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Application of transformer for improvement of noise performance of ultrasonic preamplifier

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Introduction

When an ultrasonic application requires addition of a preamplifier in order to provide the additional gain and signal-to-noise enhancement, transducer reception sensitivity is defined as the signal-to-noise ratio (SNR) achieved by the combined transducer and preamplifier noise performance. The transducer noise figure is independent of the receiver load impedance and depends critically on dissipative losses. The preamplifier noise figure performance requires noise matching [1]. The gain bandwidth of modern operational amplifiers is reaching 2GHz, which makes it attractive choice for a preamplifier design in ultrasonics [2-4]. Introduction of a transformer between the transducer and the preamplifier input can help to reduce this stage noise. Sources [5-7] present justification of this idea. It is analyzed how noise performance improvement can be achieved for a known source impedance. The limitation of the methods mentioned is an assumption of an ideal transformer. In this paper we are trying to get mathematical equations for complete input system, incorporating a transducer, a lossy transformer and a noisy operational amplifier, including the noise of the rest of electronics. We will try to evaluate influence of transformer parameters on a noise performance and to compare various optimum value computation methods.

Transformer model

For a most common case, when increase of the signal source impedance R_{gen} is giving rise for as $U_s \sim \sqrt{R_{gen}}$ (which is usually the case with transformer coupling), R_{gen} matching to R_{opt} (see below) allows to expect the better signal to noise ratio. In general, transformer application can be justified by three reasons: noise improvement thanks to ability to modify the source impedance, isolation and optimum power transfer thanks to impedance matching. We add the fourth one – effective operational amplifier direct current (DC) biasing is possible exploiting the transformer winding inductance. The last reason could be the exploitation of primary winding inductance for elimination of the transducer parasitic capacitance C_0. The complete transformer model is presented in Fig.1 [5].

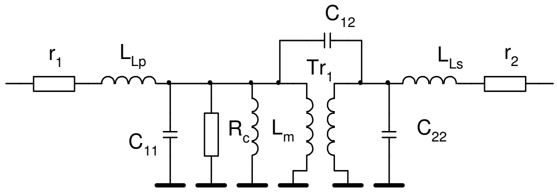

Fig. 1. **Complete transformer model**

Resistances r_1 and r_2 are presenting the losses in the primary and secondary windings, respectively. These resistances are increasing with a frequency because of the skin effect of the wire itself. Since wide-band transformers using ferromagnetic cores have fairly short wire lengths, this contribution is small and if source and load impedances are small, can be omitted. The core losses are encountered through the shunt resistance R_c. Those losses are mainly hysteresis and eddy current losses caused by the ferromagnetic material, which increases with the operating frequency as f^2 or even f^3, and are significant in the transformers that are operated near the resonance of the core material. Therefore, proper consideration must be given to the selection of the core material. The windings coupling factor defines the level of leakage inductances L_{Lp} and L_{Ls}. These inductances are small in comparison to the magnetizing inductance L_m. This inductance represents the effects, associated with a final core permeability and together with the source impedance determines the lowest operational frequency. Once operating within the transformer passband, this inductance can be omitted, since the source and the load impedances are prevailing. The cumped capacitances C_{11}, C_{22} and C_{12} are presenting the distributed capacitances resulting from interwinding coupling. In the transformers having a significant amount of wire, the interwinding capacitance can interact with the transformer inductances and create a transmission zero. Keeping in mind the frequencies of ultrasonic signals, this capacitance influence can be omitted. In further analysis we simplify the transformer model and split it depending on the case of the source impedance. In the case of a low transducer impedance only r_1 and r_2 are used since the core losses can be neglected. In the case of a high transducer impedance, the shunt resistance R_c represents the major problem, so it should be taken into account.

System noise model

It is assumed that transmission of an ultrasonic transducer noise and signal are modeled using BVD (*Butterworth-Van Dyke*) model [8]. This model is simple, but convenient for interpretation of the behavior in the near resonance frequency range. The operational amplifier is using AC coupled feedback with DC gain of unity (refer to Fig.2). The transformer having the transformation coefficient 1:n is placed between a transducer and a non-inverting operational amplifier input. The operational amplifier noise is prevailing over next stages, if the gain is large enough (>10). The operational amplifier input usually is a differential stage for voltage feedback amplifiers. Therefore the expected noise is higher than in the case of a single transistor preamplifier [7].

