Software Checking of Audio Transformers Manufacturability

Martin Pospisilik, Milan Adamek

***Abstract*—** Audio transformers seem to be quite omitted in the audio circuits design although they can be useful for their capability of noise and impedance optimization. However it is understandable that the circuit designers try to avoid them for their disadvantages, for example high price, bulky dimensions and complex design, there are still several applications in which the transformers can play important role. Because one of the disadvantages is that for each application there usually occur demands for a specific transformer, that must be designed and manufactured, usually in small series, the authors decided to search for a way how to make the transformer design easier. Therefore in this paper a simple algorithm of checking whether the calculated transformer is manufacturable or not is presented. The algorithm is created in Maple mathematics instrument and provides visualization of the dependences among the particular transformer parameters.

***Keywords*—** Audio transformers, Simulation, Computer aided design, Electrical circuits, Manufacturability.

I. Introduction

THE audio transformers are useful devices in many parts of audio electrical circuits. They are not common in Hi-Fi appliances but usually they can be found in professional microphone and line amplifiers to match the impedances of the source and the input of the successive electrical block, which usually improves the amplification factor and noise behaviour of the circuit. Sometimes they also appear at the input of moving-coil phonograph pickup amplifiers, audio amplifiers with isolated output, symmetrical to dissymmetrical line converters, distributed speaker systems using high voltage lines, older analogous telephones and, of course, vacuum valve amplifiers. In most cases the transformers are used to match the output and input impedances of two connected blocks. Although in vacuum valve circuits this is usually of a vital importance because of high internal impedances of the valves, in designs employing semiconductors the transformers can be also very important. The goal consists in the fact that input noise characteristics of the semiconductor amplifiers usually depend on their input impedances.

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The design of transformers consists of several areas that overlap each other. The construction parts (transformer cores, bobbin skeletons, wires, isolation foils) are available only in normalized dimensions. The electrical parameters are dependent not only on the number of turns and the transformer core permeability, but also on the geometrical arrangement of the windings and the dimensions of the construction parts. For example, using a thinner wire will allow the designer to increase the number of turns which will result in higher magnetizing inductance and decrease of the minimal operating frequency, but this will also lead to increasing the winding capacity and the leakage inductance, which will result in lowering the resonant frequency of the transformer. Moreover, lowering the cross-section of the wire and increasing the number of the turns will result in significant increase of the winding self-resistance which will increase the signal attenuation caused by inserted losses. Because many of the parameters are to be balanced concerning many of contradictory influences, creating some algorithms enabling the designer to cope with the transformer design seems to be reasonable. For this reason, evolutionary algorithms-based application which optimises all the transformer parameters according to the designer's demand has been created and described in [5]. However, in order the results of this application could be verified, the mathematical algorithm implemented in Maple tool in order to determine whether the transformer is manufacturable or not has been created as well and is a subject of this paper.

II. Problem Formulation

The transformer issues are quite complex so the authors decided to start their research with designing a simple step-up transformer with a symmetrical secondary winding. The behaviour and equivalent circuit for simulations of this transformer have been described in [4] and [5]. The manufacturability of such transformer depends on a compliance with a set of equations describing the transformer behaviour. A typical circuit in which such transformer can be employed is depicted in Fig. 1. It is a triode push-pull connection driven from an unsymmetrical source by the transformer. The required voltage gain of the transformer is 20 dB. This can be fulfilled provided the source impedance is low enough. Provided the outputs of the triodes are loaded with another transformer, a very simple phone amplifier with the output power of up to 0.5 W can be created, only with one dual vacuum valve and two transformers.

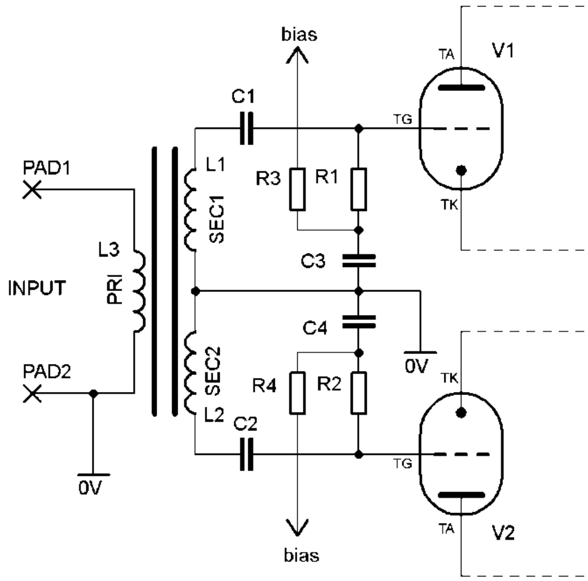

Fig. 1 – Typical connection of a step up audio transformer with double secondary winding

A. *Mechanical arrangement*

The first step in determining the transformer manufacturability consists in determining its internal arrangement. A simple internal winding arrangement considered for the procedure described in this paper can be seen in Fig. 2.

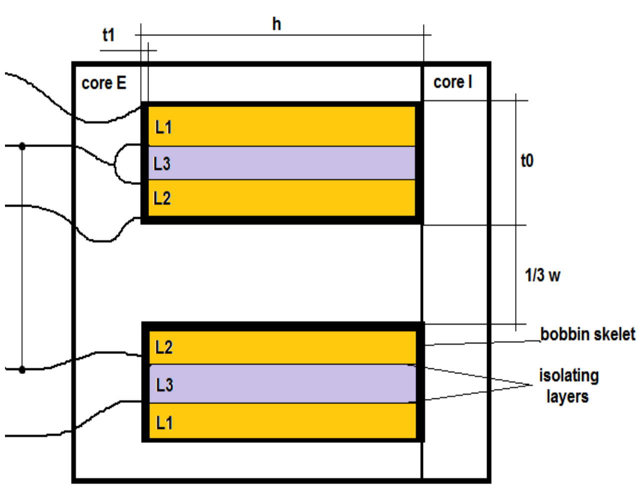

Fig. 2 – Mechanical arrangement of the transformer to be designed

As depicted in Fig. 2, the primary winding consists of only one section while the symmetrical secondary winding consists of two equal sections that are insulated from the primary winding by thin layers of isolating material. The transformer is supposed to operate with low voltages so no additive isolating layers are needed. Single primary winding section shall result in low leakage inductance but the disadvantage of this arrangement consists in significant capacities of the winding and between the adjacent layers. In the following computations 4 main capacities are to be recognised:

- the primary winding capacity CL3,
- secondary winding capacity CL1+L2,
- primary-to-secondary capacity CPS,
- secondary-to-core capacity CSC which is simplified only as L2 to core capacity as it is supposed that between L1 and the core there remains a sufficiently wide gap making the capacity L1-to-core as low as negligible.

