RIAA LCR Filter Mythos Or How To Design

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1 Introduction

1.1 The Author

My name is Claus Weber. My occupation is Electronic Engineer and I'm working for an international company with their sources in Germany. My hobby is designing and building my own tube amplifier in my workshop in Germany.

Since mid of 2011, I was delegated by my company to New York City, I've been living in the US for a couple of years. Here, I don't have the possibility and time to enjoy my hobby to a satisfying extend because of missing my own workshop.

Therefore I'm only able to make some theoretical design work for future realization, until I return to my home town in Germany.

During my design work for a symmetrical pre-amplifier, especially the RIAA filter, I searched the internet intensively and I found hundreds of discussions, publications, and schematics of passive LCR RIAA filter designs.

From my point of view, a lot of publications and discussions regarding the LCR RIAA filter seem to be a mythos. I already got some response via the internet, that there is no mythos, everything is clear for the design, everything is covered, other time constants and impedances are no problem. On the other hand I didn't find any theoretical background for clear determination of all necessary filter components. Please let me know if there is any!

Additionally, I extended the analysis under consideration of the 4^{th} time constant t_6 (refer to /1/ and /2/).

Also, I would not use a LCR filter for my symmetrical DC coupled preamplifier, but I decided to understand and analyze the theoretical background and all necessities for designing and implement such kind of filter.

That was the final reason for writing this document and to share my analysis and results with the DIY community.

1.2 Structure of the Document

This document has a clear structure and you should be able to use it in a convenient way. If you are interested in the whole theoretical background and you want to design your own filters, please read the whole document.

If you only need the equations for calculation of the filter component values, you can move directly to chapter 6 where all equations are summarized. Chapter 7 elaborates equations for error calculation.

If you are not interest in any of the equations but you still want to make your own filter design, you could go to chapter 8 where an attached design tool is described.

This document is structured as follows:

- 2 Preface
  This chapter defines the basic equations and time constants which are used for the filter analysis.
- 3 General Approach
  This chapter references to the public known RIAA LCR filter "Tango EQ-600P" and elaborates a generic LCR filter reference.
- 4 Generic Solution
  This chapter analyzes the generic approach of chapter 3 and transforms the filter into a Thevenin schematic (refer to /2/)

- 5 Specific Solution
  This chapter elaborates all necessary equations in detail which are necessary to determine all filter component values.
- 6 Summary of equation results
  This chapter shows the final schematics and summarizes all equations of chapter 5.
- 7 Filter Precision Calculation
  This chapter evaluates all necessary equations for calculation of the filter accuracy under consideration of the filter component tolerances.
- 8 Filter Design Tool
  In this chapter an attached design tool is described, which uses all the equations elaborated in the chapters before. With the help of the tool, you are able to determine the values of all filter components.
- 9 Simulation of Design Examples
  This chapter gives some examples in which the results of the design tool are transferred to a simulation tool.
- 10 Final Remarks
  This chapter summarizes the results.

1.3 References

Table 1-1 shows the references, which are used for evaluation of the component values.

Ref #	Title, Author
/1/	On RIAA Equalization Networks, Stanley P. Lipshitz, June 1997
/2/	Valve Amplifiers, Morgan Jones, 3rd Edition, ISBN: 978-0-7506-5694-8
/3/	http://www.linear.com/ : Home page of Linear Technology as reference for the free of charge simulation tool “LTSpice IV”

Table 1-1: References

1.4 Terms & Abbreviations

Table 1-2 defines the terms and abbreviations which are used in this document.

Abbreviation	Meaning	Explanation
f	Frequency	Measured in $Hz = \frac{1}{s}$
ω	Angular frequency	Measured in $\frac{1}{s}$
R	Resistor	Measured in Ω
L	Inductor	Measured in Henry: $H = \Omega s$
C	Capacitor	Measured in Farad: F = $\frac{s}{\Omega}$
X	Reactance	Imaginary part of complex impedance, see Z
Z	Complex Impedance	$Z = R + jX = \|Z\|e^{jarg(Z)}$, measured in Ω
G	Gain	Amplification factor (Loss when smaller than 1)
db	Decibel	
t	Time Constant	
φ	Phase	

Table 1-2: Terms and Abbreviations

2 Preface

Following Equations are used as basis for the evaluation:

$$s = j\omega \quad (1)$$

$$\omega = 2\pi f \quad (2)$$

$$t_x = \frac{1}{\omega_x} = C_a R_b = \frac{L_y}{R_z} \quad (3)$$

According to /1/ and /2/, following time constants are relevant for the RIAA de-emphasis including the high frequency roll-off (t_6) and the IEC standard for low frequency roll-off (t_2).

t_2 will not be considered in this white paper but t_6 is often used by the community and therefore part of the evaluation in this document.

$t_3 = 3180\mu s$ $f_3 = 50.05Hz$

$t_4 = 318\mu s$ $f_4 = 500.5Hz$

$t_5 = 75\mu s$ $f_5 = 2122Hz$

$t_6 = 3.18\mu s$ $f_3 = 50.05kHz$ (optional, high frequency roll-off)

$t_2 = 7950\mu s$ $f_2 = 20.02Hz$ (not considered, IEC low frequency roll-off)

Equation (4) is the standard equation for the RIAA de-emphasis according to /1/ and /2/. The second part of the equation separates the transfer function into two filter parts. k, k_1 and k_2 are constant frequency independent factors.

$$G_{RIAA} = k\frac{(1 + j\omega t_4)}{(1 + j\omega t_3)(1 + j\omega t_5)} = k_1\frac{(1 + j\omega t_4)}{(1 + j\omega t_3)}k_2\frac{1}{(1 + j\omega t_5)} \quad (4)$$

Equation *(5)* is the standard equation for the RIAA de-emphasis including t6 high frequency roll-off according to /1/ and /2/. The second part of the equation separates the transfer function into two filter parts.

$$G_{RIAA+t6} = k\frac{(1 + j\omega t_4)(1 + j\omega t_6)}{(1 + j\omega t_3)(1 + j\omega t_5)} = k_1\frac{(1 + j\omega t_4)}{(1 + j\omega t_3)}k_2\frac{(1 + j\omega t_6)}{(1 + j\omega t_5)} \quad (5)$$

3 General Approach

3.1 Filter Type Reference: Tango EQ-600P

Figure 3-1 shows the Tango EQ-600P which is often used in the internet as reference for a RIAA filter with an accuracy of ±0.3db. Beside the given values from the internet, I added unique identifier, which I will use in this document.

Please note that the component values of the published Tango filter sometimes deviate from the figure below. During the evaluation we will even learn that the values are not precise and the accuracy of ±0.3db is part of the Tango specification but has nothing to do with chosen LCR type.

The ±0.3db accuracy for this RIAA LCR filter type often is referenced in many internet pages and forums but it seems that everything is copied from each other without any proof of correctness.

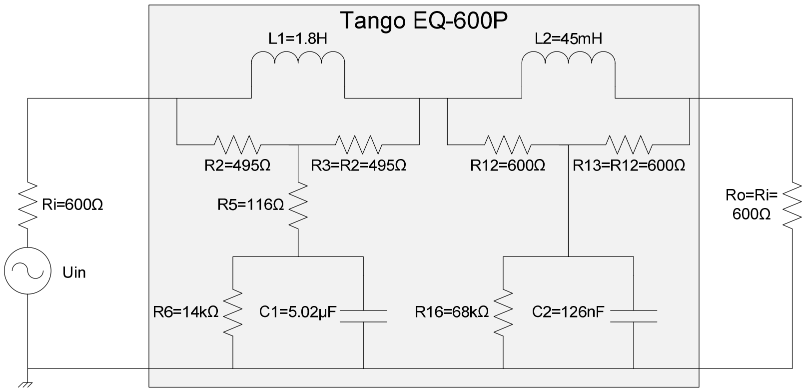

Figure 3-1: RIAA LCR filter example: Tango EQ-600P

3.2 Generic LCR Reference

Figure 3-2 shows the generic view of the Tango filter principle above as basis for the evaluation of the necessary equations and as precondition for calculating all component values precisely.

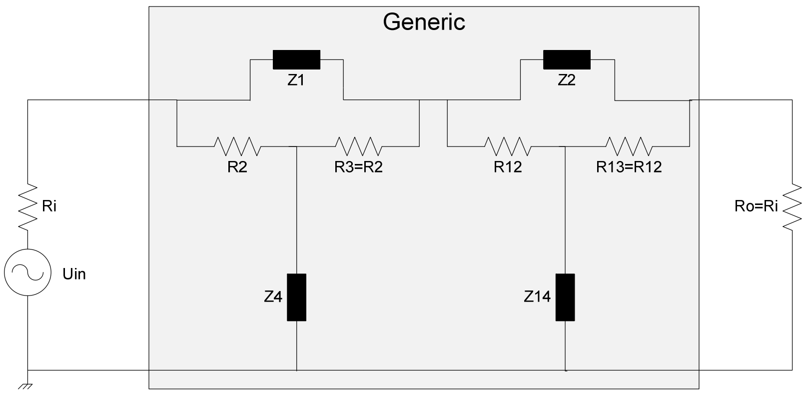

Figure 3-2: RIAA LCR filter: Generic schematic

R_2 , R_{12} , R_3 and R_{13} are simple resistors, whereas Z_1 , Z_2 , Z_4 and Z_{14} are complex impedances including an imaginary part.

Because of the filter symmetry R_3 *is equal* R_2 and R_{13} *is equal* R_{12} . The further documentation only uses R_2 and R_{12} .

4 Generic Solution

The intention of this chapter is to find unambiguous mathematical equations for the behavior of the Filter. For that reason the LCR filter circuit shall be transformed in a Thevenin equivalent circuit (see /2/ for reference), see chapter 4.3.

For the transformation the open circuit gains, as well as the source resistance of the filter, have to be determined (see chapters 4.1 and 4.2 below).

4.1 Open Circuit Filter Gain

Figure 4-1 breaks the filter down into two parts with the gain factors G_1 and G_2 .

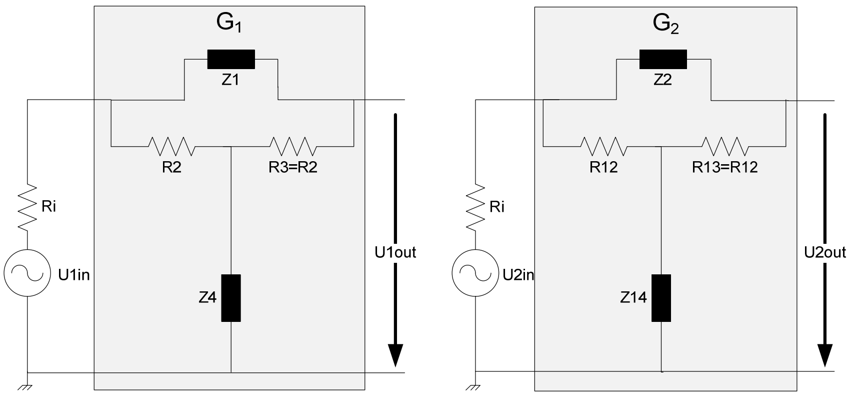

Figure 4-1: G_1/G_2 LCR filter gain

With the help of Kirchhoff's laws (refer to /2/) the circuits of Figure 4-1 were analyzed. The open loop gains G_1 and G_2 are described in the equations (6) and (7).

$$G_1 = \frac{Z_4(Z_1 + 2R_2) + R_2^2}{(Z_4 + R_i)(Z_1 + 2R_2) + R_2(Z_1 + R_2)} \tag{6}$$

$$G_2 = \frac{Z_{14}(Z_2 + 2R_{12}) + R_{12}^2}{(Z_{14} + R_i)(Z_2 + 2R_{12}) + R_{12}(Z_2 + R_{12})} \tag{7}$$

The detailed evaluation of the equations is not described in this documentation.

4.2 Source Resistance

Figure 4-2 breaks the filter down two times into two filter parts with the source resistances. One time seen from the left side (→ from the input) and one time from the right side (→ from the output).