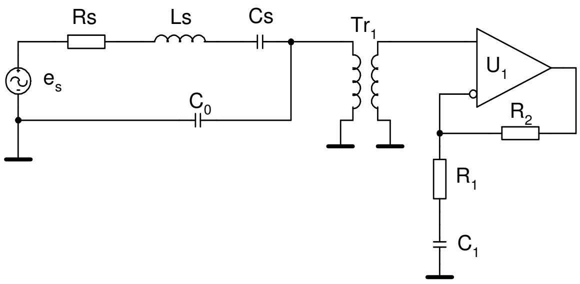

Fig. 2. **System circuit diagram**

The operational amplifier intrinsic noise can be modeled using voltage and current noise sources at the input. The operational amplifiers data sheets provide the values for noise spectral densities of those sources $i_{n+}/\sqrt{Hz}, i_{n-}/\sqrt{Hz}, e_n/\sqrt{Hz}$. The optimal source resistance R_{opt} exists, which minimizes the amplifier noise figure. It is defined as [6, 7, 9]:

$$R_{opt} = \frac{e_n}{i_{n+}}. \quad (1)$$

Table 1 gives the noise parameters of low noise representatives of FET (OPA657) and BJT (LMH6624) operational amplifiers.

Table 1. **Low noise operational amplifiers parameters**

Parameter	LMH6624	OPA657
e_n, $nV/\sqrt{Hz}$	0.92	4.8
i_n, $fA/\sqrt{Hz}$	2300	1.3
BW, MHz	1500	1500
R_{opt}, kΩ	0.4	3692
C_{in}, pF	0.9	4.5

Table 2 is used to present the two most specific ultrasonic transducer cases. One [10] is the air – coupled low impedance composite transducer. The another is also an air – coupled transducer where the matching is obtained using a special layer. This transducer is exhibiting a high electric impedance.

Table 2. **Transducer parameters**

Transducer	R_s, Ω	C_s,pF	L_s, uH	C_0, pF
Low impedance	9.3	1753	88.7	3333
High impedance	3142	38	14340	220

Winding losses model

If an ultrasonic transducer exhibits a low output impedance, only r_1 and r_2 are used and the transformer core losses can be neglected. The preamplifier noise model, incorporating the transformer *1:n* and it's winding losses is presented in Fig.3. The operational amplifier intrinsic noise is modeled using the voltage source e_n and the current noise sources i_{n+} and i_{n-}. The ultrasonics transducer has a slightly modified schematic – it is presented by the voltage source e_s, followed by the complex impedance Z_s. The transformer, except the primary and secondary winding losses r_1 and r_2, is ideal.

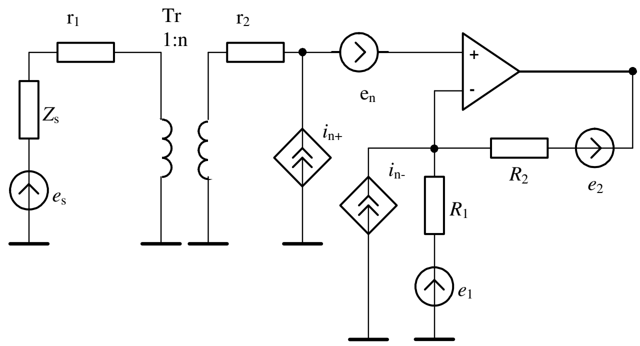

Fig. 3. **Preamplifier noise model accounting for winding losses**

The schematic above can be transformed into the equivalent circuit, presented in Fig.4.

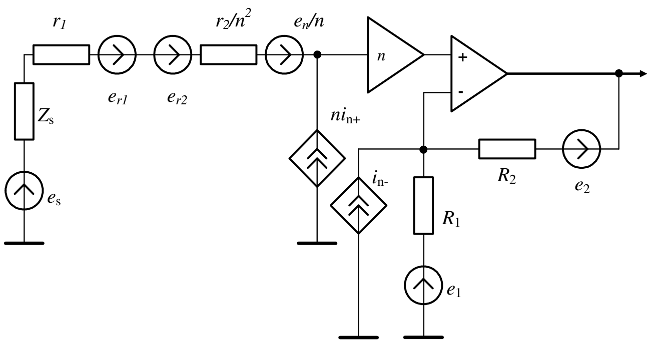

Fig. 4. **Preamplifier noise model equivalent circuit**

The noise spectral density at the operational amplifier input is given by

$$e_{ni}^2 = 4kT\left(\mathrm{Re}(Z_s) + r_1 + \frac{r_2}{n^2}\right) + \frac{e_n^2}{n^2} + \\ + i_{n+}^2 n^2 \left|Z_s + r_1 + \frac{r_2}{n^2}\right|^2. \quad (2)$$

where k=1.380658·10^{-23} [J/C] is the Boltsmann constant, T is the absolute ambient temperature in Kelvin.