As one end of L3 is connected to the ground as well as the centre tap of the secondary windings the C12 capacity is significantly lowered.

The dimensions of the EI core sheets as well as of the coil former are normalised. For the small-signal audio transformers the following EI sheets come into consideration:

Tab. 1 - Normalised dimensions of transformer cores [3]

EI core	Total width	t_0	h	Thickness*)	l_m	o	S_m
	mm						cm^2
EI30	30	5	15	10	56	56	1.0
				13		61	1.25
				16		68	1.6
EI38	38	6.5	19	10	71.5	64	1.2
				13		69	1.5
				16		76	1.92
				20		84	2.4
EI48	48	8	24	13	89	82	2.0
				16		89	2.56
				20		97	3.2
				25		107	4.0
EI60	60	10	30	16	111.4	104	3.2
				20		112	4.0
				25		122	5.0
				32		136	6.4
EI75	75	12.5	37.5	20	139	129	5.0
				25		139	6.25
				32		153	8.0
				40		169	10.0

**) The thickness is determined by number of core sheets*

The parameters t_0 and h defined in the Tab. 1 refer to Fig. 2. The meanings of other parameters are as follow:

- l_m – average length of a magnetic line of force inside the core mass,
- o – average length of a single current turn,
- S_m – core mass cross-section.

B. Transformer wires

For the simplicity, let us consider only copper conductors isolated with a lacquer coating. The thicknesses of the conductors as well as the thicknesses of the insulation coating have a crucial impact on the final transformer behavior. Generally, different conductors can be obtained. For the purposes of this paper normalized wires enlisted in the following table were considered.

Tab. 2 – Normalized transformer wires

Nominal diameter d_{in} [mm]	**Outer diameter d_{out} [mm]**	**Nominal wire cross-section [mm^2]**
0.03	0.05	0.0007
0.04	0.06	0.0013
0.05	0.07	0.0020
0.056	0.078	0.0025
0.063	0.088	0.0031
0.071	0.095	0.0039
0.08	0.105	0.0050
0.09	0.118	0.0063
0.1	0.128	0.0078
0.112	0.15	0.0099
0.125	0.165	0.0122
0.132	0.172	0.0136
0.14	0.18	0.0153
0.15	0.19	0.0176
0.16	0.2	0.0200
0.17	0.216	0.0226
0.18	0.227	0.0253
0.19	0.238	0.0282
0.2	0.25	0.0314

III. Equations

In order to determine the transformer manufacturability two sets of equations must be defined. The first set of equations serve for determining the basic structure of the transformer – according to the considered dimensions and the basic requirements the mechanical model of the transformer is created. The second set of equations is then used for visualization of the transformer parameters on the basis of which it is possible to state whether the transformer meets all the requirements and therefore it is possible to be manufactured or not.

Because the complex descriptions of all the equations would exceed the space of this paper, only a brief list of the phenomenons to be considered is enlisted here and the complex description can be found in [4] and [5].

Because the small signal audio transformer design is based not on the power rating of the transformer, but on the required frequency range and other electrical parameters as described in [4] and [5], the number of primary winding turns is determined by the minimal core magnetizing inductance. If the transformer is suspected that at large signal levels it could cause distortion, the core induction at low frequencies can obviously be calculated as a secondary parameter.

In the task discussed in this paper two parameters are considered for which the results are visualized while the other parameters are fixed. These parameters are:

- ratio of primary to secondary winding resistance that generally determines the noise of the transformer,
- relative resistance of the transformer winding to the load resistance that determines the attenuation caused by the transformer.

The designer then realizes for which of these parameters the transformer is manufacturable. On the basis of the above mentioned statement, the set of the basic equations consists of the following equations:

A. Equation of a minimum required primary winding magnetizing inductance

This equation determines the minimum required primary winding magnetizing inductance (see LP in [4]) that is needed in order the transformer low roll-off frequency was as required provided the source and the load impedances are strictly defined. The equation is as follows:

$$LP \geq \frac{(RG+RP)\cdot\left(\dfrac{RS+RL}{\left(N\cdot\left(1+\frac{m}{100}\right)\right)^2}\right)}{2\cdot\pi\cdot f_{min}\cdot\left(\dfrac{RS+RL}{\left(N\cdot\left(1+\frac{m}{100}\right)\right)^2}+RG+RP\right)} \qquad (1)$$

Where:
RG – signal source impedance simplified to resistance [Ω],
RP – primary winding resistance [Ω],
RS – secondary winding resistance [Ω],
RL – load impedance simplified to resistance [Ω],
N – secondary to primary winding turns ratio (expected voltage gain),
m - relative resistance of the transformer winding to the load resistance; this parameter serves for compensation of the attenuation caused by the resistances of the primary and

secondary winding and is considered to be unknown here as it is calculated from the system of the equations,
f_{min} – low roll-off frequency.

B. Equation for the number of turns of the primary winding according to the primary winding magnetizing inductance and the core mass cross-section

This equation enables the estimation of how many primary winding turns are needed in order the required magnetizing inductance was achieved. As obvious from (1), the magnetizing inductance together with the source and load resistances determines the frequency response of the transformer at low frequencies. From this point of view the more primary winding turns shall ensure the better performance, but usually the lowest possible number must be chosen because too many turns would result in high winding resistance (and signal losses in the transformer) and moreover, too thin conductor would have to be used, resulting in even higher resistance and also in higher capacity that would cause frequency response degradation at high frequencies.

$$n_1 \geq \sqrt{\frac{LP \cdot \left(\frac{l_m}{\mu} + l_{air}\right)}{1.26 \cdot S_m \cdot k}} \cdot 10^4 \qquad (2)$$

Where:
LP – core magnetizing inductance [H],
l_m - average length of a magnetic line of force inside the core mass [m],
l_{air} – estimated technological gap between the E and I sheets, usually 100 [μm],
μ - relative permeability of the core material, usually μ = 1,000,
S_m – core mass cross-section in [cm^2] as enlisted in Tab. 2,
k – losses estimation coefficient, usually k = 0.9.