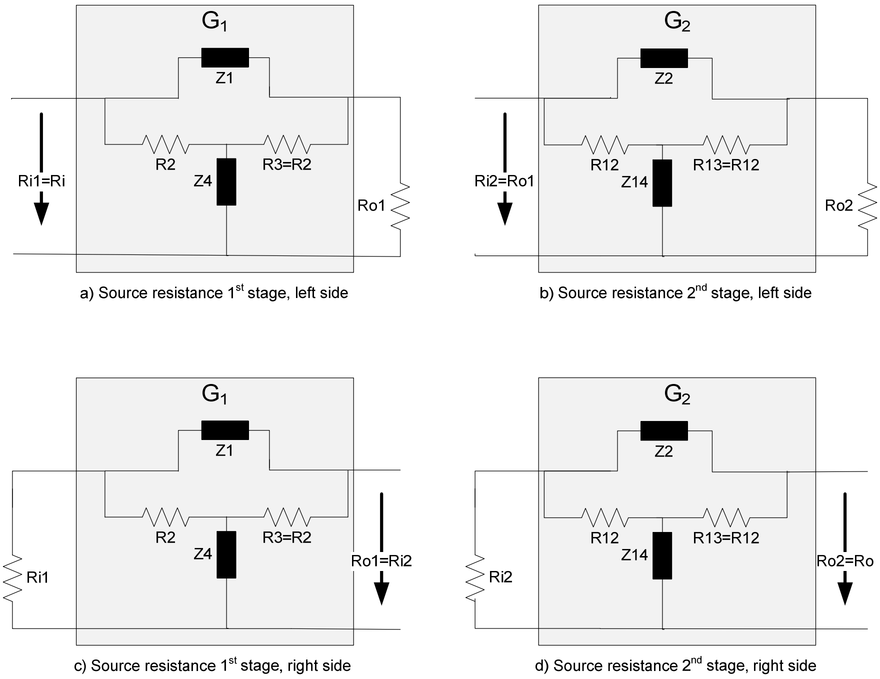

Figure 4-2: LCR Filter Source Resistance

The advantage of this filter type is the constant impedance over frequency, which shall be considered for the design and, of course, for determination of the correct equations for R_i.

For the evaluation of all equations, following is defined as requirement (refer to Figure 4-2):

$$R_i = R_{i1} = R_{i2} \tag{8}$$

$$R_o = R_{o1} = R_{o2} \tag{9}$$

Again, Kirchhoff's laws help to analyze the circuits of Figure 4-2 and to find the source resistances R_i, see equations (10) and (11) below.

$$R_i = \frac{R_o[Z_4(Z_1 + 2R_2) + R_2(Z_1 + R_2)] + Z_1R_2(R_2 + 2Z_4)}{(Z_4 + R_o)(Z_1 + 2R_2) + R_2(Z_1 + R_2)} \tag{10}$$

$$R_i = \frac{R_o[Z_{14}(Z_2 + 2R_{12}) + R_{12}(Z_2 + R_{12})] + Z_2R_{12}(R_{12} + 2Z_{14})}{(Z_{14} + R_o)(Z_2 + 2R_{12}) + R_{12}(Z_2 + R_{12})} \tag{11}$$

The detailed evaluation of the equations is not described in this documentation.

If we define following:

$$R_i = R_o \tag{12}$$

we can simplify the equations (10) and (11) above:

$$R_i = \sqrt{\frac{Z_1R_2(R_2 + 2Z_4)}{Z_1 + 2R_2}} \tag{13}$$

$$R_i = \sqrt{\frac{Z_2R_{12}(R_{12} + 2Z_{14})}{Z_2 + 2R_{12}}} \tag{14}$$

4.3 Thevenin LCR Filter Transformation

The following Figure 4-3 shows the result of the Thevenin filter transformation.

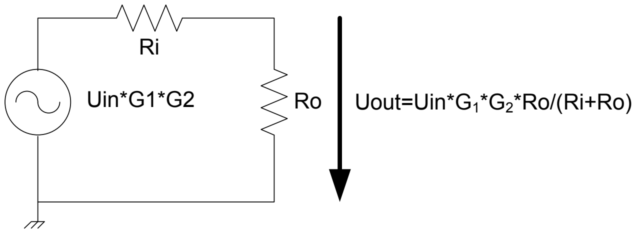

Figure 4-3: Thevenin LCR Filter Transformation

The total open loop gain is drawn in equation (15). The gain under consideration of output resistance R_o and input resistance R_i is shown in equation (16).

$$G_{tot} = G_1 G_2 \tag{15}$$

$$U_{out} = U_{in} G_{tot} \frac{R_o}{R_o + R_i} \tag{16}$$

5 Specific Solution

In this chapter the equations with specific components of the LCR filter are being elaborated. This is possible now because chapter 4ff delivers all the generic formulas.

Finally, in this chapter, all LCR filter components can be calculated precisely.

5.1 Determination of RIAA components

Figure 5-1 shows LCR RIAA filter with all necessary components. RL_1 and RL_2 represent the copper (or silver) resistances of the related inductances which are necessary to consider a precise evaluation of the equations. Also, R_6 and R_{16} are required for compensation of the copper, respectively the silver resistances, of the inductors.

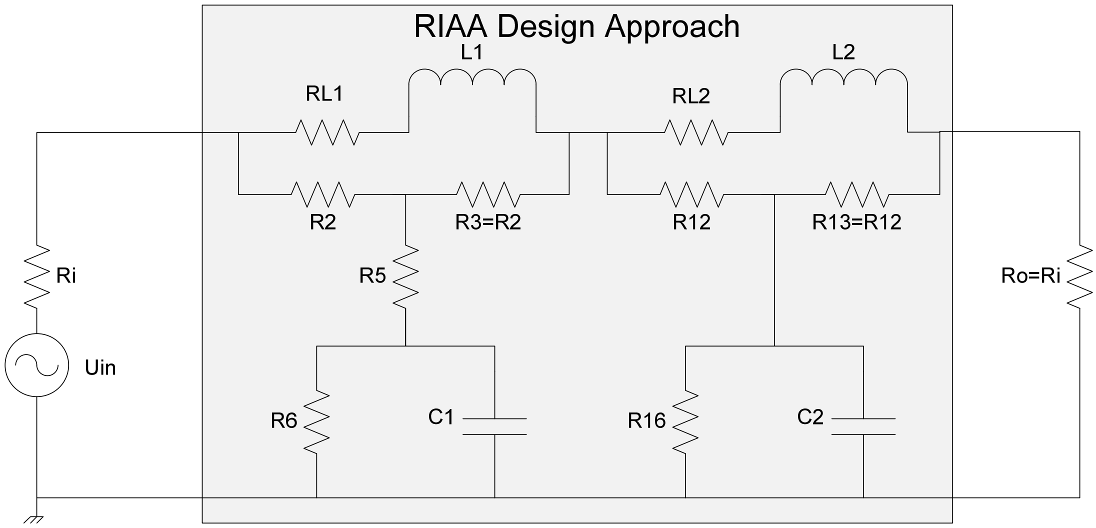

Figure 5-1: RIAA design approach

However, stray inductivities of the capacitors and the resistors, as well as stray capacities of the inductors, are not considered because of their small influence on the filter characteristic for frequencies $\leq 100\ kHz$.

5.1.1 Determination of R_i

If we compare the Figure 4-2 and Figure 5-1 we can substitute with the help of Kirchhoff's laws and complex mathematics:

$$Z_1 = R_{L1} + j\omega L_1 \tag{17}$$

$$Z_4 = R_5 + \frac{1}{\frac{1}{R_6} + j\omega C_1} = \frac{R_5 + R_6 + j\omega C_1 R_5 R_6}{1 + j\omega C_1 R_6} \tag{18}$$

With equations (13), (17) and (18) we can substitute:

$$R_i = \sqrt{\frac{(R_{L1}+j\omega L_1)R_2\left(R_2 + 2\frac{R_5 + R_6 + j\omega C_1 R_5 R_6}{1 + j\omega C_1 R_6}\right)}{R_{L1} + j\omega L_1 + 2R_2}} \tag{19}$$

The same is possible for the second part of the filter, refer to Figure 4-2 and Figure 5-1:

$$Z_2 = R_{L2} + j\omega L_2 \tag{20}$$

$$Z_{14} = \frac{1}{\frac{1}{R_{16}} + j\omega C_2} = \frac{R_{16}}{1 + j\omega C_2 R_{16}} \tag{21}$$

as well as equations (14), (20) and (21):

$$R_i = \sqrt{\frac{(R_{L2}+j\omega L_2)R_{12}\left(R_{12} + 2\frac{R_{16}}{1 + j\omega C_2 R_{16}}\right)}{R_{L2} + j\omega L_2 + 2R_{12}}} \tag{22}$$

For getting a constant R_i over frequency the following equations must be true:

$$R_i = \sqrt{\frac{L_1}{C_1}} \tag{23}$$

$$R_i = \sqrt{\frac{L_2}{C_2}} \tag{24}$$

5.1.2 Determination of G_1

If we compare the Figure 4-2 and Figure 5-1 and we consider equations (6), (17) and (18), we can substitute:

$$G_1 = \frac{\left[\frac{R_5 + R_6 + j\omega C_1 R_5 R_6}{1 + j\omega C_1 R_6}\right](R_{L1} + j\omega L_1 + 2R_2) + R_2^2}{\left\{\left[\frac{R_5 + R_6 + j\omega C_1 R_5 R_6}{1 + j\omega C_1 R_6}\right] + R_i\right\}(R_{L1} + j\omega L_1 + 2R_2) + R_2(R_{L1} + j\omega L_1 + R_2)} \tag{25}$$

In the next step, equation (25) is now modified in a more suitable form below, see (26). The detailed and complex evaluation of the parameter from equation (27) to (34) is not shown in this documentation; only the results are presented.

$$G_1 = \frac{e_1 + j\omega(C_1 d_1 + L_1 b_1) + j^2\omega^2 C_1 L_1 a_1}{u_1 + j\omega(C_1 v_1 + L_1 x_1) + j^2\omega^2 C_1 L_1 z_1} \tag{26}$$

With the following detailed parameter:

$$e_1 = (R_{L1} + 2R_2)(R_5 + R_6) + R_2^2 \tag{27}$$

$$d_1 = R_6[R_5(R_{L1} + 2R_2) + R_2^2] \tag{28}$$

$$b_1 = (R_5 + R_6) \tag{29}$$

$$a_1 = R_6 R_5 \tag{30}$$

$$u_1 = (R_{L1} + 2R_2)(R_5 + R_6) + R_2^2 + R_{L1}(R_i + R_2) + 2R_2 R_i \tag{31}$$

$$v_1 = R_6[R_5(R_{L1} + 2R_2) + R_2^2 + R_{L1}(R_i + R_2) + 2R_2 R_i] \tag{32}$$

$$x_1 = R_5 + R_6 + R_i + R_2 \tag{33}$$

$$z_1 = R_6(R_5 + R_i + R_2) \tag{34}$$

Further on equation (26) shall be transformed in the form below, see equation (35). This is necessary for determination of the time constants.

$$G_1 = k_1 \frac{(1 + j\omega t_{a1})(1 + j\omega t_{b1})}{(1 + j\omega t_{d1})(1 + j\omega t_{e1})} \tag{35}$$

For that reason, the numerator quadratic equations (26) and (35) with its complex coefficients are solved with the general known “quadratic formula”, see (36) below.

$$t_{a1/b1} = \frac{C_1 d_1 + L_1 b_1}{2e_1} \pm \sqrt{-\frac{L_1 C_1 a_1}{e_1} + \frac{(C_1 d_1 + L_1 b_1)^2}{4e_1^2}} \tag{36}$$

With the help of equations from (27) to (30) we can modify (36) as follows:

$$t_{a1} = \frac{1}{2e_1}\left[C_1 d_1 + L_1 b_1 - \sqrt{4L_1 C_1 R_2^2 R_6^2 + (C_1 d_1 - L_1 b_1)^2}\right] \tag{37}$$

$$t_{b1} = \frac{1}{2e_1}\left[C_1 d_1 + L_1 b_1 + \sqrt{4L_1 C_1 R_2^2 R_6^2 + (C_1 d_1 - L_1 b_1)^2}\right] \tag{38}$$

If we define that

$$C_1 d_1 = L_1 b_1 \tag{39}$$

we are able to simplify equation (37) and (38) to:

$$t_{a1} = \frac{1}{e_1}\left[L_1 b_1 + R_2 R_6 \sqrt{L_1 C_1}\right] = t_3 \tag{40}$$

$$t_{b1} = \frac{1}{e_1}\left[L_1 b_1 - R_2 R_6 \sqrt{L_1 C_1}\right] = t_4 \tag{41}$$

The equation for t_{a1} delivers the time constant with the lower value and shall comply with t_4, refer to chapter 2 and equation (4).