In order to minimize the noise one needs to an find optimal transformation coefficient n. This can be obtained by differentiating Eq.2 by n and setting the derivative equal zero $\frac{d\left(e_{ni}^2\right)}{dn} = 0$. Usually $|Z_s| >> \frac{r_2}{n^2}$ and this component can be omitted. After simplification:

$$n_{opt} = \sqrt[4]{\frac{4kTr_2 + e_n^2 + i_{n+}^2 r_2}{i_{n+}^2 |Z_s + r_1|^2}} = \sqrt[4]{\frac{4kT\frac{r_2}{i_{n+}^2} + R_{opt}^2 + r_2^2}{|Z_s + r_1|^2}} \quad (3)$$

It can be seen that the optimal transformation coefficient n_{opt} is defined by winding losses r_1, and r_2. Usually condition $4kTr_2 << e_n^2 >> i_{n+} r_2^2$ is satisfied, therefore r_2 can be omitted:

$$n_{opt} = \sqrt[4]{\frac{R_{opt}^2}{|Z_s + r_1|^2}} = \sqrt{\frac{R_{opt}}{|Z_s + r_1|}}. \quad (4)$$

Eq.4 allows calculation of the optimal transformation coefficient when winding losses should be taken into account.

Assuming that ultrasonic transducer impedance can not be modified it makes sense to use the noise figure instead of the signal-to-noise ratio for the preamplifier noise performance analysis. The noise factor is given by [6]:

$$F = \frac{(S/N)_i}{(S/N)_o} = \frac{N_o}{N_i}\frac{S_i}{S_o}, \quad (5)$$

where $(S/N)_i$ and $(S/N)_o$ – signal to noise ratio at the input and the output correspondingly; N_i and N_o the noise power at the input and the output likewise; S_i and S_o the signal power at the input and the output respectively.

In order to calculate the signal-to-noise ratio let us get the expression for the signal level at the input:

$$S_i = \frac{U_s^2}{|Z_s + r_1|}, \quad (6)$$

where U_s is the signal amplitude at the transformer input which is a function of frequency. The exact evaluation of this voltage is not necessary since it will be divided by the output signal power:

$$S_o = \frac{(U_s \cdot n \cdot G)^2}{Z_L}, \quad (7)$$

where $G = 1 + \frac{R_2}{R_1}$ is the amplifier gain, Z_L is the amplifier load impedance. For the noise figure the signal power ratio may be obtained by dividing Eq.6 by Eq.7:

$$\frac{S_i}{S_o} = \frac{\frac{U_s^2}{|Z_s + r_1|}}{\frac{(U_s \cdot n \cdot G)^2}{Z_L}} = \frac{Z_L}{n^2 \cdot G^2} \cdot \frac{1}{|Z_s + r_1|}. \quad (8)$$

In order to calculate the noise power ratio, the input noise power density can be used:

$$N_i = \frac{U_{ni}^2}{|Z_s + r_1|} = \frac{4kT(\mathrm{Re}(Z_s) + r_1)}{|Z_s + r_1|}, \quad (9)$$

where U_{ni} is the input noise amplitude, which is the function of the real part or Z_s and r_1. The output noise power density:

$$N_o = \frac{\left[4kT(\mathrm{Re}(Z_s) + r_1) + \frac{e_n^2}{n^2} + i_{n+}^2 n^2 |Z_s + r_1|^2\right] G^2 n^2}{Z_L} + \\ + \frac{(G-1)e_1^2 + e_2^2 + i_{n-}^2 R_2^2}{Z_L}. \quad (10)$$

