lit.8. In tube amplifiers the transformer is a STEP-DOWN transformer in which $\mathbf{N_p}$ is greater then $\mathbf{N_s}$. Introducing the low and high frequency behaviour in one equivalent circuit on the primary side of the transformer, and transfering this circuit plus the tube generator resistance $\mathbf{R_g}$ through the transformer to the secondary side where the load $\mathbf{Z_L}$ (loudspeaker) is placed, we end up with the following equivalent diagram. See figure 1-3 and the Glossary List for the meaning of the terms used.

This circuit will act as the basis for our analysis. Refinements to the circuit are possible and proposed by Flanagan (lit.8). However, the results of calculations with this simple circuit, applied to the new toroidal output transformers, are in good agreement (better then 90%) with measured values. The simplicity of this circuit has the advantage that the specifications and frequency range determing elements of an output transformer in tube amplifiers can be easily understood.

2 THE TRANSFER FUNCTION

The total transfer function of the circuit in figure 1-3 is given by formula 2-1 where $\boldsymbol{\omega}$ is the circular frequency.

$$H(\omega) = \frac{V_{load}}{V_p}$$

$$H(\omega) = T.I_{los}.L.H$$

$$I_{los} = \left[\frac{Z_L}{[R_g + R_{ip}].T^2 + R_{is} + Z_L}\right] \qquad (2-1)$$

$$L = \left[\frac{i.\omega}{i.\omega + \dfrac{[R_g + R_{ip}].T^2.[R_{is} + Z_L]}{[[R_g + R_{ip}].T^2 + R_{is} + Z_L].[L_p.T^2]}}\right]$$

$$H = \left[\frac{1}{1 + a_2.[i.\dfrac{\omega}{\omega_0}] + [i.\dfrac{\omega}{\omega_0}]^2}\right]$$

in which:

$$\omega_0 = \sqrt{\frac{[R_g + R_{ip}].T^2 + R_{is} + Z_L}{R_g.T^2.L_{sp}.C_{ip}}} \qquad (2-2)$$

$$a_2 = \omega_0.\left[\frac{L_{sp}.T^2 + C_{ip}.R_g.[R_{ip}.T^2 + R_{is} + Z_L]}{[R_g + R_{ip}].T^2 + R_{is} + Z_L}\right] \qquad (2-3)$$

In this transfer function we recognize four terms, each with their own specific function and influence.

The first term "**T**" gives the downwards transformation of the primary voltage $\mathbf{V_p}$ to the secondary side of the transformer.

The second term "$\mathbf{I_{los}}$" expresses the losses in the transformer, due to the internal resistances of the primary and secondary windings. The "loss" caused by the generator resistance $\mathbf{R_g}$ with the load impedance $\mathbf{Z_L}$ is found here too. The well known "insertion loss" of a transformer relates to this part of the transfer function (lit.8).

The third term "**L**" is important at low frequencies and describes a first order high pass filter caused by the "resistances" and the primary inductance $\mathbf{L_p}$.

The fourth term "**H**" is a second order low pass filter with a specific circular frequency ω_o (formula 2-2) and a tuning factor a_2 defined by formula 2-3. Instead of a_2 the Q-factor is often used with: $a_2 = 1/Q$.

Fortunately, the "real world" situation allows us to simplify this transfer function. Initially we can use the term β, defined in chapter 1. Secondly, through various output transformers measurements we can conclude that almost in all transformers $R_{ip} \ll R_g$ and $R_{is} \ll Z_L$. Therefore, we can leave these wire resistances out of the equations without introducing important errors. The total transfer function can now be given as:

$$H(\omega) = (T).[\frac{1}{1+\beta}].[\frac{i.\omega}{i.\omega + [\frac{\beta}{\beta+1}].[\frac{R_{aa}}{L_p}]}].[\frac{1}{1 + a_2.[i.\frac{\omega}{\omega_0}] + [i.\frac{\omega}{\omega_0}]^2}] \qquad (2-4)$$

ω_o becomes easier to handle as well:

$$\omega_0 = \sqrt{\frac{1}{L_{sp}.C_{ip}}}.\sqrt{\frac{\beta+1}{\beta}} \qquad (2-5)$$

Rearranging a_2 produces formula 2-6:

$$a_2 = \omega_0.[\frac{\frac{L_{sp}}{R_{aa}} + C_{ip}.\beta.R_{aa}}{\beta+1}] \qquad (2-6)$$

Further analysis will reveal that it is advantageous to express a_2 differently. a_2 then becomes a function of α as shown in formula 2.7 and 2.8.

$$a_2 = \alpha.\sqrt{\frac{1}{\beta.(\beta+1)}} + \frac{1}{\alpha}.\sqrt{\frac{\beta}{\beta+1}} \qquad (2-7)$$

$$\alpha = [\frac{1}{R_{aa}}].\sqrt{\frac{L_{sp}}{C_{ip}}} \qquad (2-8)$$

Using formula's 2-4 to 2-8, calculations with the transfer function have now become much easier.