The equation for t_{b1}delivers the time constant with the higher value and shall comply with t_3. In comparison to the definitions in chapter 2 and equation (4), the difference is that in chapter 2 the time constant is part of the denominator, whereas, here, it is part of the numerator. In the evaluation below we will see, how to get the correct solution.

Now, the denominator quadratic equations (26) and (35) with its complex coefficients are solved with the general known “quadratic formula”, see (42) below.

$$t_{d1/e1} = \frac{C_1 v_1 + L_1 x_1}{2u_1} \pm \sqrt{-\frac{L_1 C_1 z_1}{u_1} + \frac{(C_1 v_1 + L_1 x_1)^2}{4u_1^2}} \tag{42}$$

With the help of equations from (31)(27) to (34) we can modify (42) as follows:

$$t_{d1} = \frac{1}{2u_1}\left[C_1 v_1 + L_1 x_1 + \sqrt{4L_1 C_1 R_2^2 R_6^2 - (C_1 v_1 - L_1 x_1)^2}\right] \tag{43}$$

$$t_{e1} = \frac{1}{2u_1}\left[C_1 v_1 + L_1 x_1 - \sqrt{4L_1 C_1 R_2^2 R_6^2 - (C_1 v_1 - L_1 x_1)^2}\right] \tag{44}$$

If we define that

$$4L_1 C_1 R_2^2 R_6^2 = (C_1 v_1 - L_1 x_1)^2 \tag{45}$$

we are able to simplify equation (43) and (44) to (and set equal with (40)):

$$t_{d1} = t_{e1} = \frac{1}{2u_1}[C_1 v_1 + L_1 x_1] = t_{b1} = t_3 \tag{46}$$

If we now substitute the first part of the general RIAA transfer function defined in equation (4) with the results of equations (40), (41) and (46) we get following result:

$$G_1 = k_1 \frac{(1 + j\omega t_3)(1 + j\omega t_4)}{(1 + j\omega t_3)(1 + j\omega t_3)} = k_1 \frac{(1 + j\omega t_4)}{(1 + j\omega t_3)} \tag{47}$$

$$G_1 = \frac{e_1}{u_1} \frac{\left(1 + j\omega \frac{1}{e_1} \left[L_1 b_1 - R_2 R_6 \sqrt{L_1 C_1}\right]\right)}{\left(1 + j\omega \frac{1}{2u_1} \left[C_1 v_1 + L_1 x_1\right]\right)} \tag{48}$$

Finally, we have found the solution for the transfer function of the first RIAA filter part.

5.1.3 Determination of first filter part components

In chapters 5.1.1 and 5.1.2 we now have enough independent equations for calculating the components of the first part of the RIAA filter.

The detailed evaluation of equations below is not shown in this document; only the results are delivered below.

For the inductance of L_1 we have a little bit of freedom. Of course, L_1 shall be as small as possible because of the mechanical dimension as well as the copper resistance R_{L1}. On the other hand, the inductance of L_1 shall be high enough to fulfill following requirement:

$$L_1 > R_i(t_3 - t_4) \tag{49}$$

Otherwise, R_6 will become infinity or negative (see (53) below), and R_{L1} will become zero or negative (see (54) below), which would not be a real solution.

Note: R_{L1} is the copper resistance of L_1, or part of it combined with a serial resistor (see Figure 6-1).

The following equations show the result for calculation of the remaining components of the first RIAA filter part.

$$C_1 = \frac{L_1}{R_i^2} \tag{50}$$

$$R_2 = \sqrt{\frac{L_1 R_i (t_3 - t_4)}{C_1 R_i (t_3 - t_4) + 4 t_3 t_4}} \tag{51}$$

$$R_5 = \frac{R_i^2 - R_2^2}{2R_2} \tag{52}$$

$$R_6 = \frac{R_i^2}{\frac{L_1}{t_4} - \frac{R_i(R_i + R_2)}{R_5}} \tag{53}$$

$$R_{L1} = \frac{R_i^2}{R_6} \tag{54}$$

5.1.4 Determination of G_2

If we compare the Figure 4-2 and Figure 5-1 and we consider equations (6), (20) and (21) we can substitute:

$$G_2 = \frac{\left[\frac{\mathrm{R}_{16}}{1 + \mathrm{j}\omega \mathrm{C}_2 \mathrm{R}_{16}}\right] (R_{L2} + j\omega L_2 + 2R_{12}) + R_{12}^2}{\left\{\left[\frac{\mathrm{R}_{16}}{1 + \mathrm{j}\omega \mathrm{C}_2 \mathrm{R}_{16}}\right] + R_i\right\} (R_{L2} + j\omega L_2 + 2R_{12}) + R_{12}(R_{L2} + j\omega L_2 + R_{12})} \tag{55}$$

In the next step equation (55) is now modified in a more suitable form below, see (56).

$$\mathrm{G}_2 = \frac{\mathrm{e}_2 + \mathrm{j}\omega(\mathrm{C}_2 \mathrm{d}_2 + \mathrm{L}_2 \mathrm{b}_2)}{\mathrm{u}_2 + \mathrm{j}\omega(\mathrm{C}_2 \mathrm{v}_2 + \mathrm{L}_2 \mathrm{x}_2) + \mathrm{j}^2 \omega^2 \mathrm{C}_2 \mathrm{L}_2 \mathrm{z}_2} \tag{56}$$

The evaluation of the parameter from equation (27) to (63) was easy with the help of equations (27) to (34), the substitution of the indices and $R_5 = 0$.

$$e_2 = (R_{L2} + 2R_{12})R_{16} + R_{12}^2 \quad (57)$$

$$d_2 = R_{16}R_{12}^2 \quad (58)$$

$$b_2 = R_{16} \quad (59)$$

$$u_2 = (R_{L2} + 2R_{12})R_{16} + R_{12}^2 + R_{L2}(R_i + R_{12}) + 2R_{12}R_i \quad (60)$$

$$v_2 = R_{16}[R_{12}^2 + R_{L2}(R_i + R_{12}) + 2R_{12}R_i] \quad (61)$$

$$x_2 = R_{16} + R_i + R_{12} \quad (62)$$

$$z_2 = R_{16}(R_i + R_{12}) \quad (63)$$

Further on equation (56) shall be transformed in the form below, see equation (64). This is necessary for determination of the time constants.

$$\mathrm{G}_2 = \mathrm{k}_2 \frac{(1 + \mathrm{j}\omega \mathrm{t}_{a2})}{(1 + \mathrm{j}\omega \mathrm{t}_{d2})(1 + \mathrm{j}\omega \mathrm{t}_{e2})} \quad (64)$$

With substitution of equations (56) to (59) follows:

$$t_{a2} = \frac{C_2 d_2 + L_2 b_2}{e_2} \quad (65)$$

If we define that

$$C_2 d_2 = L_2 b_2 \quad (66)$$

we are able to simplify equation (65) to:

$$t_{a2} = \frac{2L_2 b_2}{e_2} = t_5 \quad (67)$$

The equation for t_{b2} delivers the time constant for t_5. If we compare this statement with the definitions in chapter 2 and equation (4) we see that this time constant is part of the denominator, but here it's part of the numerator. In the evaluation below we will see, how to get the correct solution.

Now, the denominator quadratic equations (56) and (64) with its complex coefficients are solved with the general known "quadratic formula", see (68) below.

$$t_{d2/e2} = \frac{C_2 v_2 + L_2 x_2}{2u_2} \pm \sqrt{-\frac{L_2 C_2 z_2}{u_2} + \frac{(C_2 v_2 + L_2 x_2)^2}{4u_2^2}} \quad (68)$$

With the help of equations from (60) to (63) we can modify (68) as follows:

$$t_{d2} = \frac{1}{2u_2}\left[C_2 v_2 + L_2 x_2 + \sqrt{4L_2 C_2 R_{12}^2 R_{16}^2 - (C_2 v_2 - L_2 x_2)^2}\right] \quad (69)$$

$$t_{e2} = \frac{1}{2u_2}\left[C_2 v_2 + L_2 x_2 - \sqrt{4L_2 C_2 R_{12}^2 R_{16}^2 - (C_2 v_2 - L_2 x_2)^2}\right] \quad (70)$$

If we define that

$$4L_2 C_2 R_{12}^2 R_{16}^2 = (C_2 v_2 - L_2 x_2)^2 \quad (71)$$

we are able to simplify equation (72) and (70) to (and set equal with (67)):

$$t_{d2} = t_{e2} = \frac{1}{2u_2}[C_2 v_2 + L_2 x_2] = t_5 \quad (72)$$

If we now substitute the second part of the general RIAA transfer function defined in equation (4) with the results of equations (67) and (72), we get following result:

$$G_2 = k_2 \frac{(1 + j\omega t_5)}{(1 + j\omega t_5)(1 + j\omega t_5)} = k_2 \frac{1}{(1 + j\omega t_5)} \quad (73)$$

$$G_2 = \frac{e_2}{u_2} \frac{1}{\left(1 + j\omega \frac{1}{2u_2}[C_2 v_2 + L_2 x_2]\right)} \quad (74)$$

Finally, we have found the solution for the transfer function of the second RIAA filter part.

5.1.5 Determination of second filter part components

In chapters 5.1.1 to 5.1.4 we now have enough independent equations for calculating the components of the second part of the RIAA filter.

The detailed evaluation of equations below is not shown in this document; only the results are delivered below.

For the inductance of L_2 we again have a little bit of freedom. L_2 shall be as small as possible because of the mechanical dimension as well as the copper resistance R_{L2}. On the other hand, the inductance of L_2 shall be high enough to fulfill following requirement:

$$L_2 > R_i t_5 \quad (75)$$

Otherwise, R_{16} will become infinity or negative (see (78) below), and R_{L2} will become zero or negative (see (79) below), which would not be a real solution.

Note: R_{L2} is the copper resistance of L_2, or part of it combined with a serial resistor (see Figure 6-1).

The following equations show the result for calculation of the remaining components of the second RIAA filter part.

$$\mathrm{C_2} = \frac{\mathrm{L_2}}{\mathrm{R_i^2}} \quad (76)$$

$$R_{12} = R_i \quad (77)$$

$$R_{16} = \frac{R_i^2}{\frac{L_2}{t_5} - R_i} \quad (78)$$

$$R_{L2} = \frac{R_i^2}{R_{16}} \quad (79)$$

5.2 Determination of RIAA components with t_6

Figure 5-2 shows LCR RIAA filter extended with $t6$ time constant, compare also with the explanations in chapter 5.1.

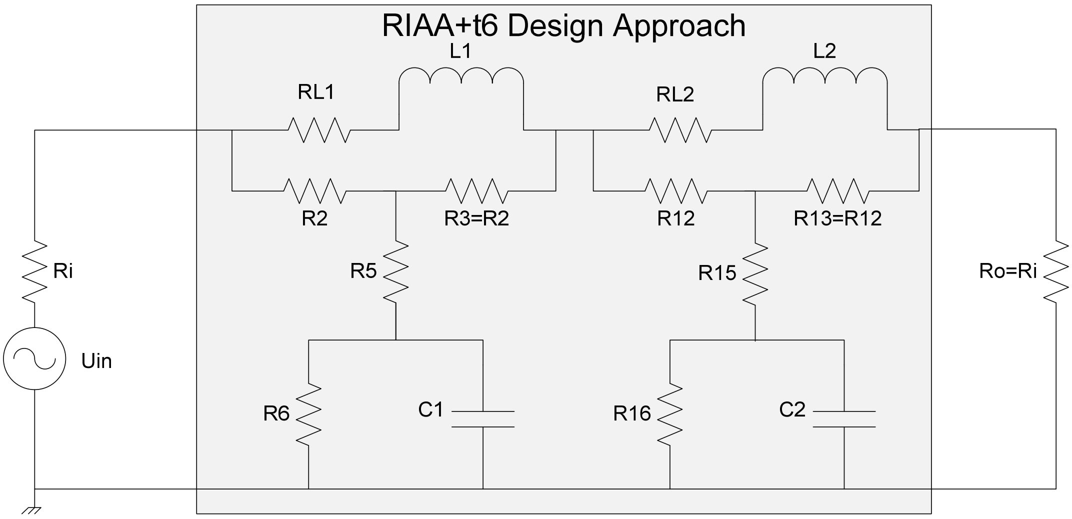

Figure 5-2: RIAA+t6 design approach

The structure of second part of the filter is identical with the first part, only the time constants $t_5$and t_6 are different. Therefore, no new derivation for determination of the second filter components is necessary.