C. Equation for determining the resistance of the primary winding

The primary winding resistance is determined by the length of the employed wire as well as with its conductivity and cross section. It is expected the winding will fill the whole area of the core window. Otherwise the average length of one current turn of the winding must be decreased.

$$RP = \frac{n_1 \cdot o \cdot \rho}{S_1} \qquad (3)$$

Where:
n_1 – number of primary winding current turns,
o – average length of one current turn for the specific EI sheets (see Tab. 1) in [m],
ρ – specific electrical conductivity of the conductor [Ω/m^2],
S_1 – primary winding conductor cross-section (see Tab. 2) in [m^2].

D. Equation for determining the resistance of the secondary winding

This equation is similar to (3). The only difference is that instead of n_1 the number of secondary winding turns n_2 are applied as well as instead of S_1 the cross section of the secondary winding conductor S_2.

$$RS = \frac{n_2 \cdot o \cdot \rho}{S_2} \qquad (4)$$

E. Equation for the relative resistance of the transformer windings

As stated above, the relative resistance of the transformer winding to the load resistance is considered. It defines by how many percents the number of secondary winding turns must be increased in order the losses in the transformer caused by the resistance of the wires were compensated. On the other hand, if this parameter, labeled with the letter m, is too high, it influences the recalculation of the secondary winding parameters to the primary part (see [4]), so the transformer load may seem too heavy when viewed from the primary winding. As a result the output of the transformer is too damped with the load.

$$m = \frac{RP + \frac{RS}{\left(N \cdot \left(1 + \frac{m}{100}\right)\right)^2}}{RG + \frac{RL}{\left(N \cdot \left(1 + \frac{m}{100}\right)\right)^2}} \cdot 100 \qquad (5)$$

F. Equation for the number of turns of the secondary winding

The number of secondary winding turns is then determined by the m ratio as well as the required N ratio:

$$n_2 = \left(1 + \frac{m}{100}\right) \cdot N \cdot n_1 \qquad (6)$$

In the transformer discussed in this paper two secondary windings are implemented. That means that the total number of the secondary winding is $2n_2$. Also the load must be calculated twice.

G. Equation for the ratio of the primary and the secondary winding resistance

This equation describes the parameter r that shows how the primary and the secondary winding resistances are balanced. Theoretically, when omitting Barkhausen's noise, the ideal noise balance is achieved when this parameter is equal to 1 and also it the source and the load impedances are matched according to the ratio of n_2/n_1.

$$r = \frac{RP \cdot \left(N \cdot \left(1 + \frac{m}{100}\right)\right)^2}{RS} \qquad (7)$$

Consequently, from the results gained from the above-mentioned equations, the following other parameters must be evaluated.

H. Relationship between the required wire cross-section and the outer wire diameter

It is necessary to determine the relationship between the outer and inner diameter of the wires. The inner diameter determines the cross-section and the resistance of the wires, while the outer diameter must be known in order one could count the number of wires in one layer of the winding. Moreover the thickness of the insulation determines the winding capacity estimation.

Because only continuous functions are employed in the algorithm, the relationship between the nominal and the outer diameter must be approximated. The easiest approximation consists in evaluating the ratio between the outer diameter d_{out} and the inner diameter d_{in} of the wires enlisted in Tab. 2. In Fig. 3 there is the d_{out}/d_{in} ratio for different wires depicted.

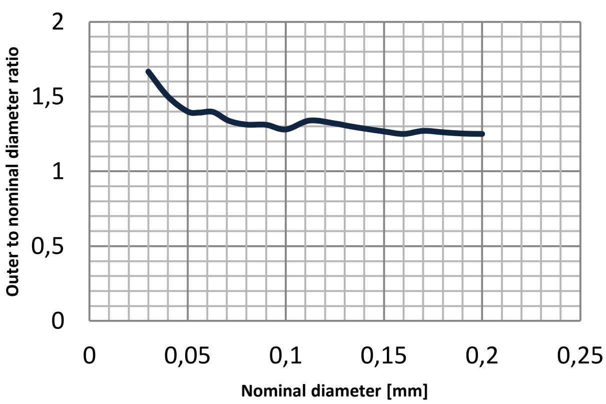

Fig. 3 – Outer to inner wire diameter ratio

It is obvious that for inner diameters higher than 0.05 mm the simple coefficient of 1.33 can be set as a satisfactory approximation so in the calculations, the outer diameter is evaluated as the inner diameter multiplied by 1.33.

I. Determining the number of layers in the winding on the basis of the cross-sections of the conductors

The number of layers in the winding is a crucial parameter because it gives the information on how many layers will be needed to complete the winding. This determines not only the dimensions of the winding but its capacity as well. In the algorithm the number of layers as well as their thickness is calculated from the primary winding conductor cross-section S_1. The primary winding cross-section is calculated as an unknown parameter from the set of equations (1) to (7). In the algorithm it is treated as a function of the parameters r and m. As a basis for the $S_1(m,r)$ calculation, the S_2 value is used. The S_2 value must be given by the user. It is the smallest value used in the transformer construction as it is supposed that the secondary winding consists of more turns, resulting in the smaller cross-section of the conductor.