However, we would like to state that for a complete analysis, without any approximations, the formulas 2-1 to 2-3 must be used and, for instance, implemented in computer programs.

3 THE -3dB FREQUENCY RANGE

In this chapter the -3dB bandwidth of the tubes plus transformer will be calculated. Only the filter sections of the transfer function need to be studied because the turns-ratio element and the "loss"-element are frequency independent.

3-1 THE LOWER -3dB FREQUENCY

The transferfunction produces the lower -3dB frequency directly; see formula 3-1.

$$f_{-3L} = \frac{R_{aa}}{2.\pi.L_p}.[\frac{\beta}{\beta+1}] \qquad (3-1)$$

As expected this frequency is determined by the primary inductance L_p plus R_{aa} and the load ratio β.

3-2 THE HIGHER -3dB FREQUENCY

The higher -3dB frequency f_{3H} is not as easy to calculate because two poles are present. We found f_{3H} as follows: first calculate the length of the second order filter **vector** in the complex domain, and then find the -3dB frequency for which this length equals 1/√2. This results in two formula's:

$$f_{-3H} = \frac{1}{2.\pi}.\sqrt{\frac{1}{L_{sp}.C_{ip}}}.[f[a_2].\sqrt{\frac{\beta+1}{\beta}}] \qquad (3-2)$$

$$f[a_2] = \sqrt{\frac{[2 - a_2^2] + \sqrt{[a_2^2 - 2]^2 + 4}}{2}} \qquad (3-3)$$

In figure 3-1, $f(a_2)$ is shown for different values of a_2. Most output transformers are used with **Q**-values between .5 and 1 (a_2 between 2 and 1).

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In this part of the function $\mathbf{f(a_2)}$ is almost a straight line and can be approximated by the linear function $\mathbf{ff(a_2)}$ with less then 5% deviation from the original function $\mathbf{f(a_2)}$.

$$ff[a_2] = 1.950 - 0.668.a_2 \qquad 1 \le a_2 \le 2 \qquad (3-4)$$

This function can be easily calculated by hand, but for a complete analyses without approximations $\mathbf{f(a_2)}$ is the best choice.

4 TUNING FACTOR AND FREQUENCY DECADE FACTOR

The Tuning Factor will now be introduced. The -3dB bandwidth will be calculated with the use of this Tuning Factor and the Quality Factor of the transformer. The Frequency Decade Factor couples the Tuning and Quality Factors.

4-1 INTRODUCING THE TUNING FACTOR

When we divide formula 3-2 by formula 3-1, we compare the highest -3dB frequency to the lowest -3dB frequency. This results in:

$$\frac{f_{-3H}}{f_{-3L}} = f[a_2] \;.\; [\frac{\beta + 1}{\beta}]^{1.5} \;.\; [\frac{1}{R_{aa}}.\sqrt{\frac{L_{sp}}{C_{ip}}}] \;.\; [\frac{L_p}{L_{sp}}] \qquad (4-1)$$

This formula has a few interesting aspects.
The first term expresses the tuning (**Q**- or $\mathbf{a_2}$- factor) at the high frequency side.
The second term shows the influence of the generator impedance $\mathbf{R_g}$ (the tubes) and $\mathbf{Z_L}$ (the load) on the -3dB bandwidth.
The third term compares the characteristic primary impedance $\mathbf{Z_{ip}}$ (formula 4-2) to the primary impedance $\mathbf{R_{aa}}$ (caused by $\mathbf{Z_L}$ and **T**).

$$z_{ip} = \sqrt{\frac{L_{sp}}{C_{ip}}} \qquad (4-2)$$

The fourth term is the well known QUALITY FACTOR of the transformer, defined as (see for instance lit.10):

$$QF = \frac{L_p}{L_{sp}} \qquad (4-3)$$

We can conclude from this, that the first three terms of formula 4-1 depend on how a transformer is used, which loads are present, which generator resistance is formed by the tubes and the value of the Q-factor that has been chosen at the high frequency side.

So the first three terms determine the tuning of the transformer when used under certain conditions. For this reason we can now define the TUNING FACTOR as:

$$TF = f[a_2].[\frac{\beta + 1}{\beta}]^{1.5}.[\frac{Z_{ip}}{R_{aa}}] \qquad (4-4)$$

This then results in a basic formula that compares the highest and lowest -3dB frequencies:

$$\frac{f_{-3H}}{f_{-3L}} = TF \,.\, QF \qquad (4-5)$$

4-2 TUNING FACTOR EXAMPLES

Initially we examined the values of the Tuning Factor when different tubes or tube configurations were used. For that reason we changed $\mathbf{R_g}$ and kept $\mathbf{R_{aa}}$ constant (which meant that the turns ratio **T** and $\mathbf{Z_L}$ stayed constant). In figures 4-1, 4-2 and 4-3 the results of these calculations can be found for values of β from .1 to 10. The values of the ratio $\boldsymbol{\alpha}$ were .5 , 1 and 2 respectivily. The Q-factors (= $1/\mathbf{a_2}$) of these tunings are shown in the same figures (right-hand scale).