Only the exchange of the indices are necessary and the results are shown in the following chapter.

5.2.1 Determination of R_i

$$R_i = \sqrt{\frac{(R_{L2}+j\omega L_2)R_{12}\left(R_{12} + 2\frac{\mathrm{R_{15} + R_{16} + j\omega C_2 R_{15} R_{16}}}{\mathrm{1 + j\omega C_2 R_{16}}}\right)}{\mathrm{R_{L2} + j\omega L_2} + 2R_{12}}} \tag{80}$$

$$\mathrm{R_i} = \sqrt{\frac{\mathrm{L_2}}{\mathrm{C_2}}} \tag{81}$$

5.2.2 Determination of G_2 with t_6

$$G_2 = \frac{e_2}{u_2}\frac{\left(1 + j\omega\frac{1}{e_2}\left[L_2 b_2 - R_{12}R_{16}\sqrt{L_2 C_2}\right]\right)}{\left(1 + j\omega\frac{1}{2u_2}\left[C_2 v_2 + L_2 x_2\right]\right)} \tag{82}$$

with:

$$e_2 = (R_{L2} + 2R_{12})(R_{15} + R_{16}) + R_{12}^2 \tag{83}$$

$$b_2 = (R_{15} + R_{16}) \tag{84}$$

$$u_2 = (R_{L2} + 2R_{12})(R_{15} + R_{16}) + R_{12}^2 + R_{L2}(R_i + R_{12}) + 2R_{12}R_i \tag{85}$$

$$v_2 = R_{16}[R_{15}(R_{L2} + 2R_{12}) + R_{12}^2 + R_{L2}(R_i + R_{12}) + 2R_{12}R_i] \tag{86}$$

$$x_2 = R_{15} + R_{16} + R_i + R_{12} \tag{87}$$

5.2.3 Determination of second filter components with t_6

Note: R_{L2} is the copper resistance of L_2, or part of it combined with a serial resistor (see Figure 6-2).

$$L_2 > R_i(t_5 - t_6) \tag{88}$$

$$\mathrm{C_2} = \frac{\mathrm{L_2}}{\mathrm{R_i^2}} \tag{89}$$

$$R_{12} = \sqrt{\frac{L_2 R_i(t_5 - t_6)}{C_2 R_i(t_5 - t_6) + 4t_5 t_6}} \tag{90}$$

$$R_{15} = \frac{R_i^2 - R_{12}^2}{2R_{12}} \tag{91}$$

$$R_{16} = \frac{R_i^2}{\frac{L_2}{t_6} - \frac{R_i(R_i + R_{12})}{R_{15}}} \tag{92}$$

$$R_{L2} = \frac{R_i^2}{R_{16}} \tag{93}$$

6 Summary of equation results

Figure 6-1 and Figure 6-2 below show the final schematics for both filter types under consideration of the inductance copper resistances. R_{L1} and R_{L2} are separated in the copper resistances $R_{L1.Cu}$ / $R_{L2.Cu}$ and series resisters $R_{L1}A$ / R_{L2A}.

From my point of view, this is very helpful because the inductance copper (or may be silver) resistances are not exactly known during design. When the inductors are produced and available, resistances and inductivities should be measured as precise as possible.

Additionally, the copper resistances change with temperature (more dramatically than the other resistors). Therefore, the values of the real operation temperature shall be considered. Otherwise, the filter characteristic is not as precise as expected.

Figure 6-1: RIAA Filter

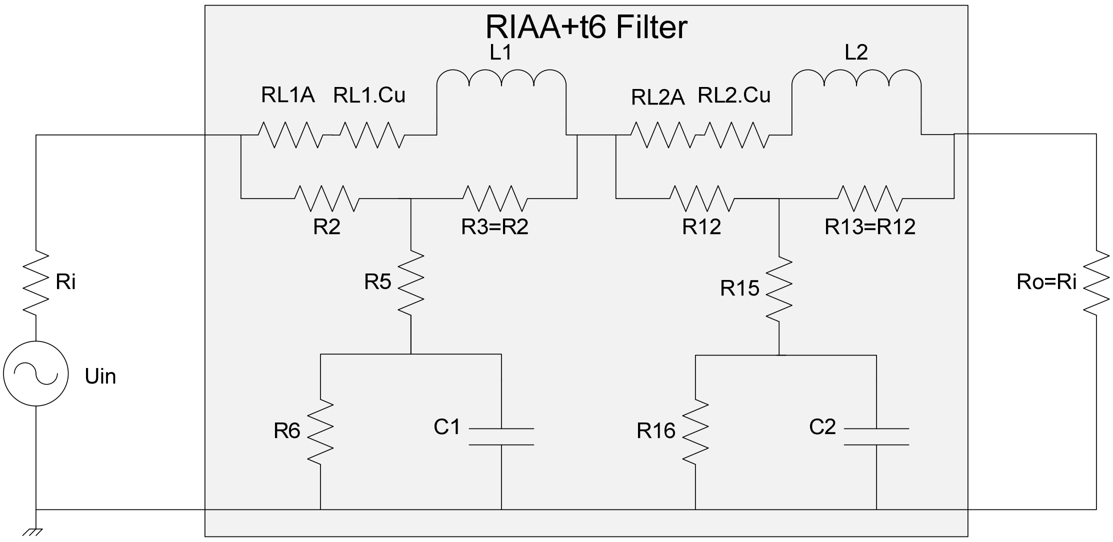

Figure 6-2: RIAA+t6 Filter

The following Table 6-1 summarizes all necessary design equations.

Refer to schematics Figure 6-1 and Figure 6-2.

Component	RIAA	RIAA + t_6
R_i	can be theoretically chosen free, but inductivities increase roughly proportional	
L_1	$> R_i(t_3 - t_4)$	
C_1	$= \frac{L_1}{R_i^2}$	
R_2	$= \sqrt{\frac{L_1 R_i(t_3 - t_4)}{C_1 R_i(t_3 - t_4) + 4t_3 t_4}}$	
R_5	$= \frac{R_i^2 - R_2^2}{2R_2}$	
R_6	$= \frac{R_i^2}{\frac{L_1}{t_4} - \frac{R_i(R_i + R_2)}{R_5}}$	
R_{L1}	$= \frac{R_i^2}{R_6};\ R_{L1} = R_{L1A} + R_{L1.Cu}$	
G_1	$\frac{\left(1 + j\omega \frac{1}{e_1}\left[L_1 b_1 - R_2 R_6 \sqrt{L_1 C_1}\right]\right)}{\left(1 + j\omega \frac{1}{2u_1}\left[C_1 v_1 + L_1 x_1\right]\right)}$ for coefficients, refer to chapter 5.1.2	
L_2	$> R_i t_5$	$> R_i(t_5 - t_6)$
C_2	$= \frac{L_2}{R_i^2}$	
R_{12}	$= R_i$	$= \sqrt{\frac{L_2 R_i(t_5 - t_6)}{C_2 R_i(t_5 - t_6) + 4t_5 t_6}}$
R_{15}	*Not required (=0)*	$= \frac{R_i^2 - R_{12}^2}{2R_{12}}$
R_{16}	$= \frac{R_i^2}{\frac{L_2}{t_5} - R_i}$	$= \frac{R_i^2}{\frac{L_2}{t_6} - \frac{R_i(R_i + R_{12})}{R_{15}}}$
R_{L2}	$= \frac{R_i^2}{R_{16}};\ R_{L2} = R_{L2A} + R_{L2.Cu}$	
G_2	$= \frac{e_2}{u_2} \frac{1}{\left(1 + j\omega \frac{1}{2u_2}\left[C_2 v_2 + L_2 x_2\right]\right)}$ for coefficients, refer to chapter 5.1.4	$= \frac{e_2}{u_2} \frac{\left(1 + j\omega \frac{1}{e_2}\left[L_2 b_2 - R_{12} R_{16} \sqrt{L_2 C_2}\right]\right)}{\left(1 + j\omega \frac{1}{2u_2}\left[C_2 v_2 + L_2 x_2\right]\right)}$ for coefficients, refer to chapter 5.2.2
G	$= G_1 G_2 \frac{R_o}{R_i + R_o}$	

Table 6-1: Final Design Equation

7 Filter Precision Calculation

7.1 Basis Equations

In chapter 6 we have summarized all equations for determination of the filter component values, but probably you will not find the exact values on the market. Therefore you have to make compromises.

Nevertheless, it is of great interest to know the nominal and maximal error of the filter transfer function.

The following equations (which are copies from chapters above) are the basis for evaluation of generic transfer function G under consideration of component value failures (i.e., filter impedance and designed transfer function not correct):

$$G_1 = \frac{Z_4(Z_1 + 2R_2) + R_2^2}{(Z_4 + R_i)(Z_1 + 2R_2) + R_2(Z_1 + R_2)} \tag{6}$$

$$G_2 = \frac{Z_{14}(Z_2 + 2R_{12}) + R_{12}^2}{(Z_{14} + R_i)(Z_2 + 2R_{12}) + R_{12}(Z_2 + R_{12})} \tag{7}$$

$$R_i = \frac{R_o[Z_4(Z_1 + 2R_2) + R_2(Z_1 + R_2)] + Z_1R_2(R_2 + 2Z_4)}{(Z_4 + R_o)(Z_1 + 2R_2) + R_2(Z_1 + R_2)} \tag{10}$$

$$R_i = \frac{R_o[Z_{14}(Z_2 + 2R_{12}) + R_{12}(Z_2 + R_{12})] + Z_2R_{12}(R_{12} + 2Z_{14})}{(Z_{14} + R_o)(Z_2 + 2R_{12}) + R_{12}(Z_2 + R_{12})} \tag{11}$$

$$\mathrm{Z_1 = R_{L1} + j\omega L_1} \tag{17}$$

$$\mathrm{Z_4 = R_5 + \frac{1}{\frac{1}{R_6} + j\omega C_1} = \frac{R_5 + R_6 + j\omega C_1 R_5 R_6}{1 + j\omega C_1 R_6}} \tag{18}$$

$$\mathrm{Z_2 = R_{L2} + j\omega L_2} \tag{20}$$

The following equation (94) is substituted from equation (18) above for the second filter part, i.e. RIAA+t6 transfer function.

$$\mathrm{Z_{14} = R_{15} + \frac{1}{\frac{1}{R_{16}} + j\omega C_2}} = \frac{R_{15} + R_{16} + j\omega C_2R_{15}R_{16}}{1 + j\omega C_2R_{16}} \tag{94}$$

The nominal gain error of the transfer function G is calculated with the chosen components you bought from the market. The maximal gain error considers the maximal specified tolerances of all components. The same is valid for the phase error $\Delta\varphi$.

For calculation of the maximal errors, all combinations of minimal and maximal values of each component shall be analyzed. All together 11 components for the RIAA filter and 12 components for the RIAA+t6 filter have to be considered.

Consequently, $2^{11} = 2048$ complex calculations for the RIAA filter and $2^{12} = 4096$ for the RIAA+t6 filter over wide frequency range are necessary. This could be realized with software.