Eq.10 contains additional noise components, which are caused by the external resistances R_1, R_2, (refer to Fig.2). The criteria for selection of the resistances R_1, R_2 in order to minimize their noise contribution and resulting noise analysis are presented in [3]. When the gain is large enough (G>>1) and the selection criteria are obeyed, these additional components can be removed from equation. The resulting noise ratio is

$$\frac{N_0}{N_i} = \frac{G^2 n^2 |Z_s + r_1| \left[4kT(R_s + r_1) + \frac{e_n^2}{n^2} + i_{n+}^2 n^2 |Z_s + r_1|^2\right]}{4kT(\mathrm{Re}(Z_s) + r_1) Z_L}. \quad (11)$$

Inserting Eq.8 and 11 to Eq.5 after some simplification we obtain:

$$F = 1 + \frac{e_n^2}{4kTn^2(\mathrm{Re}(Z_s) + r_1)} + \frac{i_{n+}^2 \cdot n^2 |Z_s + r_1|^2}{4kT(\mathrm{Re}(Z_s) + r_1)}. \quad (12)$$

The noise figure:

$$NF = 10\lg F = 10\lg\left(1 + \frac{e_n^2}{4kTn^2(\mathrm{Re}(Z_s) + r_1)} + \frac{i_{n+}^2 n^2 |Z_s + r_1|^2}{4kT(\mathrm{Re}(Z_s) + r_1)}\right). \quad (13)$$

After inserting Eq.4 into Eq.12 and Eq.13 we get the minimal noise factor and the noise figure:

$$F_{\min} = 1 + 2\frac{e_n \cdot i_{n+} |Z_s + r_1|}{4kT(\mathrm{Re}(Z_s) + r_1)}. \quad (14)$$

$$NF_{\min} = 10\lg\left(1 + 2\frac{e_n \cdot i_{n+} |Z_s + r_1|}{4kT(\mathrm{Re}(Z_s) + r_1)}\right). \quad (15)$$

Core losses model

If an ultrasonic transducer has a high output impedance, the shunt resistance R_c represents the major problem, so it should be taken into account. The winding losses r_1 and r_2 can be neglected in such case. Fig.5 indicates the preamplifier equivalent circuit for modeling of noise performance when transformer core losses are included.

Using the circuit presented above we calculate the noise spectral density at the preamplifier input:

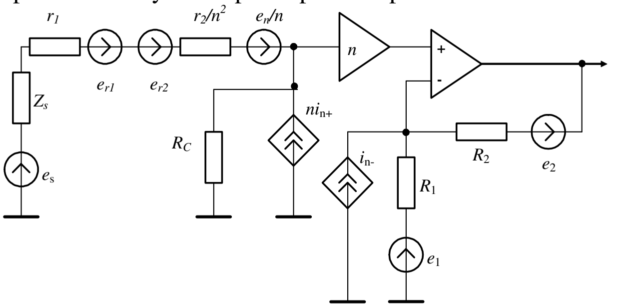

Fig. 5. **Core losses incorporating preamplifier noise model**

$$e_{ni}^2 = 4kT\,\mathrm{Re}\left(\mathrm{Re}(Z_s) + r_1 + \frac{r_2}{n^2}\right)\frac{R_c^2}{\left|Z_s + r_1 + \frac{r_2}{n^2} + R_c\right|^2} + \frac{e_n^2}{n^2} + i_{n+}^2 n^2 \frac{\left|Z_s + r_1 + \frac{r_2}{n^2}\right|^2 R_c^2}{\left|Z_s + r_1 + \frac{r_2}{n^2} + R_c\right|^2}. \tag{16}$$

In order to simplify the equation, it is assumed that both r_1 and r_2/n^2 are much smaller than $|Z_s|$, then from Eq.16:

$$e_{ni}^2 = 4kT\,\mathrm{Re}(Z_s)\frac{R_c^2}{|Z_s + R_c|^2} + \frac{e_n^2}{n^2} + i_{n+}^2 n^2 \frac{|Z_s R_c|^2}{|Z_s + R_c|^2}. \tag{17}$$

In the same way as for Eq.3 we find the optimal transformation coefficient when the core losses are taken into account:

$$n_{opt} = \sqrt{R_{opt}\frac{|Z_s + R_c|}{|Z_s R_c|}}. \tag{18}$$

The similar method can be used for the noise factor:

$$F = 1 + \frac{e_n^2 |Z_s + R_c|^2}{4kT\,\mathrm{Re}(Z_s) R_c^2 n^2} + i_{n+}^2 \frac{|Z_s|^2 \cdot n^2}{4kT\,\mathrm{Re}(Z_s)}. \tag{19}$$