We examined the values of the Tuning Factor when the load changes. Figures 4-4, 4-5 and 4-6 show the results. In these calculations it is assumed that $\mathbf{Z_L}$=1 Ohm when $\mathbf{R_g}$=$\mathbf{R_{aa}}$ (figure 4-4). This is almost equivalent to a balanced pair of triodes driving the output transformer. In figure 4-5 we assume that $\mathbf{Z_L}$=1 Ohm when $\mathbf{R_g}$=3*$\mathbf{R_{aa}}$ (almost Ultra Linear configuration). Figure 4-6 shows the results for $\mathbf{R_g}$=10*$\mathbf{R_{aa}}$ when $\mathbf{Z_L}$=1 Ohm (balanced Penthode configuration). For $\mathbf{Z_L}$=1 Ohm we assumed that $\boldsymbol{\alpha}$=1.

Conclusions:

1) under different loading and tuning conditions, the changes in the Tuning Factor are large and range from approx. 0.1 to almost 10. This means that for an indication of the -3dB frequency range of the transformer in every application, the value of the Quality Factor alone is not enough.

2) the Q-factor is surprisingly stable in figure 4-1. Calculations show that when $\alpha = .65$ the value of **Q** stays constant at .66 when $\beta > 1$.

3) a rather stable frequency behaviour, almost independant of the tube plate resistances, is attained for $\alpha >= 2$ (figure 4-3)

4) in the penthode mode especially (figure 4-6) the tuning factor decreases rapidly when the load impedance increases. In practice the impedance of some speakers increases at higher frequencies (due to the inductance of the speaker-coil). This partially explains why some tube amplifiers transfer less high frequency information when loaded with a speakers like this.

4-3 INTRODUCING THE FREQUENCY DECADE FACTOR

When calculating the size of $\mathbf{f_{3H}/f_{3L}}$ one usually ends up with large values. But what do these values tell us? They provide an impression of the -3dB frequency bandwidth. However, these values are much easier to handle and to interpretate when we calculate their logarithmic value. We then have a clear indication of how many frequency DECADES are spanned by the transformer and its tuning. For this reason the FREQUENCY DECADE FACTOR can be defined as:

$$FDF = \log \frac{f_{-3H}}{f_{-3L}} \qquad (4-6)$$

Rearranging produces:

$$FDF = \log[(TF).(QF)] = \log(TF) + \log(QF) = TDF + QDF \qquad (4-7)$$

We have added extra factors: the TUNING DECADE FACTOR

$$TDF = \log(TF) \qquad (4-8)$$

and the QUALITY DECADE FACTOR:

$$QDF = \log(QF) \qquad (4-9)$$

Through the use of a few examples we will show the usefulness of these factors.

4-4 FREQUENCY DECADE FACTOR EXAMPLES

Example 1: suppose $\mathbf{L_p}$=100H and $\mathbf{L_{sp}}$=5mH. Then **QF**=20,000.
The number of frequency decades that can be spanned by this transformer, based on the Quality Decade Factor, is 4.30. Proper tuning can expand this range. I.e. using the Butterworth tuning (optimaly flat) where $\mathbf{a_2}$=sqrt2 and $\alpha=1$ (this means that $\beta = 1$). The Tuning Factor then equals 2.83 and the Tuning Decade Factor is equal to 0.452. The total amount of frequency decades spanned is now 4.75. Suppose $\mathbf{f_{-3L}} = 1.0$ Hz, then $\mathbf{f_{-3H}} = 10^{4.75} = 56$ kHz. Further investigation will show that $\mathbf{R_{aa}} = 1.257$ kOhm. $\mathbf{C_{ip}}$ should be 3.16 nF.

Example 2: using the same transformer ($\alpha=1$) we will now tune for optimal constant time behaviour ($\mathbf{a_2}$=sqrt3). In this case $\beta=.5$ (formula 2-7). The tuning factor equals 4.12 and **TDF**=.61. The total amount of decades spanned is now: **FDF**=4.91. By using the formulas of chapter 3 we now can calculate $\mathbf{f_{-3L}}$ and $\mathbf{f_{-3H}}$. Their values are respectivily .67 Hz and 55 kHz. Because α equals 1, $\mathbf{C_{ip}}$ should still be 3.16 nF. However, now the generator resistance $\mathbf{R_g}$ has to be equal to 629 Ohm. This means, compared to example 1, that the number of power tubes is doubled. Surprisingly, this example shows that the lower value of $\mathbf{R_g}$ did not influence the highest -3dB frequency but the lowest -3dB frequency!