7.2 Final Error Equation

All equations in chapter 7.1 above were completely transformed with the generic result in equation (95) below. The coefficients are defined in equations (96) to (103). The detailed and complex transformation is not shown in this document.

$$\boldsymbol{G = \frac{R_o a_1 a_2}{(w_1 + R_i d_1)(d_2 + R_o c_2) + (w_2 + R_o d_2)(d_1 + R_i c_1)}} \tag{95}$$

$$a_1 = \frac{R_5 + R_6 + j\omega C_1 R_5 R_6}{1 + j\omega C_1 R_6}(2R_2 + R_{L1} + j\omega L_1) + R_2^2 \quad (96)$$

$$a_2 = \frac{R_{15} + R_{16} + j\omega C_2 R_{15} R_{16}}{1 + j\omega C_2 R_{16}}(2R_{12} + R_{L2} + j\omega L_2) + R_{12}^2 \quad (97)$$

$$c_1 = 2R_2 + R_{L1} + j\omega L_1 \quad (98)$$

$$c_2 = 2R_{12} + R_{L2} + j\omega L_2 \quad (99)$$

$$w_1 = R_2(R_{L1} + j\omega L_1)\left(R_2 + 2\frac{R_5 + R_6 + j\omega C_1 R_5 R_6}{1 + j\omega C_1 R_6}\right) \quad (100)$$

$$w_2 = R_{12}(R_{L2} + j\omega L_2)\left(R_{12} + 2\frac{R_{15} + R_{16} + j\omega C_2 R_{15} R_{16}}{1 + j\omega C_2 R_{16}}\right) \quad (101)$$

$$d_1 = \frac{R_5 + R_6 + j\omega C_1 R_5 R_6}{1 + j\omega C_1 R_6}(2R_2 + R_{L1} + j\omega L_1) + R_2^2 + R_2(R_{L1} + j\omega L_1) \quad (102)$$

$$d_2 = \frac{R_{15} + R_{16} + j\omega C_2 R_{15} R_{16}}{1 + j\omega C_2 R_{16}}(2R_{12} + R_{L2} + j\omega L_2) + R_{12}^2 + R_{12}(R_{L2} + j\omega L_2) \quad (103)$$

The formulas can be used for both filter types, i.e., RIAA and RIAA+t6. For the RIAA filter R_{15} shall be deleted, i.e., $R_{15} = 0$.

With reference to equations (4) and *(5)* we can formulate the inverse RIAA as well as the inverse RIAA+t6 filter transfer functions:

$$\overline{G_{RIAA}} = \frac{1}{k}\frac{(1 + j\omega t_3)(1 + j\omega t_5)}{(1 + j\omega t_4)} \quad (104)$$

$$\overline{G_{RIAA+t6}} = \frac{1}{k}\frac{(1 + j\omega t_3)(1 + j\omega t_5)}{(1 + j\omega t_4)(1 + j\omega t_6)} \quad (105)$$

If we multiply $\overline{G_{RIAA}}$ with G (see equations (104) and (95)) or multiply $\overline{G_{RIAA+t6}}$ with G (see equations (105) and (95)) under consideration that $k = G(\omega = 0)$, as result we will get the linearity gain error over frequency.

Of course, we can also firstly convert $\overline{G_{RIAA}}$, and G into dB as well as $\overline{G_{RIAA+t6}}$ and G. In this case we only have to add the pairs and, again, as result we will get the linearity gain error over frequency.

If we calculate the phases for the inverse transfer function as well as for G, we also are able to determine phase error over frequency (i.e., the difference is the error result).

I used all formulas above for nominal gain and maximal gain error calculation as well as for phase error calculation as basis for development of a small filter design tool, which is explained in chapter 8.

8 Filter Design Tool

I developed a “small” but helpful tool for determination of the components which are necessary for a LCR RIAA or RIAA+t6 filter. I decided to use Excel 2007 including the VBA software languages. The decision bases on the widespread deployment and the possibility to calculate complex equations without additional software development.

The tool is named “CalcRIAACompX.Y.xlsm” where “X.Y” represents the actual version.

I used all equations summarized in chapter 6 and 7 in this document.

The tool helps you to:

- calculate the exact values of all filter components,
- support you with your nominal filter precision requirements,
- determine capacitor and resistor values which you are able to find on the market,
- show you the nominal filter error over frequency,
- show you the maximal possible filter error over frequency,

You are able to define your necessary impedance (e.g., 600Ω is frequently used but often not the preferred solution.

You are also able to use other time constants if you want to follow other organization standards (e.g., Pre-1954 DG, European, see /2/).

You have the freedom to define the values of the inductors, if the minimum required values are considered (refer to Table 6-1 in chapter 6).

This is the first version of the tool and maybe improvements are necessary over time. I’m really confident that the tool calculates the correct values but it may contain glitches/bugs. I don’t take any responsibility of wrong calculation because this a privately developed tool. On the other hand it would be fine that you maybe response to me, if you find any glitches/bugs or how I may be able to improve the tool.

8.1 Introduction

The tool altogether has 5 tabs. Input, calculation and output is carried out via the first two tabs “RIAA-Calc.” or “RIAA+t6-Calc.”, see also Figure 8-1 and Figure 8-2 below). Tab “References” shows the schematics and component identifier used within the tool (and also used in this document). The tabs “RIAA-Back” and “RIAA+t6+Back” only support the plot calculations of the first two tabs with complex calculation over frequency.

All fields, where inputs are required to calculate the correct component values, have “white” background color.

All fields with “yellow” background color can be calculated by the tool, but can be optionally overwritten by you if you are not satisfied with the tool’s recommendation.

All “green” background colored fields are automatically calculated by the tool and cannot be modified by the user.

All fields with “mint” background colors are automatically calculated by the tool and are accessible by the user for data export.

All other fields, as well as the macro code, are access protected and cannot be edited by the user. The primary reason is not to hide information but to make the tool robust against unwanted modifications.

Macros shall be enabled; otherwise the tool is not usable.

The tool was developed on a computer with up-to-date virus protection software. The tool excel file was virus checked before deployment.

8.2 Requirements

You need Excel 2007 on your computer. Other concrete requirements I cannot offer.

My notebook has an i5 processor, 4GB RAM and a graphic solution of 1600 by 900 pixels. Everything runs fast without any long delay except follows below.

For the maximal filter error calculation all together hundreds of thousands of complex math functions must be executed over a frequency band from 1Hz to 100,000Hz (refer to 7ff). My computer needs approximately 2 min for the RIAA and 4 min for the RIAA+t6 filter.

8.3 Instructions

In the following chapters all necessary and optional inputs as well as the calculations and outputs are explained. For reference you can use Figure 8-1 and Figure 8-2 or execute the tool directly.

The instruction is explained with the “RIAA-Calc.” tab. The “RIAA+t6-Calc.” tab is only mentioned if additional input is necessary or additional output is shown. Principally the handling is identical.

If you enter or change the values for the impedance, time constants or inductors, the tool automatically calculates (or tries to) the other filter components. Real results are not always possible; the tool reacts accordantly. Please try.

8.3.1 Filter Impedance

You have the free choice to define the filter impedance R_i, e.g. 600Ω. You shall consider that high impedances require higher inductance values which may be limited by dimensions and quality of the inductance.

For the calculation $R_o = R_i$, is set.

8.3.2 Time constants

Default, the RIAA time constants are set (refer to chapter 2, /1/ and /2/). The “RIAA+t6” tab adds the 4th necessary time constant.

You are able to modify all time constants if you want to design a filter for a different standard. You shall be aware that the default time constants will not be restored automatically by the tool if overwritten by you, but you can type in the default values again, refer to chapter 2.

t_3 must be higher than t_4 and t_5 must be higher than t_6; otherwise the filter characteristic is wrong.

8.3.3 Inductances and ideal Filter Components

8.3.3.1 Inductance Choice and Input

If filter impedance and time constants are defined, both inductance values shall be input.

The minimum required values for $L_1$and $L_2$are defined by the equations in Table 6-1. These values are also controlled by the tool. These minimum values consider a real resistance of 0Ω which is, of course, not possible in reality. Therefore additional information is necessary and the inductor values have to be “a little” higher.

Note: For a 600Ω impedance and RIAA characteristic the minimum value for $L_1 > 1.7172H$.

For a good design, the inductivities shall be as low as possible but the copper resistances (or if you have enough money, the silver resistances) shall be considered. You can input the resistance under consideration of the temperature, where the resistance is measured, as well as the material, which have slightly different temperature coefficients.

Additionally, you shall estimate the operation temperature, which may be different from the measured temperature. For a precise design, this shall be considered because copper and silver have a real bad temperature coefficient in comparison to metal film resistors. Of course, you can measure the resistance at operation temperature.

Maybe you don't have any inductors at this design stage and you have manufactured them yourself or you have to order them from a reliable vendor. In this case you shall specify the values with the help of this tool.

For $L_1 = 1.8H$ the copper resistance probably is in the range of 30Ω, but ask your preferred vendor or measure after manufacturing. Don't choose the inductivity too low, otherwise you are not able to get proper values for the other components. You can "play" with the tool.

Please have a look to "RL1A" and "RL2A" (see also "References" tab) which represent series resistances. You can use them for compensation and precise adjustment of your filter after you measured the inductors which you manufactured yourself or got delivered by a vendor.

If the real values differ from the specification and the inductivities are not too small, you can input the real values and all other components are calculated accordingly.

Please make sure that firstly, the coil core material is qualified for a most constant inductivity over the audio frequency band, secondly, there is very low distortion and ,of course, your measurements are as precise as possible. The goal should be to measure the inductivity values $\pm 1\%$ and the inductor resistances $\pm 0.2\%$.

8.3.3.2 Ideal Components Calculation

All remaining filter component values are calculated automatically and correctly after the filter impedance, all inductance parameter and time constants are input. The values are shown with "green" background color in the column "Value".

If not all preconditions are fulfilled, the not realistic results are shown with red background color or with error messages.

Of course, the results are ideal component values and probably not available on the markets. Compromises as precise as possible have to be to found. The tool tries to support a good solution; see chapters below.

8.3.4 Filter Precision

Finally, it does not help you so much that we have calculated the ideal component values. You have to decide which components are available on the market.

You are able to define the maximal error you want to tolerate for the nominal values. You can input the maximal accepted resistor tolerance (refer to "Max R-Failure") and the maximal tolerable Capacitor tolerance (refer to " Max C-Failure").

Additionally, you can decide which E-serie standard you want to consider for the components (refer to "E Serie (Res.)" and "E-Serie (Cap.)").

From my point of view you shall use metal film resistors with low noise, but of course it is your choice.

The determination of the "correct" capacitors is much more difficult; there are many "philosophies" within the communities. From the engineering point of view I refer to the explanation in /2/, but of course it's your choice again. Maybe the tool can help you to define the correct values but the you have to decide the types.

8.3.5 Determination of Filter Component

Please press the button "Calculate Components", so the tool tries to find the best solutions within seconds under consideration of your filter precision requirements, see the values with "yellow" background color.

The tool searched for the best solution under consideration of parallel two resistors as well as two capacitors (see columns"Xy.1" and "Xy.2") and shows the calculated results in column "Xy.1 // Xy.2" and the nominal error in relation to the theoretical correct values (see column "Value") in column "Error", "Nominal Error".

If you get error messages, the tool was not able to find a solution. A couple of reasons maybe apply:

- Your required filter precision in relation to the chosen E-serie do not meet:
  Try to change it.
- The tool calculates resistors with a maximal value of approximately 2MegΩ and even these values are not easy to find on the market with the required values. High values are necessary for R_6 and R_{16} if RL_1 as well as RL_2 values are very low.
  Try to change or determine the values manually, also see explanations below.

You are always able to calculate your component values manually or with the help of another tool. You can override the automatically calculated values into the "yellow" fields; single component values or paralleled. The results are always shown in column "Xy.1 // Xy.2" and the nominal error in relation to the theoretical correct values (see column "Value") in column "Error", "Nominal Error".

Please be cautious that after repetition of pressing the button "Calculate Components", your manually inputted values will be overwritten by the tool.

8.3.6 Nominal Filter Error

The plot "Nominal Error" shows the Nominal Error over the frequency range from 1Hz to 100,00Hz:

- Linearity Gain Error averaged in db (blue line)
  Note: The plot does not show the effective gain but the linearity error
- Total Phase Error in degree (red line)

The fields "Generic: G…" and "Real: G…" show the ideal gain under consideration of the ideal component values as well as the gain under consideration of the chosen values for $\omega = 0$ as rate and in db.

8.3.7 Component Tolerances

All component values are afflicted with tolerances; normally specified direct with the components. These values shall be input in percentage into the tool; "white" background color in columns "Xy.1" and "Xy.2".

After input, the tool is able to calculate the maximally possible linearity and phase error of the filter design see chapter 8.3.8 below.

The automatically calculated values of column "Xy.2" for the resistors are much higher, whereas the values for the capacitors are much lower than the values in column "Xy.1". Therefore, the influence of the column"Xy.2" values have minor influence on the precision; their tolerances can be higher.

The minimal and maximal error values are shown in columns "Max Error Calculations" "Min" and "Max". The column "Calc. Val." is explained in chapter 8.3.8 below.

8.3.8 Calculation of Maximal Filter Error

Chapter 7.2 delivers all the equations for calculation of the maximal possible linearity and phase error under consideration of the component tolerances.