Inserting Eq.18 into Eq.19 we get the minimal noise factor:

$$F_{\min} = 1 + 2i_{n+}\frac{e_n |Z_s + R_c| \cdot |Z_s|}{4kT\,\mathrm{Re}(Z_s) R_C}. \tag{20}$$

The noise figure is given by

$$NF = 10\lg\left(1 + 2 \cdot i_{n+}\frac{e_n |Z_s + R_c| \cdot |Z_s|}{4kT\,\mathrm{Re}(Z_s) R_C}\right). \tag{21}$$

Lossless model

It should be noted that both cases analyzed above are using the amplifier noise parameters the voltage source e_n and the current noise sources i_{n+} and i_{n-}. In the case when FET amplifier is used, the sources i_{n+} and i_{n-} disappear for a conventional ultrasonic transducer. One would be interested to calculate an optimal transformer turns ratio, omitting transformer losses. Solution for such case is given in literature [11]. An equivalent circuit diagram is presented in Fig.6.

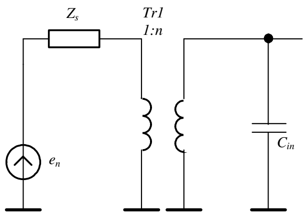

Fig. 6. **Lossless transformer preamplifier noise model**

Application of a noiseless transmission circuit with the gain K allows improvement of the noise factor

$$F = 1 + \frac{1}{K^2}\cdot\frac{R_{namp}}{R_{neq}}, \tag{22}$$

where R_{namp} is the amplifier noise modeling resistance, R_{neq} is the ultrasonic transducer equivalent noise resistance. The transformer load is accounted as the amplifier input capacitance C_{in}. The transmission coefficient of such a circuit is maximized when

$$n = \frac{1}{\sqrt{\omega C_{in}|Z_s|}}. \tag{23}$$

Then the noise factor can be calculated:

$$F_{\min} = 1 + 2\omega C_{in}|Z_s| \cdot \frac{R_{namp}}{R_{neq}}. \tag{24}$$

Model application results

The optimal turns ratio n_{opt} can be determined using Eq.3 and Eq.4 for a low impedance transducer (refer a Table 2.). For this purpose the transformer parameters need to be evaluated. Measurement results of 1:3 transformers dedicated for a high source impedance, low frequency (high L_m is needed) and low source impedance, high frequency, are presented in Table 3 and core loss behavior versus frequency measurement results are shown in Fig.7.

Table 3. **Transformer parameters**

Parameter	L_m	r_1	r_2	L_{LP}	L_{LS}
For low Z_s	0.95mH	0.3 Ω	1.7 Ω	0.12uH	1.08uH
For high Z_s	10mH	5.1 Ω	28 Ω	2uH	7uH

The operational amplifiers using FET input exhibit an extremely low current noise i_{n+} and i_{n-}. Therefore R_{opt} is a megaohms range (refer to Table 1). The source [9] recommends using those when the source impedance is high. If Eq.4 is used for a low impedance transducer (refer to Table 1) the turns ratio n_{opt} becomes very high (~200). The realization of such a transformer will get too complicated. The amplifiers using BJT exhibit a lower voltage noise e_n, but much higher current noises i_{n+} and i_{n-}. Therefore R_{opt} is in a hundreds ohms range. Application of a step-up transformer in such case increase the ultrasonic transducer impedance by n^2. The turns ratio n_{opt} have reasonable values, which can be achieved in practice.

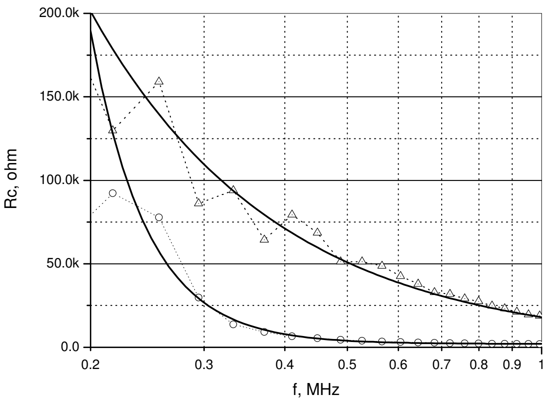

Fig. 7**. Measured core losses R_c**

Therefore for a low impedance transducer we use only BJT amplifier. Fig.8. is indicating the ratio n_{opt} change versus frequency for two transformer winding resistances (refer to Table 3).