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4-5 EXPLANATION OF THE USEFULLNESS OF DECADE FACTORS

The reasons for introducing the Tuning Factor and the Frequency Decade Factor are as follows:

1) Until now the Quality Factor was used as an indication of the "quality" of a transformer. The greater the **QF**, the better the transformer, which meant a larger -3dB frequency bandwidth. In earlier transformer designs **QF**-values ranged from 20.000 to 70.000 (lit.10). Nowadays transformers have **QF**-values up to 146.000 (100/.000685; see lit.11). In chapter five we will introduce new toroidal wide bandwidth output transformers with **QF** values of 274.000 (360/.001312). However, when using the **Q**uality **D**ecade **F**actor, a more realistic impression of the influence of the higher **QF**-values on the -3dB frequency bandwidth can be achieved.

2) Every transformer can be tuned in many different ways. Numerous **TF** values are possible by changing the values of $\mathbf{Z_L}$ and $\mathbf{R_g}$. For instance: the lower the value of $\mathbf{R_g}$, the higher the value of the **TF**. The same is true when $\mathbf{Z_L}$ is lowered. Calculating either the Tuning Factor or the **T**uning **D**ecade **F**actor will show us directly how large the extra frequency range is, using different tunings.

3) The Frequency Decade Factor will give us a direct indication of the frequency bandwidth of the output transformer for a certain application. E.g. a **FDF** value of 6 implies that we can range from 1 Hz to 1 MHz or from 10 Hz to 10 Mhz etc.

Conclusions:

a) The **QF** shows us what is possible to achieve with the transformer, independent of the tuning. From the **QF**, the **QDF** can be derived, which may, in turn, be used as an indication of the bandwidth. This value can then be used to compare different brands of transformers.

b) The **TF** supplies us with a good impression of the high frequency behaviour of the transformer. The **TDF** shows us directly, the extra bandwidth that can be obtained through the use of different tunings.

c) The **FDF** indicates directly the total size of the -3dB bandwidth.

5 NEW TORIODAL WIDE BANDWIDTH OUTPUT TRANSFORMERS

In this chapter a new toroidal output transformer, for tube amplifiers, will be introduced. In accordance with the theory in the previous chapters the possibilities will be calculated, measured and explained.

5-1 GENERAL DESCRIPTION

In 1984 our first attempt was made to construct a toroidal push pull output transformer for tube amplifiers. This resulted in a simple design with rather good specifications. Research showed us that a optimized toroidal design will have some very interesting advantages compared to EI-core designs. With toroidal cores and special winding techniques we were able to create very high coupling factors between primary and secondary windings. This resulted in small leakage inductance values. We noticed that high values of the primary inductance $\mathbf{L_p}$ could be achieved as well. Combining these high $\mathbf{L_p}$ values with the small $\mathbf{L_{sp}}$ values, we are able now to create very high Quality Factor values.

Research showed that low values of the internal capacitance $\mathbf{C_{ip}}$ could be achieved as well, using special winding techniques and careful positioning of winding layers.

The power capability of our new transformers ranges from 20 Watt to 100 Watt with the lowest -3dB POWER frequencies between 20 and 30 Hz. However, $\mathbf{f_{-3L}}$ is close to 1 Hz due to the high $\mathbf{L_p}$ values (see figure 5-1). We were able to create a high degree of symmetry for alternating currents and voltages. For instance: the leakage inductance from one halve of the primary to the other halve of the primary has a small value, almost equal to the low leakage inductance and thus showing the high degree of symmetry in the transformer. Due to this we are able to use these transformers to high power levels with relatively small cores, without entering the region of core saturation.

Compared to previous designs, we have achieved high primary inductances, high coupling, low leakage inductances, the same or even lower internal capacitances, a high degree of balancing, low losses in the core by using a quiet and fast core material, and we have even lowered the heat losses in the windings due to low internal resistances.

5-2 SPECIFICATIONS

At the moment (1994) five standard types are available with primary impedances of 1 to 8 kOhm. Their parameters are listed in figure 5-1. The transformers are constructed with taps for Ultra Linear tube configurations, which means that they can be used with Triodes, Ultra Lineair Configurations and Penthodes. All these transformers are intended for push pull tube drive.

We will now discuss, in detail, the model with the lowest primary impedance, the VDV1080. The parameters of the other models are given as well in figure 5-1. Using the theory described in chapters 1 to 4 all the calculations can be performed on the other transformers.

5-3 SECONDARY IMPEDANCE AND TAPS

The secondary impedance of this transformer is optimized to drive 5 Ohms speakers. Due to the fact that a speaker's impedance varies with the frequency (see for example figure 5-2), the size of the secondary impedance was choosen to work optimally with the majority of available speakers. If secondary taps are required for other speaker impedances, they can be delivered on request. A tap exactly in the middle of the secondary coil is possible too so that cathode feedback or balanced speaker drive or balanced negative feedback can be applied.

5-4 QUALITY FACTOR AND QUALITY DECADE FACTOR

The value of the primary inductance $\mathbf{L_p}$ was measured at 200 Volts and 50 Hz , or 240 Volts and 60 Hz (the same fluxdensity). This measurement can be repeated at lower or higher primary voltages. Then $\mathbf{L_p}$ will deviate slightly from our values due to the changes in the relative magnetic permeablity as a function of the magnetic fieldstrength.