By pressing the "Calculate max. Error" button, the calculation starts and the program combines all minimal and maximal component values. On my computer it takes about 2 min for the RIAA filter and 4 min for the RIAA+t6 filter.

Start time, degree of completion and duration are shown right beside the start button.

After program completion, the component values for the maximal linearity error are shown in column “Calc. Val.”. The maximal “Linearity Error [db]” and the “Phase Error [total °]” are shown below.

The plot “Maximal Error” shows the Maximal Error over the frequency range from 1Hz to 100,00Hz:

- Linearity Gain Error averaged in db (blue line)
  Note: The plot does not show the effective gain but the linearity error
- Total Phase Error in degree (red line)

From my point of view this plot is very helpful because it shows you whether you filter design fulfills your requirements or not, even under worst case conditions.

Note: Complete fulfillment of worst case conditions is not completely required because it is very unlikely that all components have their worst tolerances in an unique filter at the same time.

8.4 Export of Component Values

After calculation of the components by pressing the button “Calculate Components” (refer to chapter 8.3.5) all values are ready for export via the “mint” colored background fields (and the clipboard) if you scroll the tab down.

You are able to export to all values separately or as special option:

If you are using the free of charge simulation tool “LTSpice IV” from Lineal Technology /3/ and you are using the same identifier within “LTSpice IV” as within this tool you have an interoperable interface. Please copy the field “Export parameters for LTSpice” into the Clipboard and past the values as “Spice Directive” into the LTSpice schematic.

Examples are given in chapter 9ff.

8.5 RIAA Filter Tab

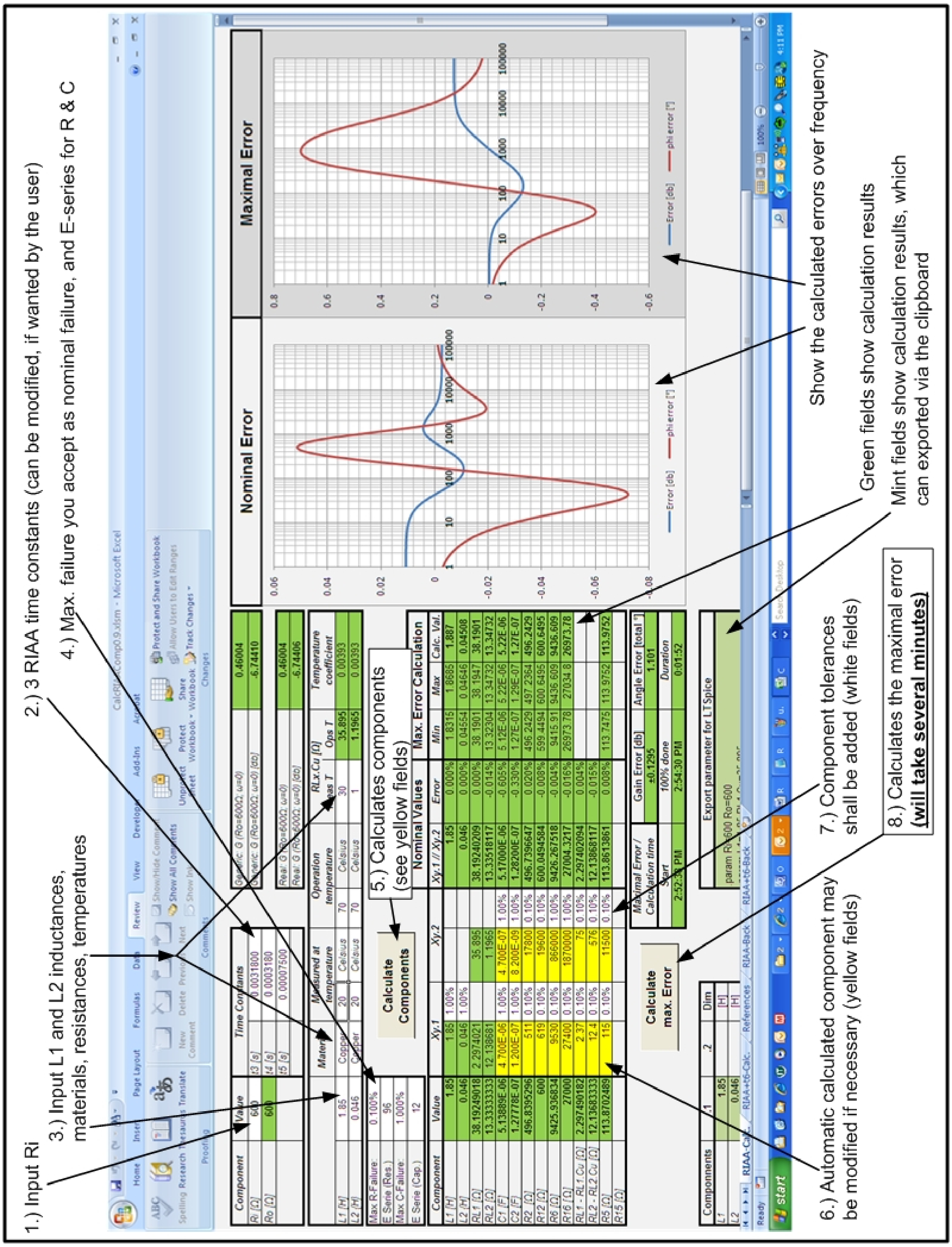

Figure 8-1: RIAA Filter Tab

8.6 RIAA+t6 Filter Tab

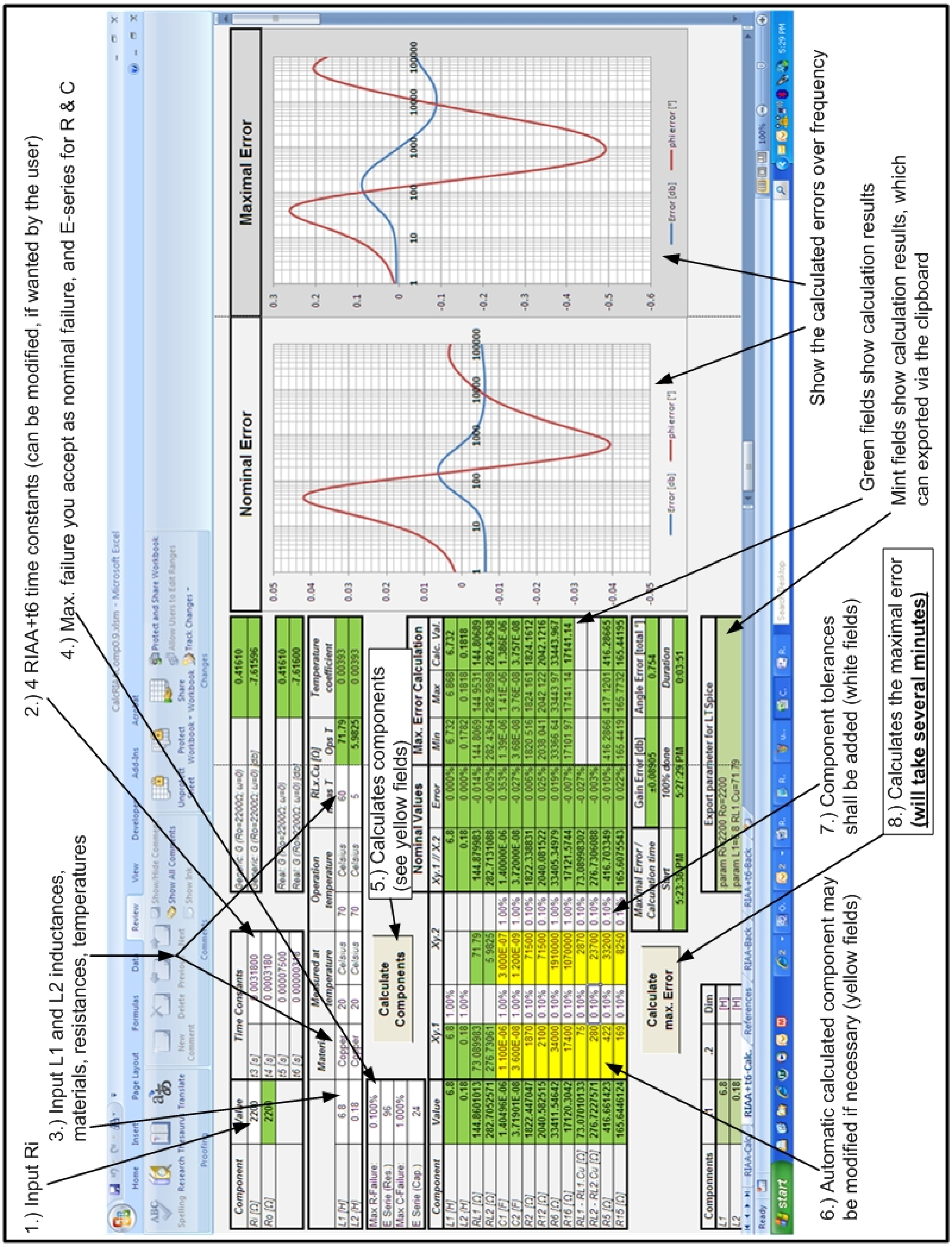

Figure 8-2: RIAA+t6 Filter Tab

9 Simulation of Design Examples

9.1 Introduction

In this chapter I want to give some simple but also some more comprehensive generic design examples which I simulated with the LTSpice simulation tool, see /3/ for reference.

I used this tool in parallel with evaluation of all equations and writing this document. Finally, I was able to verify all my equations (chapter 6 and 7) as well as my developed Excel tool (chapter 8) with LTSpice.

This simulation tool is free of charge for downloading, well known in many communities and, from my point of view, powerful enough to verify your design ideas.

9.2 Passive RIAA filter

The following Figure 9-1 shows a passive 600Ω RIAA filter. I generated the component values with the excel tool presented in chapter 8 and imported the values into LTSpice via the interface described in chapter 8.4.

The plot of Figure 9-1 shows a gain of about -7.5db if $R_i = R_o = 600\Omega$. The filter transfer function will not change but the gain will, if you modify R_i or R_o. If you change both parameters, the filter transfer function will change and not anymore be in accordance with the RIAA behavior.

In the figure you see that I added copper resistances to the inductors and I used compensation resistors for a more precise filter behavior.

The plot of Figure 9-1 shows a very small linearity error as well as a small phase error of the frequency range from 1Hz to 100kHz. The shown errors do not come from the Excel or the Simulation tool; the values were calculated correctly by the Excel tool.

The errors come from the proposed values by the Excel tool under consideration of available vendor values.