As can be seen from Fig.8, n_{opt} is changing in a wide range. In practice such transformer is not realizable. Therefore only one value of n_{opt} should be used. Let us examine how noise performance will degrade in such a case. Fig.9 is indicating the noise figure for a theoretical case when the ratio n_{opt} is maintained over a whole frequency range (the solid curve). The other curves indicate the various alternatives, when the transformation ratio is fixed. The case n=1 (dot-dash curve) is when no transformer is used.

The transducers under analysis are using the series a transformer resonance frequency range, therefore application of turns to be useful here. The noise figure versus frequency and the transformation coefficient contour plots are useful for choosing the right turns ratio in a desired frequency range (refer to Fig.10).

In the same way noise reduction of a high impedance transducer with a transformer application may be analyzed.

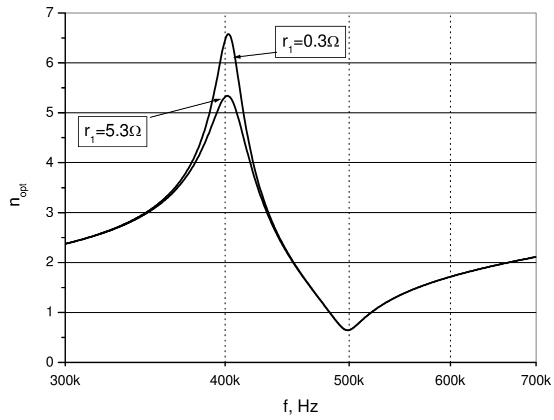

Fig. 8. **Low impedance transducer n_{opt} when winding losses accounted**

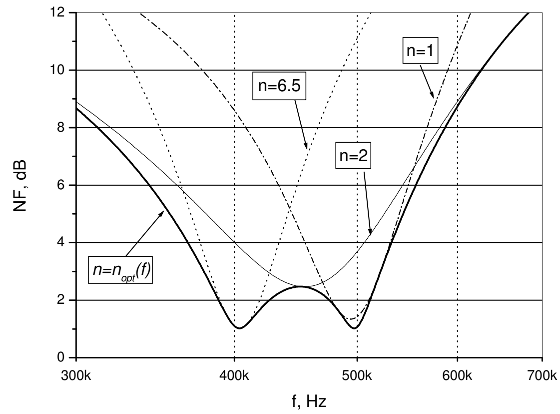

Fig. 9. **Noise figure for a low impedance transducer**

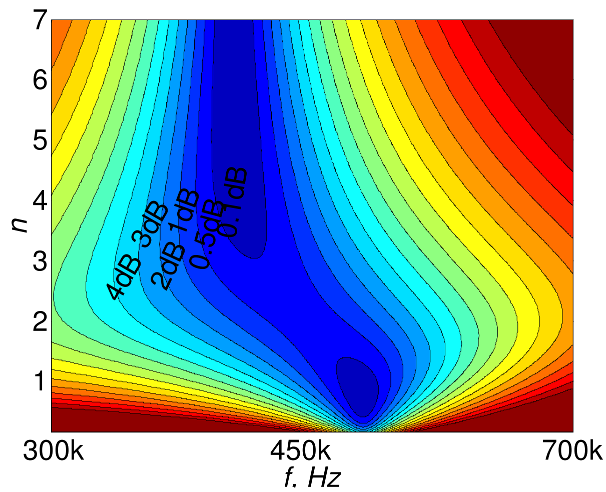

Fig. 10. **Noise figure contour plots for a low impedance transducer.**

Here the operational amplifiers using FET input are main candidates, since they exhibit an extremely low current noise, which in turn will allow lowering the noise component due to $i_{n+}/Z_s/$. The R_c losses should be accounted here so n_{opt} is calculated using Eq.18. The n_{opt} shape is similar to Fig.7 with turns the ratio value equal 42 at the ultrasonic transducer series resonance and 28 at the parallel resonance. Such ratios are not practical. Again, n_{opt} is varying with frequency, therefore such a transformer can not be realized. Investigation of a noise performance with fixed n revealed that degradation at the lower than optimum transformation coefficient is not significant. The noise figure change versus frequency and the transformation coefficient contour plots are presented in Fig.11 (OPA657 amplifier) and Fig.12 (LMH6624).

It should be noted here that the transformation coefficient n for BJT amplifier is lower than 1, e.g. the step-down transformer should be used.