The Quality Factor is equal to 274,390. We will continue our calculations for reasons of accuracy with 2.74E5 (2.74 times 10 to the power 5).

The Quality Decade Factor is now 5.44. Which means, if all is tuned properly, we can at least expect 5.44 frequency decades to be spanned.

5-5 WIRE RESISTANCES

The values of $\mathbf{R_{ip}}$ and $\mathbf{R_{is}}$ are 37.8 and 0.16 Ohm respectivily. We will drive the transformer with a generator resistance, $\mathbf{R_g}$, of 1200 Ohm. The primary heat losses will only be 3 % of the transfered power and the secondary losses will equal 3 % as well. Our calculations will neglect these losses and use the simpler formula's starting at formula 2-4 . The linear approximation $\mathbf{ff(a_2)}$ will be used as well.

5-6 CALCULATION OF THE -3dB BANDWIDTH

In this transformer $\mathbf{C_{ip}}$ is chosen so that the characteristic impedance ($\mathbf{Z_{ip}}$) of the primary is almost equal to the primary impedance. The results of our calculations: $\mathbf{Z_{ip}}$ = 1487 Ohm. On the secondary side the transformer is loaded with a 5 Ohm load which produces an $\mathbf{R_{aa}}$ equal to 1239 Ohm. The value of α is 1.200 and β will be .969. Formula 2-7 results in a value of $\mathbf{a_2}$ = 1.453 and **Q** = 0.688. This is a healthy tuning between the optimally flat tuning (**Q** = 0.577) and the Butterworth tuning (**Q** = 0.707).

Formula 3-4 delivers a value for $\mathbf{ff(a_2)}$ of 0.979. Now the tuning factor can be calculated (**TF** = 3.40) as well as the Tuning Decade Factor (**TDF** = 0.53). Combining the Quality Decade Factor and the Tuning Decade Factor we find that 5.97 decades will be spanned. When we apply formula's 3-1 and 3-2 we can calculate the lower and higher -3dB frequencies. Their values are respectivily: 0.270 Hz and 252 kHz.

If we repeat these calculations without any approximations we will find values of 0.278 Hz and 251 kHz, respectivily. The approximation of neglecting $\mathbf{R_{ip}}$ and $\mathbf{R_{is}}$ caused only a slight mistake of 2.9 % and .4 %, respectivily. (See figure 5-1 where the results of these calculations are given).

The last calculations are with the -3dB frequencies with and without approximations: ${}^{10}\log(\mathbf{f_{-3H}}/\mathbf{f_{-3L}})$ = 5.97 and 5.96 decades respectivily, showing good agreement (and so it should to be!).

In figure 5-3 the calculated and measured frequency responses are shown (no approximations). The measurement was performed by replacing each of the tubes by a resistor of .5.$\mathbf{R_g}$ and driving the transformer, on the primary side, with an oscillator at a 20 Volts peak to peak level (see figure 5-4).

6 CONCLUSIONS

1) Tube Amplifiers are back in business again! For this simple reason it is of great importance to re-study old technologies, to use valuable experience and to combine this with modern technology. We have tried to apply all this when we designed and constructed our new toroidal output transformers.

2) For frequency analysis it is useful to replace the power tube by a voltage source with its plate resistance in series, as a generator resistance. This simple model gives us a good impression of the influence of the powertube on the transferfunction.

3) The output transformer can be replaced by a simple equivalent circuit which allows easy calculation of the transferfunction. The results are at least within 90 % of the measurements with the discussed output transformer.

4) It is of great importance to know at least the following parameters of an output transformer: T, L_p, L_{sp}, C_{ip}, R_{ip}, R_{is}. With this set of parameters the complete transferfunction can be calculated when the transformer is used with certain power tubes (R_g) and loads (Z_L). Only the lowest -3dB power frequency and the nominal power are needed extra, to produce a complete picture of the power capabilities of an output transformer.

5) We can only hope that every transformer company will supply these parameters for comparison between different brands and for optimization of the tunings and implementations.

6) The well known transformer **Q**uality **F**actor gives good information about the ratio of the primary inductance and the primary leakage inductance. This information is independent of how the transformer is used.

7) The new **Q**uality **D**ecade **F**actor translates the **QF**-value to the number of frequency decades which can at least be spanned by the transformer. For reasons of comparision between brands, the **QDF** gives more "realistic" information then the large **QF** values.

8) The newly introduced **T**uning **F**actor supplies information on how to implement the transformer optimally in the amplifier. Together with the **Q**uality **F**actor the -3dB bandwidth can be calculated easily.

9) The newly introduced **T**uning **D**ecade **F**actor, derived from the **T**uning **F**actor, results in the number of frequency decades that can be spanned on top of the **QDF**.