Provided the cross-sections of the conductors are known, the number of layers can be computed as follows:

$$n_{l1}(m,r) = \left\lceil \frac{n_1 \cdot \frac{\sqrt{\frac{4}{\pi} \cdot S_1(m,r)}}{1000} \cdot 1.33}{h - 2t_1} \right\rceil \qquad (8)$$

$$n_{l2}(m,r) = \left\lceil \frac{n_2 \cdot \frac{\sqrt{\frac{4}{\pi} \cdot S_2(m,r)}}{1000} \cdot 1.33}{h - 2t_1} \right\rceil \qquad (9)$$

Where:

$n_{l1}(m,r)$ – number of primary winding layers,

$n_{l2}(m,r)$ – number of secondary winding layers; in the transformer considered in this paper two secondary windings are implemented,

h – core window width (see Tab. 1 and Fig. 2) [m],

t_1 – winding former material thickness [m],

$S_1(m,r)$ – primary winding wire cross-section [mm^2],

$S_2(m,r)$ – secondary winding wire cross-section [mm^2]

J. Winding thickness

The thickness of the winding is determined by the number of the layers and the outer diameter of the wire. The outer diameter of the wire for primary and secondary winding can be expressed according to the following equation:

$$d_{out1,2}(m,r) = \frac{\sqrt{\frac{4}{\pi} \cdot S_{1,2}(m,r)}}{1000} \cdot 1.33 \qquad (10)$$

Then the thickness of any winding can be expressed as follows:

$$t_{n1}(m,r) = \lceil n_{l1}(m,r) \cdot d_{out1}(m,r) \rceil \qquad (11)$$

$$t_{n2}(m,r) = \lceil n_{l2}(m,r) \cdot d_{out2}(m,r) \rceil \qquad (12)$$

The total thickness of the winding can then be expressed according to the following equation:

$$t_w(m,r) = t_{n1}(m,r) + 2t_{n2}(m,r) + t_1 + t_2 \qquad (13)$$

In the equation (13) the isolation layers between the windings are expressed by the t_2 parameter. Only the thickness of the primary winding $t_{n1}(m,r)$, two secondary windings $t_{n2}(m,r)$ and the former material t_1 are considered. The transformer is considered as manufacturable if the following condition is fulfilled:

$$t_w \leq t_0 \qquad (14)$$

Where t_0 is the thickness of the window in the transformer core (see Fig. 2 and Tab. 1). Because the equations are valid only for t_w being near to t_0, when $t_w << t_0$ the calculation should be processed again with different parameters. This will probably result in better transformer performance. The difference between t_w and t_0 can be filled with insulation among the windings.

K. Transformer attenuation

Due to the wiring resistance and the source and load resistance combinations the transformer always show additional attenuation that degrades the voltage gain obtained by the secondary to primary winding ratio. Partially this attenuation is compensated by employing the m parameter. However, it is not compensated fully and therefore worth evaluating. The attenuation can be expressed as follows:

$$A(m,r) = \\ = -20log\left(\frac{\frac{RL}{\left(N\cdot\left(1+\frac{m}{100}\right)\right)^2}}{RG+RP(m,r)+\frac{RS(m,r)}{\left(N\cdot\left(1+\frac{m}{100}\right)\right)^2}+\frac{RL}{\left(N\cdot\left(1+\frac{m}{100}\right)\right)^2}}\right) \qquad (15)$$

L. Frequency response description

The equations for the transformer frequency response description are too complex and exceed the range of this paper. Comprehensive description of this issue can be found in [4] and [5].

Generally it can be said that at low frequencies, the transfer function of the transformer is determined mainly by the combination of the source and load resistance and the magnetizing inductance of the transformer (1). At high frequencies the situation is more complicated. Firstly, the windings of the transformer show a leakage inductance that acts in series with the winding resistance. Secondly, there are several parasitic capacities spread across the winding. The capacities occur also among the windings. Together with the leakage inductance the capacities generate several resonance circuits. One of the resonances usually prevails and is estimated by the algorithm according to the theory published in [4] and [5]. For the proper operation the resonance frequency must lie above the bandwidth of the transformed signal.

IV. Solution

In order to determine the manufacturability of a small-signal transformer a specialized algorithm has been created to be operated in the Maple mathematics tool. This algorithm evaluates all the equations mentioned above and gives the graphical output describing how the parameters of the transformer depend on two selected parameters. As stated above, the selected parameters in this task were the ratio of primary and secondary winding resistance that generally determines the noise of the transformer and the relative resistance of the transformer winding to the load resistance that determines the attenuation caused by the transformer but, of course, another parameters can be selected instead of these and the visualization will be provided for them.

The operation of the algorithm is as follows:

1. The user specifies parameters that are fixed for the type of the transformer to be manufactured. These parameters are the material dimensions, thicknesses etc.
2. The user specifies parameters that are variable, for example load resistance, thinnest wire cross-section and so on. For these parameters the calculation can be processed repeatedly in order the parameters were tuned until the required solution is obtained.
3. Once started, the algorithm processes the equations (1) to (7) and gains the following functions of the (m, r) parameters:
    a. magnetizing inductance LP(m,r),
    b. primary winding resistance RP(m,r),
    c. secondary winding resistance RS(m,r),
    d. primary winding wire cross-section proposal S_1(m,r),
    e. number of primary winding turns n_1(m,r),
    f. number of secondary winding turns n_2(m,r),
4. The set of the parameters calculated in the previous step is returned in the matrix of the basic functions describing the transformer in the dependence on the parameters (m,r). The secondary parameters are calculated on the basis of this matrix:
    a. attenuation A(m,r),
    b. primary winding thickness t_{n1}(m,r),
    c. secondary winding thickness t_{n2}(m,r),
    d. number of primary winding layers n_{l1} (m,r),
    e. number of secondary winding layers n_{l2}(m,r),
    f. total winding thickness t_w (m,r).
5. The parameters crucial for the physical manufacturability of the transformer are selected and compared to the predefined values that cannot be exceeded:
    a. The total winding thickness t_w is compared to the space in the core t_0 according to the condition (14),
    b. The attenuation caused by the transformer is compared to the attenuation acceptable by the user (designer),
    c. The cross-sections of the wires are compared to the smallest applicable cross-section defined by the user (designer).
6. For each of the above mentioned comparisons one point is added if the appropriate comparison gives the positive result. A "manufacturability function" M(m,r) is created. This function has a limited range of values to integers from -1 to 2. If there is a combination of (m,r) for which M(m,r) = 2, the transformer is considered to be manufacturable.

7. In addition, estimated frequency response of the transformer is explored for the parameters (m,r) selected by the user according to the previous results. According to the theory published in [4] and [5] the algorithm calculates the leakage inductance and parasitic capacitances and by employing the model presented in [4] it calculates the frequency response.