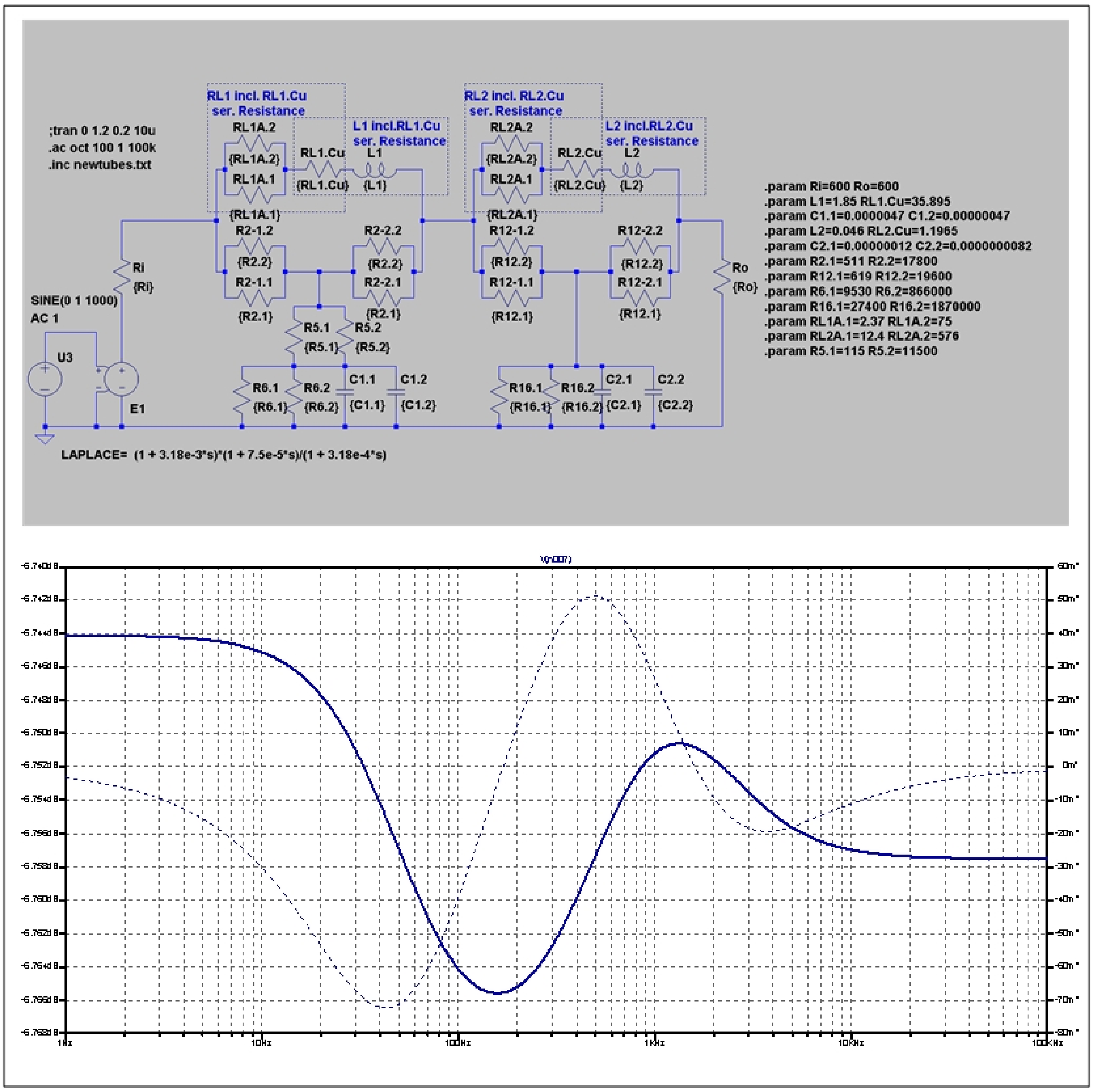

Figure 9-1: 600Ω RIAA Filter Simulation Example

9.3 Passive RIAA+t6 filter

Figure 9-2 below shows another passive filter but with 2200Ω impedance and with RIAA+t6 filter characteristic. The explanation I gave in chapter 9.2 is also valid for this example.

The example also verifies that, with raising the impedance, also the inductor values rise and may become very large, as well as the dimensions (see $L_1 = 6.8H$).

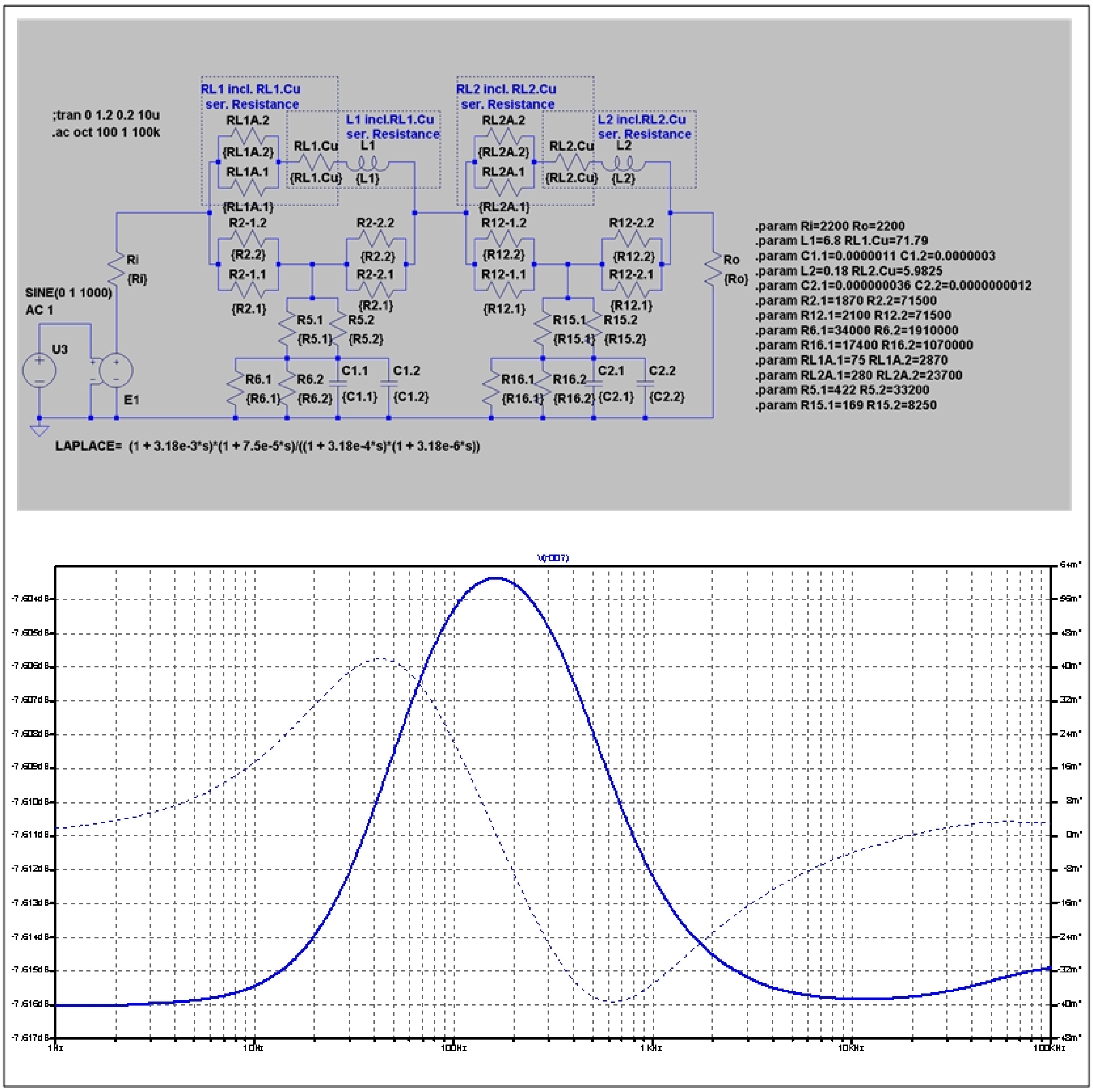

Figure 9-2: 2200Ω RIAA+t6 Filter Simulation Example

9.4 RIAA Tube Pre-Amplifier

The following Figure 9-3 shows a RIAA tube preamplifier design example for MM cartridge. For a MC cartridge, a step-up transformer should be necessary, but this is not considered here because it is not in focus.

The design is not final and not everything is considered; but maybe it could be used for a detailed design and implementation. I only focus on the principle design and the linearity of the pre-amplifier.

The preamplifier is fed by -40db at 1kHz from U1 via the inverse RIAA transfer function E1.

For the first tube stage I used (V1) a C3G tube connected as a triode. This is one of my preferred tubes for pre-amplifiers because of the long life, very low noise, incredible linearity, high gm and gain as well as a low R_i.

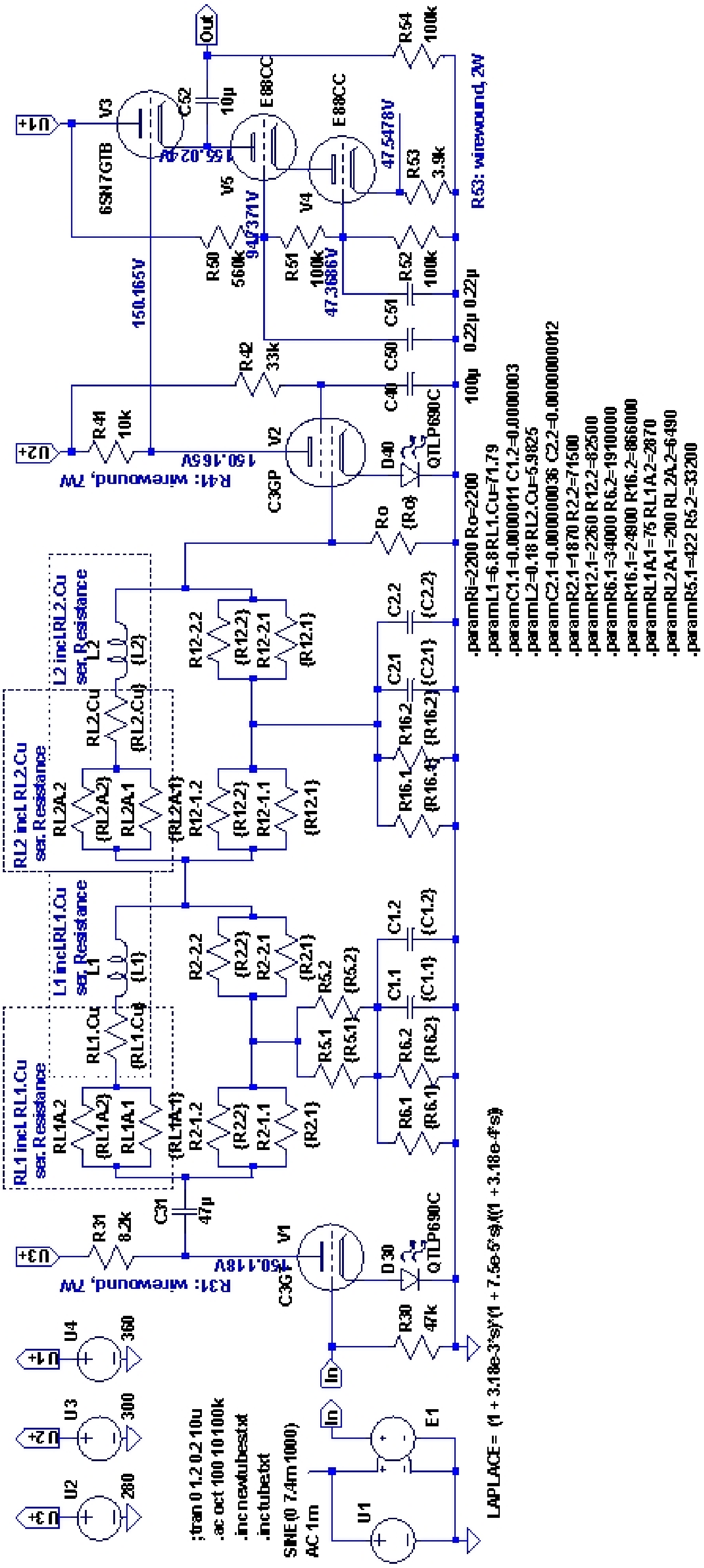

Figure 9-4: 2200Ω RIAA Filter Tube Preamplifier Schematic

For the D30 a cheap red LED with about 1.8V-1.9V voltage drop shall be used. The cathode current of V1 shall be approximately 16mA for a nice operation point.

The anode resistor R31 shall be a wirewound type because of the high DC voltage drop:

- Excess noise is virtually not existent (in contrast to film resistors)
- They are designed to dissipate significant power

You shall be careful to use “inductance free” or wirewound resistors with low inductance because it could influence the overall linearity.

The first stage is coupled via C31 with the input of the RIAA filter. The RIAA filter is designed with $R_i = 2200\Omega$ which considers the ability of V1.

The filter is designed with the Excel tool (refer to chapter 8). The filter output is terminated with Ro and directly connected to the second stage (grid of V2).

V2 again is a C3G, but here connected as pentode. Also, operating the C3G in pentode mode, the noise is very low, the linearity is still above the average standard and the gain of course is much higher than in a triode configuration.

Again, D40 shall be a cheap red LED with about 1.8V-1.9V voltage, the cathode current of V2 shall be approximately 16mA and the anode resistor R41 shall be a wirewound type.

The anode of V2 is directly coupled with the grid of V3 where I chose 6SN7, known for excellent linearity also if high amplitude is required. The tube is operating as cathode follower with an active load.

The active load is realized by a cascoded current source with very high impedance which guarantees low distortion. The current source is realized by the double triode E88CC (see V4 and V5). R53 shall be a wirewound type.

The plot of Figure 9-5 shows the accurate linearity over the frequency range and an approximate gain of 42db at 1kHz; see -40db input source above.

