The Calculation Of Audio Transformers

… a simple to use cooking recipe

By Barbara E. Gerhold, "TUBECLINIC"; Linz/AUSTRIA

Introduction

There are two different kinds of Audio transformers –

- the output power transformer or OPT, which matches the output power of a tube to its load (e.g. the speaker). This topic is covered in PART 1.
- the voltage transformer or VTX, which serves only the task to present a big as possible voltage to the following amplification stage. This topic is covered in PART 2.

1 The Audio Output Power Transformer or OPT

Like already mentioned its task is to give the optimum power transformation, but as well it must do that with the widest frequency band and the flattest respond curve possible.

1.1 Determining the turns ratio [r_t]

$$r_t = \frac{w_2}{w_1} = \sqrt{\frac{R_l}{R_w}} \qquad (1)$$

r_t = turns ratio

w_2 = secondary turns count

w_1 = primary turns count

R_l = load resistance [Ω]

R_w = optimum load resistance of the tube [Ω]

R_l must be specified (e.g. speaker) while R_w can be found in the datasheet of the specific tube. It can be determined too by selecting the optimum slope of the resistance line in the U_a/I_a diagram. Please note, that deviations in the range of ±20% will do no greater harm to the tube as well as the performance of the amp.

For triodes and class-A operation, R_w can be calculated as

$$R_w \cong 0{,}6\frac{U_a}{I_a} \qquad (2)$$

U_a = plate (anode) voltage [V]

I_a = plate current [A]

$$R_w \geq 2R_p \qquad (2a)$$

Condition: R_p = plate resistance [Ω] -> datasheet

For pentodes and class-A operation, R_w can be calculated as

$$R_w \cong \frac{U_a}{I_a} \qquad (3)$$

U_a = plate (anode) voltage [V]

I_a = plate current [A]

$$P_l \geq U_a I_a \qquad (3a)$$

Condition: P_l = rated plate power dissipation of the tube [W]

According to 3a, the rated plate power dissipation must never be exceeded.

In ***"Push-Pull Class-A"*** - with the whole operational range inside the steep and linear part of the chart – each tube is loaded by the same resistance R_w. Total primary resistance – called R_{aa} or resistance from anode to anode (or – plate to plate) – is therefore $2xR_w$.

$$R_{aa} = 2R_w$$ R_{aa} = total resistance [Ω] of the primary winding -> datasheet 4

In ***"Push-Pull Class-B"*** only one tube works at each half-wave. Total primary resistance from anode to anode is therefore $4xR_w$.

$$R_{aa} = 4R_w$$ R_{aa} = total resistance [Ω] of the primary winding -> datasheet 5

In "Push-Pull Class-AB" the factors gather somewhat in between the above shown for R_{aa}. That depends on the value, at which the amp transits from class-A to class-B operation.

1.2 Calculation of the primary and secondary inductance

$$L_1 = \frac{R_p R_{aa}}{2\pi f_u \left(R_p + R_{aa}\right)}$$ L_1 = primary inductance [H]
f_u = lowest freq. limit -3dB [Hz] 7

The secondary inductance is determined by the turn's ratio

$$L_2 = L_1 (r_t)^2$$ L_2 = secondary inductance [H] 8

1.3 Calculation of the possible output power of amp stages

The maximum output power is determined by the maximum distortion limit admissible. In Audio and HiFi amps, possible output power will be significantly less than in a guitar amp, though the same tubes are used. There is another reason to reduce the output, because distortion is not distortion -> while triodes will produce mostly even order harmonics, pentodes will produce more of the odd order ones. Most people will anticipate the even order harmonics as a pleasant adding of highs (e.g. Audio Enhancer or Exciter), while odd order will not be accepted with HiFi – even at really low percentage.

Single Ended Class-A ->

$$P_{out} = 0{,}25 P_{DC} \leq 0{,}25 P_l$$ P_{DC} = DC-power loss triode D < 5% 10

$$P_{out} = 0{,}4 P_{DC} \leq 0{,}4 P_l$$ pentode D < 2% 11

Push-Pull Class-B ->

$$P_{out} = 0{,}6 P_{DC} \leq 1{,}5 P_l$$ P_{DC} = DC-power loss triode D < 5% 12

$$P_{out} = 0{,}7 P_{DC} \leq 2{,}3 P_l$$ pentode D < 2% 13

Again "Push-Pull Class-AB" will give output power in between the values shown above.

1.4 Physical dimensions of the OPT; core selection and turns count

The size of the OPT and esp. its core depends on the needed AC power and the lowest freq. limit. The following calculation is quite conservative. Most products from the market use somewhat smaller cores. Therefore, if you do not drive a subwoofer (!), factor *k* might be inserted at 20 – 30% less value.

$$A_{Fe} = k\sqrt{\frac{P_{out}}{f_u}}$$

A_{Fe} = cross section of the OPT's core (eff. core-section) [cm^2]

k = saturation coefficient; insert 15 … 25

HiFi and SE-A -> 25, PP-A -> 20 (14)

Guitar and SE-A -> 20, PP-AB -> 15

OPT for class-B -> 17

$$airgap = 0{,}4\sqrt{A_{Fe}}$$

The width of the air-gap for SE operation in [mm] (15)

OPTs for SE-A use need an air-gap, in order to withstand the DC-bias. Because half of the air-gap appears at both outer sections of the core, the actual gap to build is 0,5 times the calculated value. It must be filled with appropriate non-magnetic material like acryl, paper, cardboard, etc. Standard copy paper of 80g/m^2 shows a thickness of app. 0,1mm per sheet.