10) The complete -3dB bandwidth is expressed by the **F**requency **D**ecade **F**actor, which is the sum of **QDF** and **TDF**. The discussed new toroidal output transformer is able to span almost 6 frequency decades while being tuned without any ringing (which starts to occur at Q>.7).

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GLOSSARY LIST

a_2 : inverse of **Q** []
α : ratio of Z_{ip} and R_{aa} []
B : magnetic fluxdensity in the core [T]
ß : load ratio; ratio of R_g and R_{aa} []
C_{ip} : effective capacitance of the output transformer on the primary side loading the output tubes [F]
FDF : Frequency Decade Factor = ${}^{10}\log(f_{-3H}/f_{-3L})$ []
f_s : frequency at which the core saturates when v_p is applied at the terminals of the primary winding [Hz]
f_{-3H} : highest -3dB frequency of the transferfunction [Hz]
f_{-3L} : lowest -3dB frequency of the transferfunction [Hz]
$f(a_2)$: -3dB vector length function of a second order low pass filter []
$ff(a_2)$: first order straight line approximation of $f(a_2)$ valid betweem $1<=a_2<=2$; deviation from $f(a_2)$ smaller then 5 %. []
$H(\omega)$: transfer function of tubes plus output transformer []
i : square root of minus 1
I_a : Anode current through a tube [A]
L_p : inductance of the primary winding of the output transformer [H]
L_{sp} : leakage inductance of the primary winding of the output transformer [H]
N_p : primary turns of the output transformer []
N_s : secondary turns of the output transformer []
Q : Q-Factor of second order low pass filter ($=1/a_2$)
QDF : Quality Decade Factor = ${}^{10}\log(QF)$ []
QF : transformer Quality Factor ($=L_p/L_{sp}$) []
R_{aa} : Primary impedance of the output transformer [Ohm]
R_g : total effective internal resistance of the power tubes driving the output transformer [Ohm]
r_i : plate resistance of a tube in its working point [Ohm]
R_{ip} : resistance of the total primary winding of the output transformer [Ohm]
R_{is} : resistance of the total secondary winding of the output transformer [Ohm]
s : mutual conductance of a tube [A/V]
T : turnsratio of the output transformer []
TDF : Tuning Decade Factor = ${}^{10}\log(TF)$ []
TF : tuning factor of the transformer when loaded []
V_{ak} : Voltage between anode and cathode of a tube [V]
V_{gk} : voltage between grid and cathode of a tube [V]
V_p : total alternating voltage of the tube(s) driving the output transformer [V]
ω : circular frequency [Hz]
ω_o : specific circular frequency of second order low pass filter [Hz]
Z_{ip} : characteristic impedance of the primary side of the transformer due to L_{sp} and C_{ip} [Ohm]
Z_L : impedance loading the output transformer on the secondary side [Ohm]
$Z_{L,n}$: normalized secondary load []

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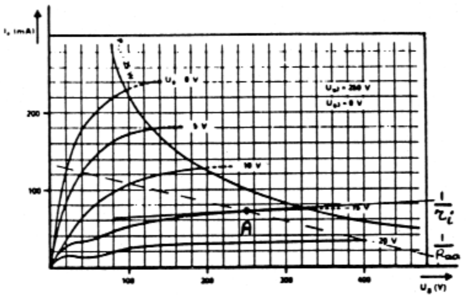

FIGURE 1-1: EL34 Characteristics
(Courtesy Elektor lit.13)

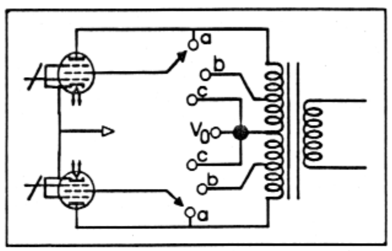

Figure 1-2: different balanced output modes: (a)=Triode, (b)= Ultra Linear, (c)= Penthode

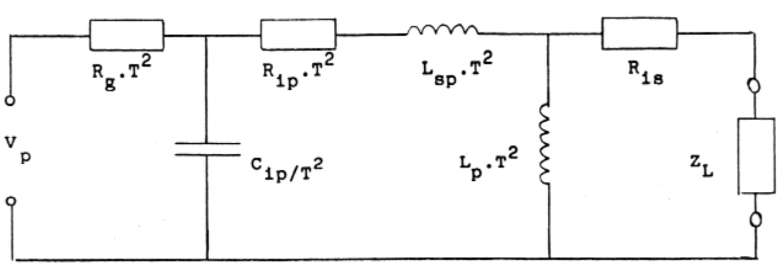

Figure 1-3: Equivalent Circuit Step-Down Output Transformer

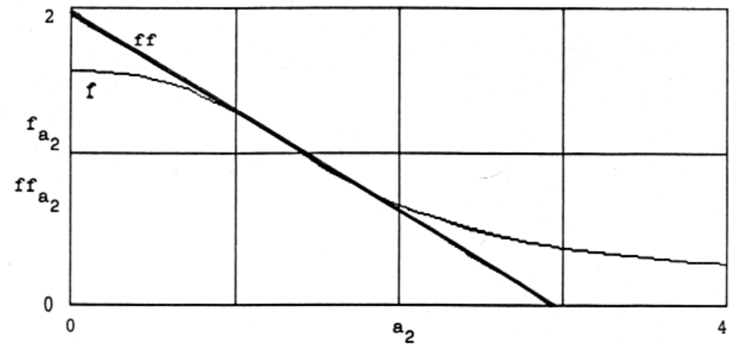

FIGURE 3-1: f(a2) and its straight line approximation ff(a2) for 1 <= a2 <= 2. Deviation from f(a2) < 5 %.