However, the output given by the algorithm is indicative, giving the information on whether it is even possible to create the transformer of the requested dimensions, configuration and parameters. According to the obtained result the designer is encouraged to process accurate calculations and to verify the overall transformer behavior. In order to simplify the design, several of the artificial intelligence based algorithms were also created, as described in [5], [6], [7].

V. EXAMPLE

In order to describe the outputs provided by the algorithm, the check of the transformer manufacturability was processed on several examples. One of the example task input is described in Tab. 3.

Tab. 3 – Transformer to be checked

Mechanical parameters – EI30/13 core	
Parameter	**Description**
$S_m = 1.25\ cm^2$	Core cross-section
$t_0 = 5$ mm	Winding window width
h = 15 mm	Winding window height
o = 61 mm	Average current-turn length
$l_m = 56$ mm	Average length of a magnetic line of force inside the core mass
$t_1 = 0.5$ mm	Former material thickness
$t_2 = 0.2$ mm	Total thickness of the isolation layers between the windings
μ = 1,000	Relative permeability of the core
$l_{air} = 0.1$ mm	Estimated technological gap between the E and I sheets
k = 0.9	Losses estimation coefficient
Electrical parameters	
RG = 200 Ω	Source resistance
RL = 15,000 Ω	Load resistance
CL = 10 pF	Load parasitic capacity
$f_{min} = 30$ Hz	Low roll-off frequency
N = 6	Secondary to primary winding turns ratio (required voltage gain)
$S_2 = 0.0007\ mm^2$	Minimal secondary winding wire cross-section
A = - 5 dB	Acceptable attenuation
$r_{min} = 0.1$	Lower limit of the r parameter
$r_{max} = 10$	Upper limit of the r parameter
$m_{min} = 1$	Lower limit of the m parameter
$m_{max} = 100$	Upper limit of the m parameter

The algorithm was run for the parameters specified according to Tab. 3. The outputs of the algorithm are depicted on the figures below.

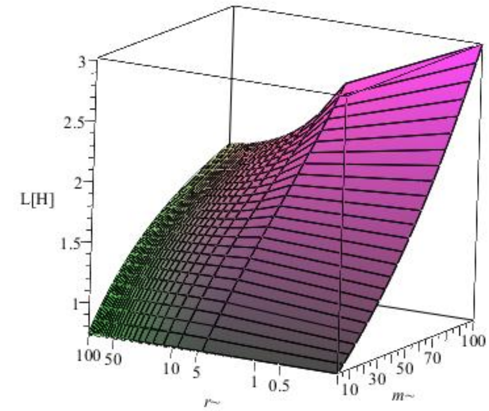

Fig. 4 – Core magnetizing inductance dependence on the (m,r) parameters

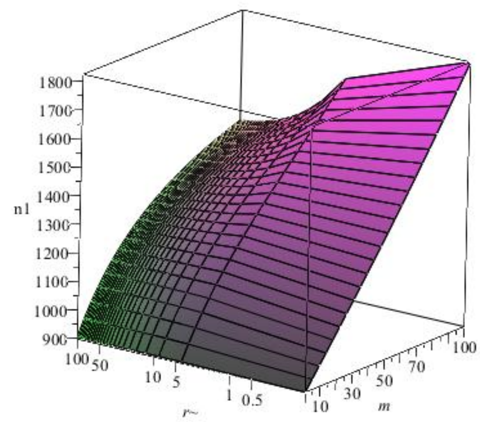

Fig. 5 – Number of primary winding current turns in dependence on the (m,r) parameters

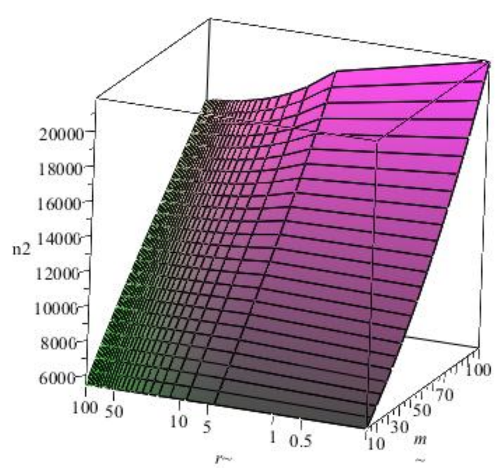

Fig. 6 – Number of secondary winding current turns in dependence on the (m,r) parameters