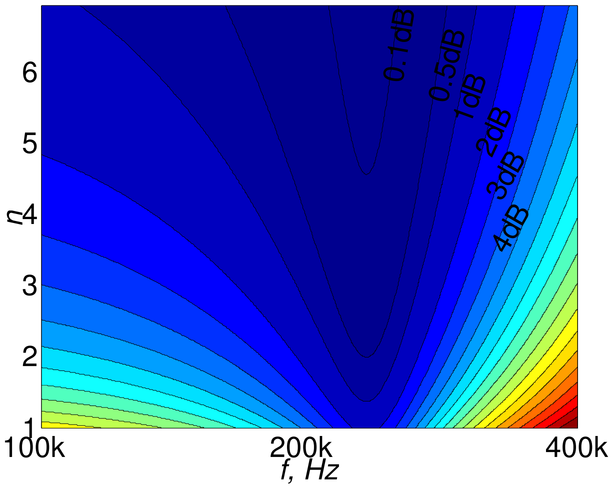

Fig. 10. **NF for high impedance transducer and FET amplifier**

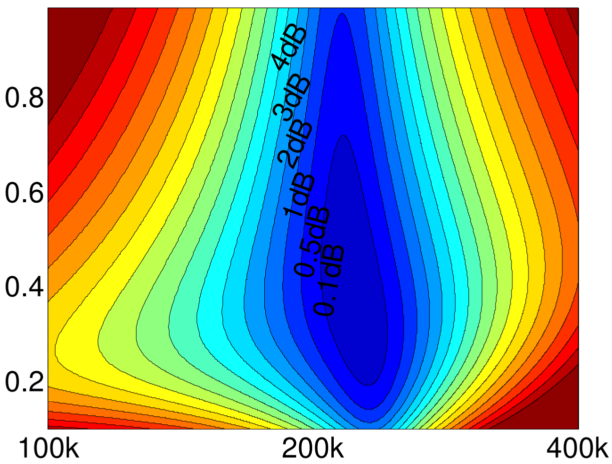

Fig. 11. **NF for high impedance transducer and BJT amplifier**

If FET amplifier is used, Eq.23 can be used for calculation of n_{opt}. The calculation results indicate the turns ratio value equal 9 at the ultrasonic transducer series resonance and 5.5 at the parallel resonance.

Conclusions

Application of a transformer can be justified by five reasons: noise improvement by modification of the source impedance, isolation, optimum power transfer, transformer winding inductance exploiting for amplifier DC biasing and elimination of the transducer capacitance C_0. Unfortunately, the transformation coefficient can not be varied over the frequency, therefore degradation of the noise figure is expected due to the non-optimal n. The high turns ratio will degrade the bandwidth and losses performance. Therefore a low turns ratios should be considered. Analysis has shown that the degradation is not significant even using lower than the required n values.

Theoretical analysis indicates that in the case of a high impedance ultrasonic transducer matching to BJT (low R_{opt}) application of a step-down transformer is necessary. This idea requires examination of the signal-to-noise ratio for further proof.

Further noise improvement analysis using a transformer should be proven by experimental investigations.

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Transformatorių naudojimas ultragarsinio trakto pradinio stiprintuvo triukšmo charakteristikoms pagerinti

Reziumė

Nagrinėjama, kaip transformatoriai galėtų pagerinti stiprintuvo triukšmines charakteristikas pradiniame jo laipsnyje. Transformatorių nuostoliai modelyje buvo įvertinti apvijų nuostolių varžomis esant mažiems ultragarsinio keitiklio išėjimo impedansams. Esant dideliems ultragarsinio keitiklio išėjimo impedansams, šerdies nuostoliai modelyje vertinami

nuostolių varža R_C. Nesant galimybės keisti ultragarsinio keitiklio vidinio impedanso, triukšminei analizei prasminga naudoti triukšmo koeficientą, o ne signalo ir triukšmo santykį. Gautos išraiškos transformatorių su nuostoliais triukšmo koeficientui apskaičiuoti naudojant skirtingus elektroninės dalies modelius. Remiantis šiomis išraiškomis sudarytos formulės transformatorių su nuostoliais optimaliems transformacijos koeficientams apskaičiuoti. Pateikti konkrečių ultragarsinių keitiklių ir operacinių stiprintuvų optimalaus transformacijos koeficiento ir triukšmo koeficiento skaičiavimų rezultatai.

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