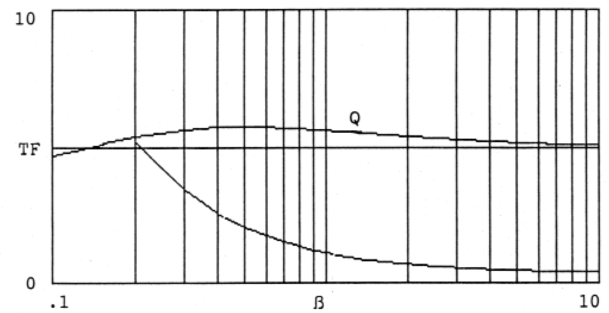

FIGURE 4-1: Tuning Factor (left hand scale) and Q-factor (right hand scale) for α = .5

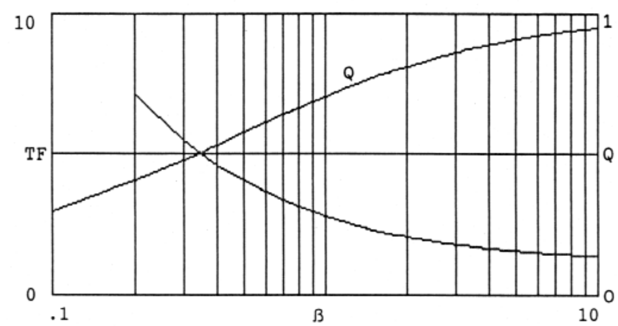

FIGURE 4-2: Tuning Factor (left hand scale) and Q-factor (right hand scale) for α = 1

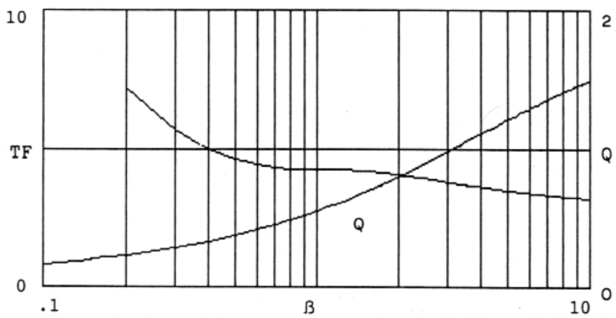

FIGURE 4-3: Tuning Factor (left hand scale) and Q-factor (right hand scale) for α = 2

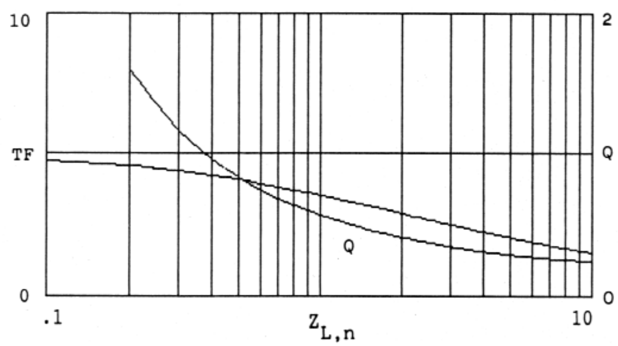

FIGURE 4-4: Tuning Factor as function of normalized load (α = 1 , ß = 1 when ZL = 1 Ω) (balanced Triode mode)

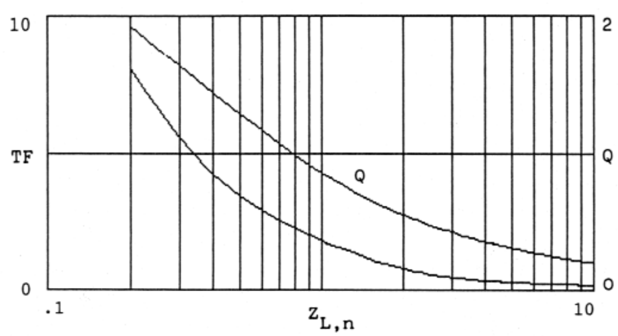

FIGURE 4-5: Tuning Factor as function of normalized load (α = 1 , ß = 3 when ZL = 1 Ω) (balanced mode)