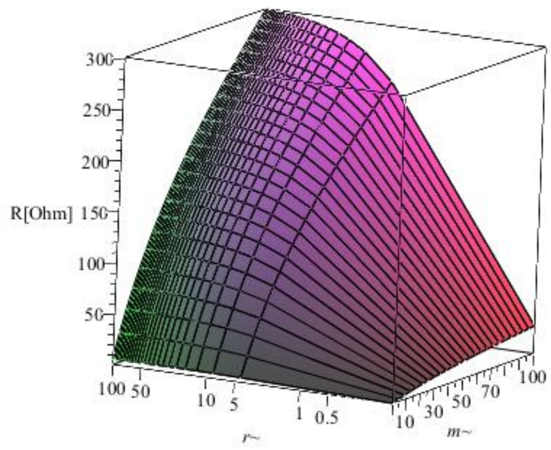

Fig. 7 – Primary winding resistance dependence on the (m,r) parameters

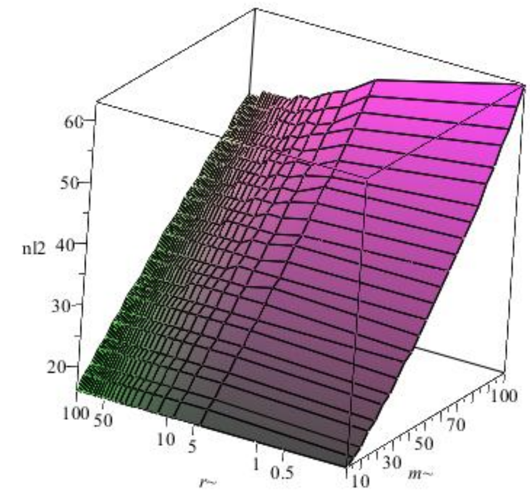

Fig. 10 – Number of secondary winding layers dependence on the (m,r) parameters

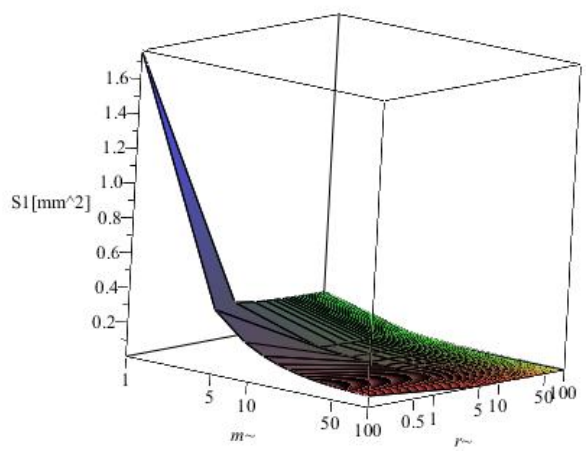

Fig. 8 – Primary winding wire cross-section dependence on the (m,r) parameters

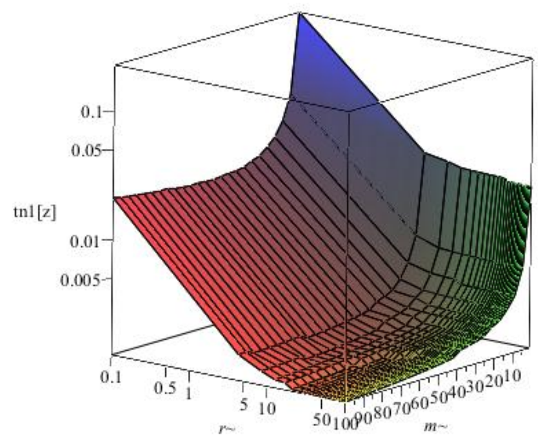

Fig. 11 – Primary winding thickness dependence on the (m,r) parameters

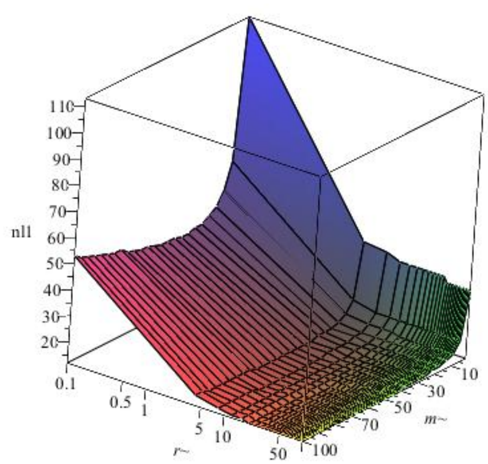

Fig. 9 – Number of primary winding layers dependence on the (m,r) parameters

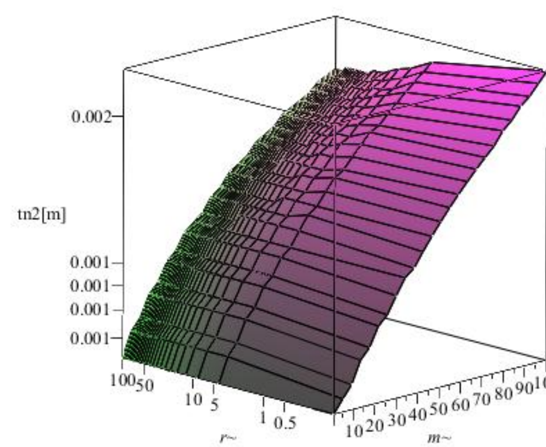

Fig. 12 – Secondary winding thickness dependence on the (m,r) parameters (one of two windings is considered)

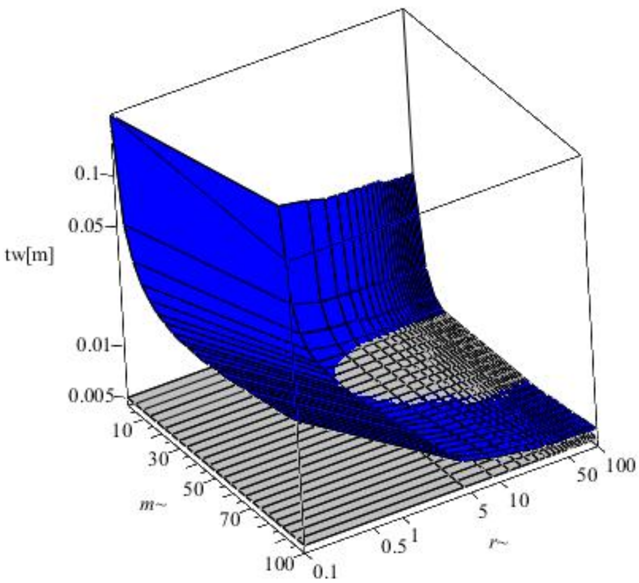

Fig. 13 – Total winding thickness dependence on the (m,r) parameters; the light gray plane comply to the core window height h

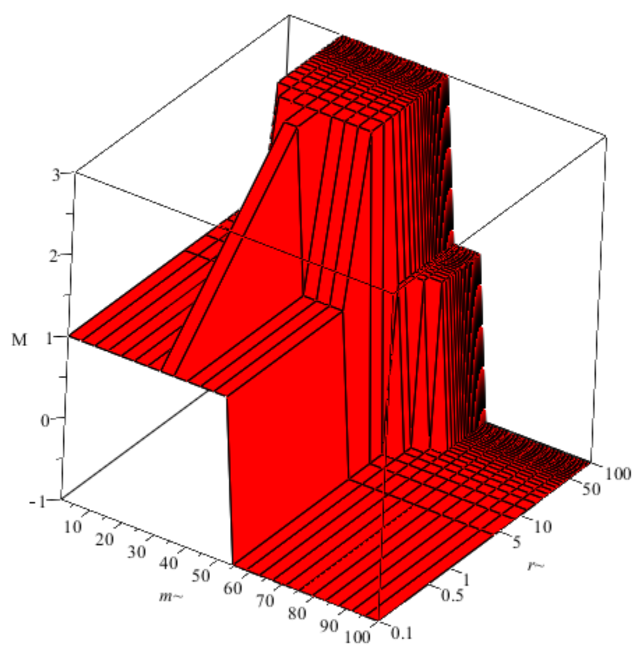

Fig. 14 – Manufacturability function M

The graphs depicted in Fig. 4 to Fig. 14 represent the dependences of several basic parameters of the transformer on the (m,r) parameters. They help the designer to find a compromise among the restrictions given by the mechanical and the electrical parameters. Moreover, they give an insight into the trends that can be explored when the other transformer parameters are changed.