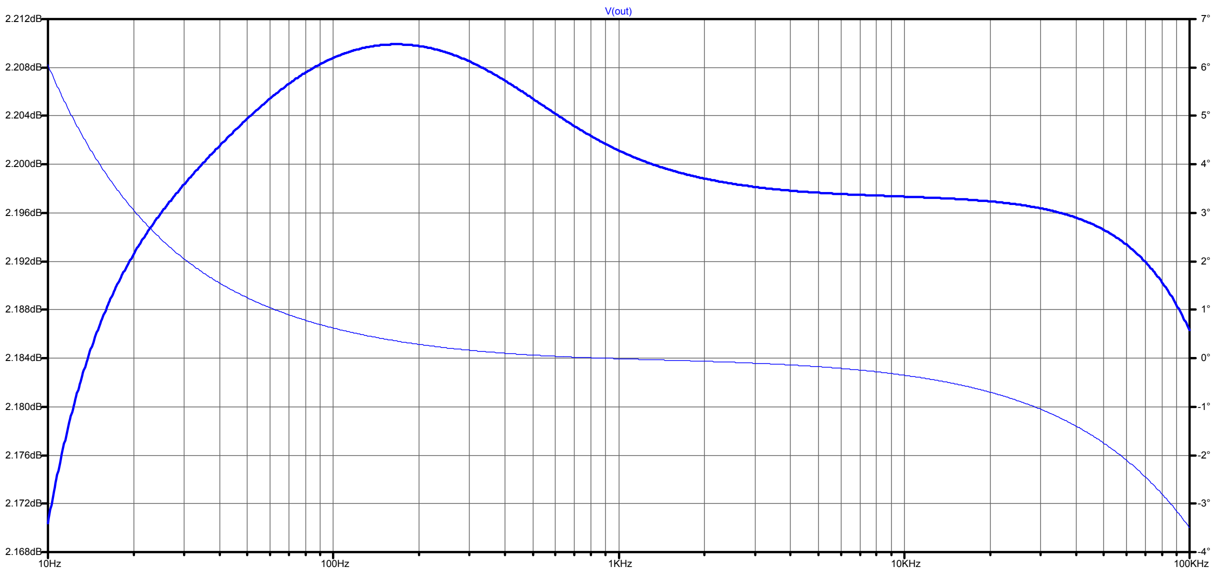

Figure 9-5: 2200Ω RIAA Filter Tube Preamplifier Gain Plot

9.5 RIAA+t6 Tube Pre-Amplifier

Figure 9-6 shows a RIAA+t6 tube preamplifier design example for MM cartridge. Also, for a MC cartridge, a step-up transformer, should be necessary.

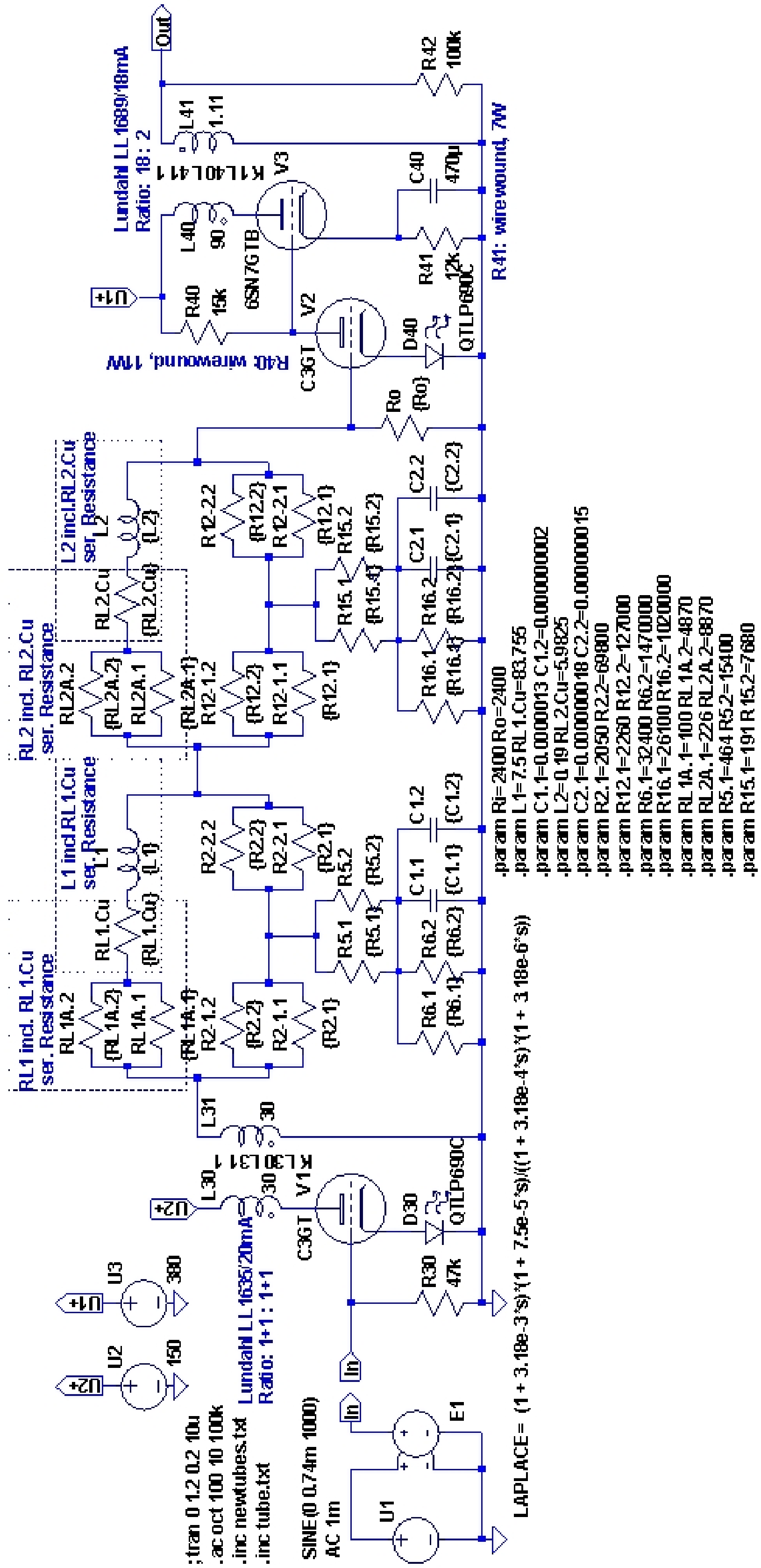

Figure 9-6: 2400Ω RIAA+t6 Filter Tube Preamplifier Schematic

Also, this design is not final and not everything is considered; but maybe it could be used for a detailed design and implementation. Again, I only focus on the principle design and the linearity of the pre-amplifier.

The preamplifier is fed by -40db at 1kHz from U1 via the inverse RIAA transfer function E1.

I, again, used a C3G connected as a triode for the first tube stage (V1).

For the D30 a cheap red LED with about 1.8V-1.9V voltage drop shall be used. The cathode current of V1 shall be approximately 16mA for a nice operation point.

The amplified signal at the anode of V1 is transformed, DC-decoupled by L30/L31 and connected to the RIAA+t6 filter input. For this design simulation, I used a Lundahl LL1635/20mA transformer:

- Ratio: 1+1 : 1+1
- Primary and secondary series resistance: 68Ω

The RIAA+t6 filter is designed with $\mathrm{R_i} = 2400\Omega$ under consideration the C3G (V1) ability and the series resistances of the transformer.

The filter is designed with the Excel tool (refer to chapter 8). The filter output is terminated with Ro and directly connected to the second stage (grid of V2).

V2 again is a C3G connected as triode. Again, D40 shall be a cheap red LED with about 1.8V-1.9V voltage, the cathode current of V2 shall be approximately 16mA and the anode resistor R40 shall be a wirewound type.

The anode of V2 is directly coupled with the grid of V3 where I chose 6SN7, known for excellent linearity, even if high amplitude is required. The tube is operating as common cathode amplifier. The value for cathode resistor R41 is determined by an operating point with a cathode current of approximately 13mA; a wirewound type is required.

R41 is bypassed with C40 for high AC gain under consideration of low frequency cut-off. This capacitor shall probably a combination of an electrolyte type and a high quality foil type.

The amplified signal at the anode of V3 is transformed, DC-decoupled by L40/L41 and connected to the output. For this design simulation I used a Lundahl LL1689/18mA transformer:

- Ratio: 18 : 2
- Primary series resistance: 1310Ω
- Secondary series resistance: 16.8Ω

The transformation of 9:2 is possible and necessary because the amplitude at V3 anode is high enough and the output resistance of the preamplifier shall be as low as possible.

The plot of Figure 9-7 shows the linearity over the frequency range and an approximate gain of 41db at 1kHz; see -40db input source above.

The transformer coupling is the reason for low frequency cut-off and not the RIAA+t6 filter. Maybe an improvement is possible, if a transformer with higher inductivity can be used.

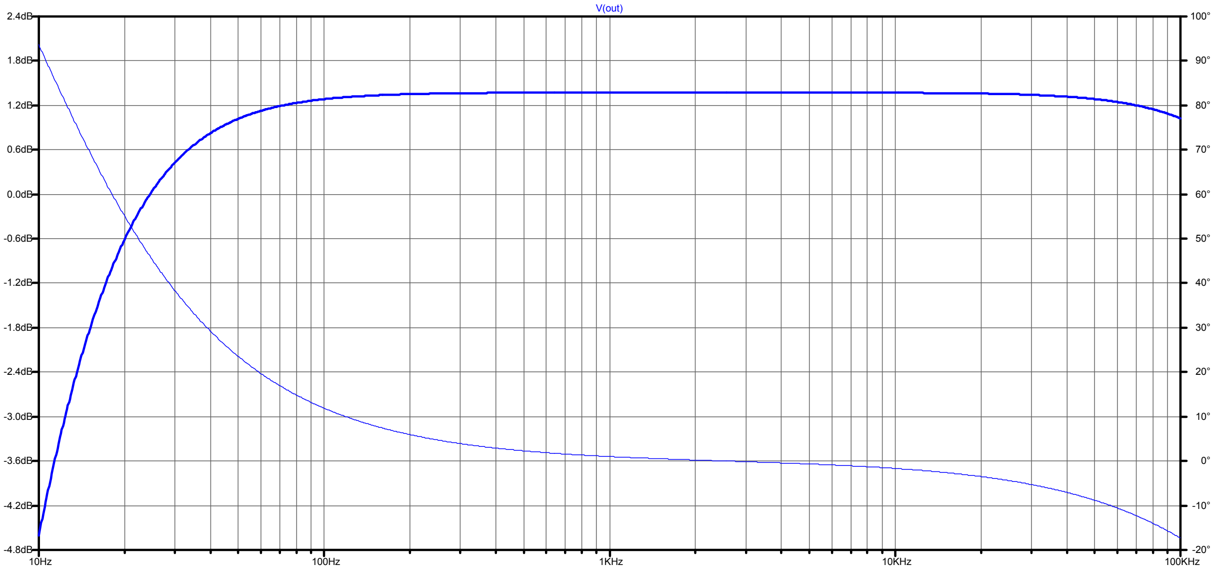

Figure 9-7: 2400Ω RIAA+t6 Filter Tube Preamplifier Gain Plot

10 Final Remarks

From my point of view, this document shows that you should be able to design a high precise RIAA or RIAA+t6 filter and the equations as well as the attached design tool are able to support you.

In the beginning I mentioned the RIAA LCR filter "Tango EQ-600P" which was one reason to write this document. I haven't shown the simulation of this filter within this document but you can test it on your own with the simulation tool LTSpice, refer to /3/. With the nominal component values, shown in Figure 3-1, the simulation shows an error of less than $\pm 0.01db$ which is excellent. From my understanding, the often in the internet used $\pm 0.3db$ precision of this filter comes from the component tolerances, especially the inductors. I haven't proofed it but maybe the community could help.

On the other hand, the often used argument in the internet that with this filter type a precision of (only) $\pm 0.3db$ could be reached is not correct. This is validated with this document because all component values could be calculated precisely. The final filter error depends on a precise design and accurate component choice under consideration of their tolerances.

I'm sure a maximal filter error of $\pm 0.1db$ should be possible, if precise inductors with tolerances of $\pm 1\%$ could be used. I'm looking forward to getting feedback from the community.

Finally, the design of the RIAA LCR filter is not a mythos for me anymore!