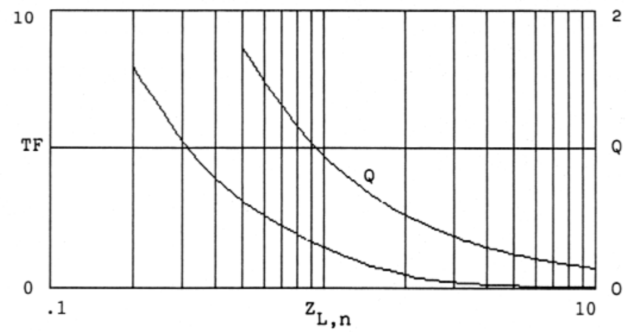

FIGURE 4-6: Tuning Factor as function of normalized load (α = 1 , ß = 10 when ZL = 1 Ω) (balanced Penthode mode)

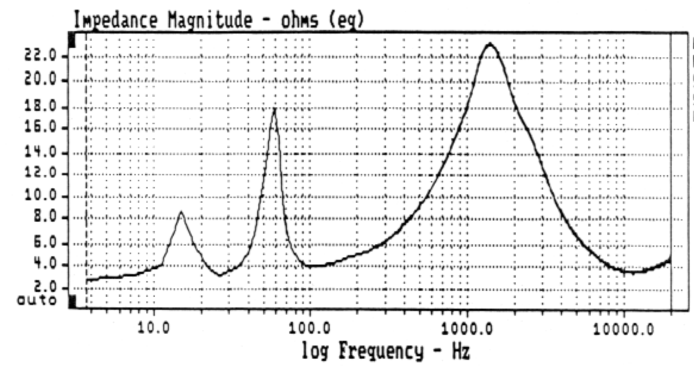

FIGURE 5-2: example of measured impedance of a loudspeaker

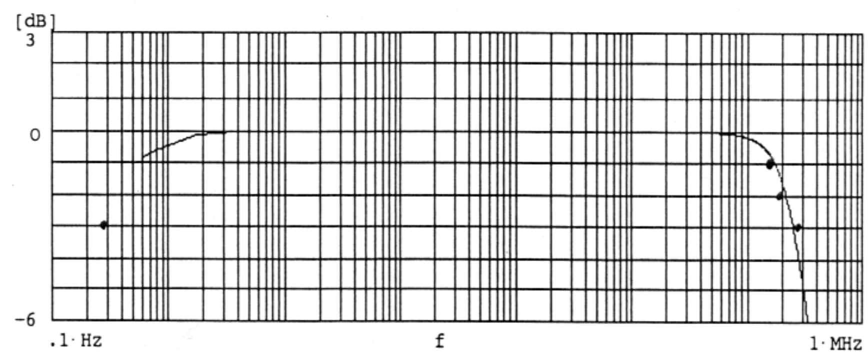

FIGURE 5-3 : frequency response VDV1080; line = calculation
dots = measurement

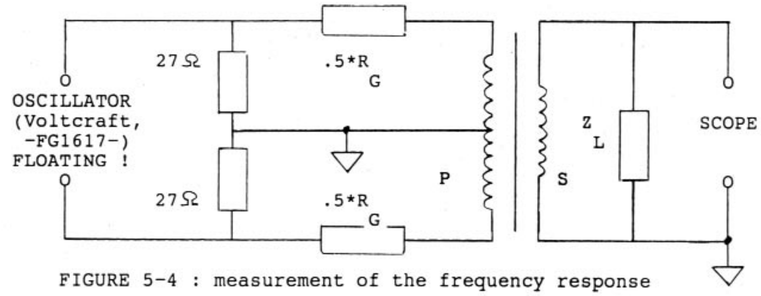

FIGURE 5-4 : measurement of the frequency response

mo-del	N_p/N_s	power	f_{-3}, power	L_p	L_{sp}	C_{ip}	R_{ip}	R_{is}
1080	15.74	80	20.5	360	1.312	593	37.8	.16
2100	19.42	100	20.7	530	1.8	585	104	.18
3070	23.48	70	22.7	490	2.6	558	173.7	.168
6040	34.29	40	25	535	3.7	613	68.1	.158
8020	40	20	28.5	485	8.0	250	155.4	.161
	[]	Watt	Hz	H	mH	pF	Ohm	Ohm

mo-del	R_{aa}	R_g	Q	f_{-3L}	f_{-3H}	**QDF**	**TDF**	**FDF**
1080	1.239	1.2	.682	.278	251	5.44	.52	5.96
2100	1.885	2.0	.695	.304	217	5.47	.38	5.85
3070	2.756	2.0	.639	.400	187	5.28	.39	5.67
6040	5.878	5.3	.496	.847	99	5.16	-.09	5.07
8020	8.000	16.0	.671	1.793	132	4.78	.09	4.87
	kOhm	kOhm	[]	Hz	kHz	[]	[]	[]

FIGURE 5-1: Transformer Parameters
and Calculations without any approximations.
($\mathbf{Z}_L$ is 5 Ohm in all calculations)