Before selecting a specific core-size you should have a look about what is available from the market in datasheets of a manufacturer, table books on electro-mechanics or at the web.

$$w_1 = 2000\sqrt{\frac{L_1}{A_{Fe}}}$$

w_1 = turns count of the primary winding (16)

$$w_2 = w_1 r_t = w_1\sqrt{\frac{R_l}{R_{aa}}}$$

w_2 = turns count of the secondary winding, due to turns ratio (17)

The primary winding as well as the secondary winding should be divided into several winding blocks.

A rule of thumb says - the better the quality, the more winding blocks needed. A good standard for a power triode in SE-A is to wind the primary in 5 to 7 winding blocks – always in a way, that the secondary winding blocks are enclosed by the primary.

For example: 7 winding blocks of primary (all connected in series) with 6 winding blocks of the secondary (all connected in parallel).

1.5 Defining the correct wire diameters

When you have chosen a sudden core type, you need to look-up for the correct coil former for this type. At the datasheet you will find the depth (d) and the width (w) of the section [mm^2] for windings. The primary and the secondary each will need half of the section.

Under normal winding conditions the filling factor for copper will be app. 0,5. This understands that in the section of windings, the portion of Cu will be 50%. You can calculate the diameter of the wires ->

$$d_1 = \sqrt{\frac{dw}{\pi w_1}}$$

d_1 = diameter of the wire for the primary winding [mm] (18)

$$d_1 = \sqrt{\frac{dw}{\pi p w_2}}$$

p = number of parallel secondary winding blocks

d_2 = diameter of each wire of the several winding blocks of the secondary winding [mm] (19)

1.6 Checking the construction

Normally a manufacturer lists the maximum possible power of a core together with the type in his datasheet. Have a look there. The listed power is the maximum possible at 50Hz (or 60Hz in the US). If you inserted a lower frequency in your calculations, the possible power listed needs to be corrected by the value -> **f_u/50Hz** resp. **f_u/60Hz**.

<u>Example</u>: If the listed power was 100VA @ 50Hz and you wanted an OPT for fu = 20Hz, the correction factor is 20/50 or 0,4. Therefore it will be possible to transform 40VA @ 20Hz.

The listed power is furthermore assigned to the max. flux density possible. But it is only possible to calculate the OPT by using this value, if the primary voltage is rather constant – e.g. like if it was standard mains voltage. In our case, the primary voltage will vary widely. So it was better to reduce the max. flux density -> $\mathbf{B_{red}}$ (app. by 10% to 20%). Like before, HiFi will settle near -20% and an instrumental amp will be good at -10%. This will decrease max power again by the same value.

<u>Example</u>: Like before our OPT was able to transform 40VA @ 20Hz from its 100VA core. Decreasing it by 20% for less flux density will achieve 32VA.

$$P_{out} = \frac{B_{red} P_{core} f_u}{50}$$ B_{red} = reduction factor of max. flux density (80 to 90%) = 0,8 – 0,9 21

The former calculations derive from the “main transformer equation” ->

$$w_1 = \frac{2252.U_1}{f_u.A_{Fe}.B}$$ U_1 = prim. voltage [V] 22

B = flux density [T]

$$U_1 = \sqrt{P_{out}.R_{aa}}$$ 23

$$I_1 = \sqrt{\left(\frac{P_{out}}{U_1}\right)^2 + \left(I_{bias}\right)^2}$$ The rms-current across each primary half is a combination of AC and DC. 24

<u>Checking the wire diameter:</u>

In the range of 10cm² to 40cm², laminated iron-cores show a current density of app. 3A/mm². C-cores and ring-cores are somewhat better, while ring-cores are only usable with tube-stages that are free of DC-bias (e.g. PP-amps). Now check if the calculated diameter from [18] is thick enough ->

$$d_1 \geq \sqrt{\frac{4I_1}{1000\pi S}}$$ I_1 results from [24]; in [mA] 25

S = current density (app. 3A/mm²)

If this is true for w_1, it will be true too for w_2, because you used the same space for both windings.

2 The Audio Voltage Transformer or VTX

These TX are necessary to match the impedance, output voltage of a mike or a phono-cartridge to an input. Somewhat rare but possible -> they can be used too to match two amplifier stages instead of usual capacitive coupling (Interstage-TX). In all cases the VTX is loaded by the impedance of the following stage only.

2.1 Definition of the inductances

The primary inductance L_1 is determined by the internal impedance of the source. If R_i is unknown, it can be measured by a “V and I”- test.

$$L_1 = \frac{R_i}{2\pi f_u}$$ R_i = internal impedance of the signal source 26

The maximum secondary inductance is limited by the upper frequency limit (f_o), stray-effects and capacitive loading. For instrumental purposes (f_o = 7kHz), a stray-factor of 0,05 and a total capacitive load of C_2 = 100pF we app. get L_2 = 200 to 300 [H].

Doing the same calculation for HiFi (f_o = 20kHz) will give a max. value for L2 of app. 75 [H].

2.2 Core dimensions and turns counts

The size of such a VTX, esp. the core-size, results from the primary power applied. Nonetheless the smallest items should be considered M42. This comes due to possible DC-bias by the source or by plate-DC. OTOH an M-type core shows a really small air-gap of app. 0,15mm - if it was laminated with all sheets from the same direction. After you determined the primary and secondary inductance, you can calculate the primary turns count via (16) and the secondary via (17).

If there is real DC-bias, the small air-gap of the M-type core will not be sufficient and an EI-type core must be chosen.

If you have any further question, you can contact me via support@tubeclinic.com .