For example, from Fig. 5 and 6 the importance of the m parameter is obvious. The increase in the number of secondary winding turns $n_2(m,r)$ is more steep than the increase in the number of primary winding turns $n_1(m,r)$ because when the number of turns is increased, the attenuation losses caused by the wire resistances are increased as well and the compensation is reached by increasing the number of the secondary winding turns even more. From this point of view there is no reason in increasing the m factor but for very low m, the primary winding wire cross-section increases rapidly, as depicted in Fig. 8. For this reason also the number of primary winding layers is increased (see Fig. 9), resulting in increased overall thickness of the winding (see Fig. 11). From Fig. 13 it is obvious that the winding fits into the core window only for several (m,r) parameters, when the total thickness $t_w(m,r)$ is smaller than the window height represented by the parameter t_0 and the light gray plane in Fig. 13.

In Fig. 14 the “manufacturability function” is depicted, as described above. Only for those (m,r) combinations at which M = 3 the transformer can be manufactured (the winding is thin enough, the attenuation is below the upper limit and the wires cross-sections are above the lower limit. In practice this means that only the transformer the r parameter of which is higher than approximately 5 can be manufactured. In other words, with the specification according to Tab. 3 it is impossible to create the transformer that would be optimally noise balanced (r = 1). However the noise balancing is more complex and exceeds the purpose of this application.

The output depicted in Fig. 14 gives the designer a range of (m,r) parameters for whose the transformer can be designed. In order the choice of the proper (m,r) combination was more accurate, the algorithm provides an indicative analysis of leakage inductance, capacities and the overall resonant frequency. The results of such analysis are depicted below. From the results an indicative overview of the frequency response of the transformer can be obtained.

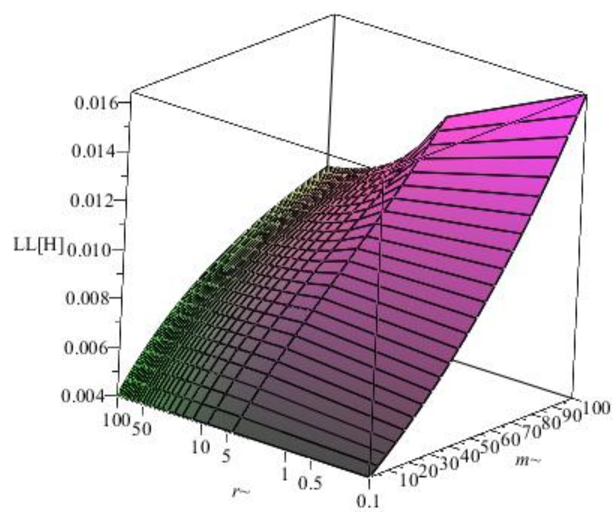

Fig. 15 – Estimation of leakage inductance dependence on (m,r) parameters

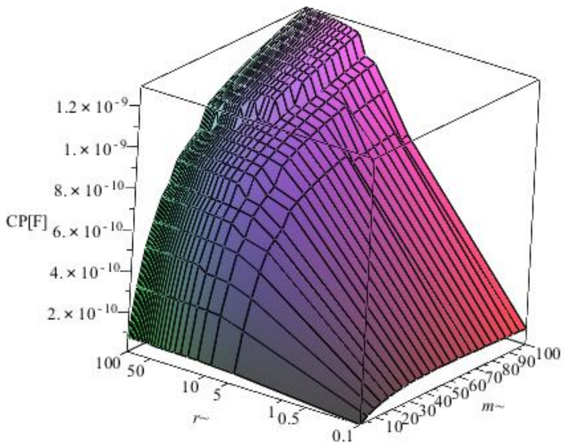

Fig. 16 – Primary winding capacity dependence on the (m,r) parameters

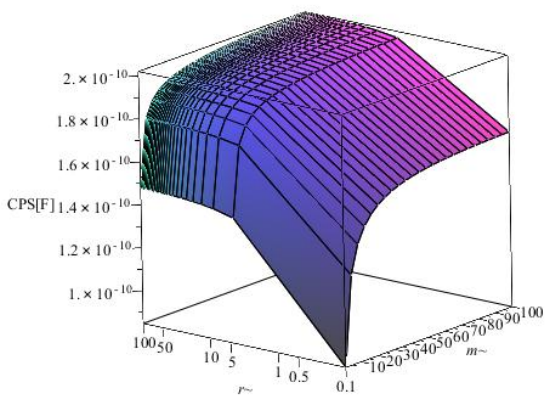

Fig. 17 – Primary to secondary winding capacity dependence on the (m,r) parameters

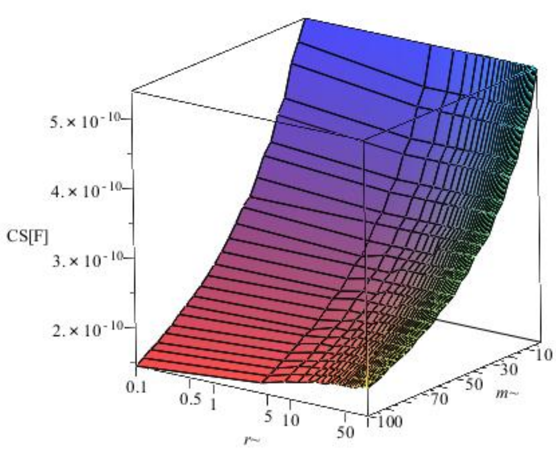

Fig. 18 – Secondary winding capacity dependence on the (m,r) parameters

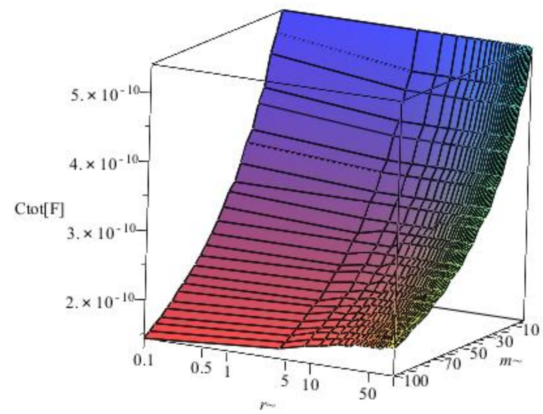

Fig. 19 – Total winding capacity recalculated to the primary side of the transformer dependence on the (m,r) parameters

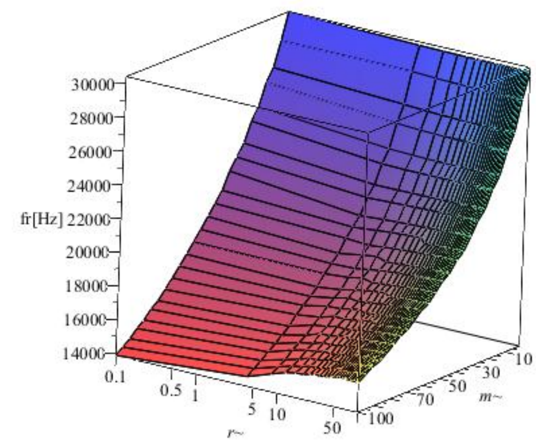

Fig. 20 – Estimated main resonant frequency of the transformer dependence on the (m,r) parameters

According to the results obtained by the algorithm the designer can decide for which parameters the transformer should be optimized. Several cases of optimization approach are described below.

A. High frequency response

From Fig. 20 it is obvious that in order the highest resonant frequency was achieved the m and r parameters of the transformer should be as low as possible.

From the Fig. 14 the parameters r = 10 and m = 25 seem to be the most convenient ones. Therefore it is worth selecting them in continuing in the transformer frequency response evaluation.

For the above mentioned parameters the algorithm returns estimated frequency response as depicted in Fig. 21.

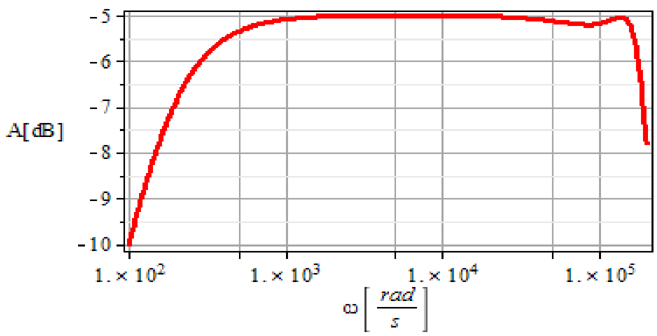

Fig. 21 – Estimated frequency response of the transformer for r = 10 and m = 25

The algorithm also allows computing the phase response and the input impedance response on demand.

As depicted in Fig. 21, the discussed transformer would be capable of operation between the frequencies 150 rad/s and 200 krad/s (24 Hz and 32 kHz), but its estimated main resonant frequency is only 23.15 kHz. If employed in the feedback loop, its frequency range should be limited below the resonant frequency.

The fact that the attenuation at the transformer is exactly – 5 dB indicates that parameters from the border of the “manufacturability function” M were applied.

B. Optimal noise balance

If the optimal noise balance is prioritized, the r parameter should be as close to 1 as possible and also the secondary winding load recalculated to the primary part when the m parameter is considered should be equal to the source resistance.

For the transformer and his operating conditions, both defined in Tab. 3, the load resistance is 15 kΩ and the source impedance is 200 Ω. In order they were equal; the secondary to primary winding ratio N should be 8.66. According to Tab. 3 N = 6. This indicates that the m parameter should be 45. Therefore one must search for the combination r = 1 and m = 45 or the closest possible one. From Fig. 14 the closest combination is r = 5 and m = 35. When the optimal noise balance is required, the designer can exploit the frequency response of the transformer for these parameters. The final frequency response is depicted in Fig. 22.

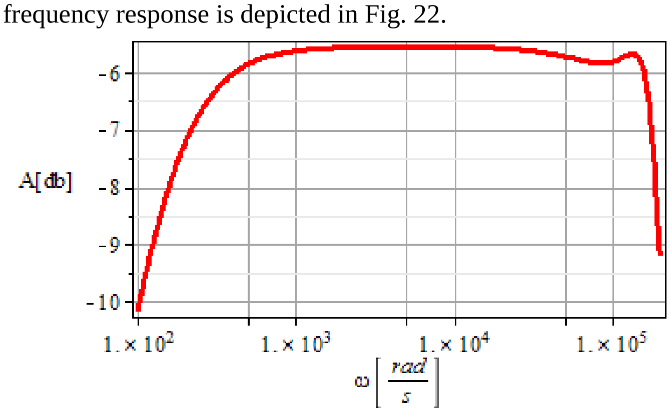

Fig. 22 - Estimated frequency response of the transformer for r = 5 and m = 35

When Fig 21. and Fig 22 are compared, one can see that the frequency response of the noise optimized transformer is worse than the frequency response of the resonant frequency optimized one. The resonant frequency of the transformer optimized for the optimal noise balance decreased to 20.6 kHz. Also the attenuation is higher than 5 dB. According to the theory discussed above, the algorithm should even not propose such combination of (m,r) parameters because the limit was set to – 5 dB. The authors believe that this error was caused by values rounding when the graph displayed in Fig. 14 was rendered. Anyway, such a slight deviation can be considered as negligible.

VI. Conclusion

In this paper a method of checking whether the transformer is manufacturable or not under the considered requirements by means of graphical expression of the winding thickness is described. Other parameters can be checked and added into evaluation of the “manufacturability function” depicted in Fig. 14 the highest values of which indicate the manufacturability of the transformer. Because this topic is quite wide, more papers as [4] and [5] has been presented in order to describe the problem of designing the small-signal audio transformers. The authors consider their research to be open and are continuing in further work on transformer optimization tasks.

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