THE ULTRASONIC TRANSDUCER PREAMPLIFIER NOISE PERFORMANCE

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Abstract

The preamplifier noise performance is important in the case of a medical ultrasonic inspection.

In this paper we analyze the noise by using the complete mathematical model for input stage, incorporating transducer, transformer, operational amplifier and the external passive components. The analysis is used for noise parameters prediction. The theoretical results have been tested experimentally. The system for signal propagation and an absolute noise level measurement over the frequency range has been developed. The experimental results have been used to calculate the noise performance.

The theoretical and experimental investigation confirmed the ability to improve the ultrasonic preamplifier noise performance.

1. Introduction

In medical ultrasonic inspection transmitted power is limited in order to protect the tissue. This will limit transducer reception sensitivity [1-3].

Therefore improving the preamplifier noise response is very important. Noise performance can be defined by absolute noise level, signal-to-noise ratio (SNR), noise figure (NF) [4, 5]. All the above can be analyzed either as the frequency-dependent response or as root-mean-square (RMS) integral over passband.

The input circuitry, the amplifier external components and its topology influence the noise and signal propagation to the output. Transformer introduction between the transducer and the preamplifier input can be used to alter SNR of the input stage [6-8].

In order to analyze the noise performance the mathematical model is needed for complete preamplifier schematics [9, 10].

2. Noise model

The gain bandwidth of modern operational amplifiers is reaching 2GHz, which makes it attractive choice for preamplifier design in ultrasonics. Therefore we limit our investigation to the operational amplifier schematics.

2.1. General preamplifier model

We decided to use the analytical model incorporating both transducer and electronics [7]. Then the noise sources can be separately analyzed.

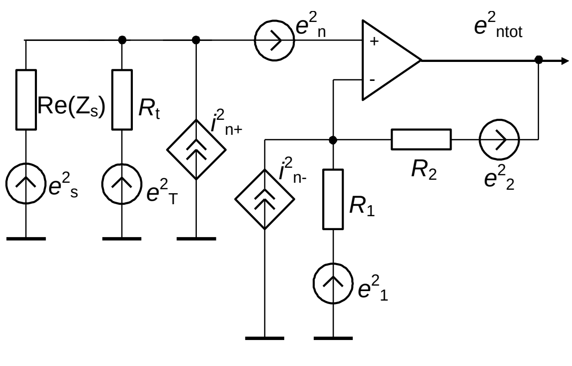

Figure 1. Noise model circuit

The ultrasonic transducer noise and signal transmission is modelled using BVD (*Butterworth-Van Dyke*) model [9]. The noise spectral density of the is input resistance R_t

$$e_T^2 = 4kTR_t \,, \qquad (1)$$

where k is the Bolzmann constant, T is the absolute ambient temperature.

The transducer noise spectral density is determined by the real part of the transducer impedance [4]

$$e_s^2 = 4kT\,\mathrm{Re}(Z_s)\,. \qquad (2)$$

The feedback circuit resistors contribute the noise densities

$$e_1^2 = 4kTR_1\,; \quad e_2^2 = 4kTR_2\,. \qquad (3)$$

Operational amplifier intrinsic noise is modelled using voltage source e_n and current noise sources i_{n+} and i_{n-}. With the amplifier noise gain

$$G = \frac{R_1 + R_2}{R_1} \qquad (4)$$

we get the equation for the output noise density calculation:

$$e_{ntot}^2 = \left|\frac{GR_t}{R_t + Z_s}\right|^2 e_s^2 + \left|\frac{GZ_s}{R_t + Z_s}\right|^2 e_T^2 + \\ + \left|\frac{GR_tZ_s}{R_t + Z_s}\right|^2 i_{n+}^2 + G^2 e_n^2 + \\ + (G-1)^2 e_1^2 + e_2^2 + R_2^2 i_{n-}^2 \qquad (5)$$

Similar way one can obtain the expression for signal at the amplifier output [5]. Then noise figure [6]:

$$NF = 10\lg\frac{SNR_i}{SNR_o}\,. \qquad (6)$$

where – SNR_i and SNR_o – signal to noise ratio at the at input and output. Optimal source resistance R_{opt} exists minimizing the amplifier NF [4]:

$$R_{opt} = \frac{e_n}{i_{n+}}\,. \qquad (7)$$

For reference, R_{opt} for OPA657 is 3.7 MΩ and 400 Ω for LMH6624.

2.2. Transformer model

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. It also allows effective operational amplifier biasing via transformer winding inductance.

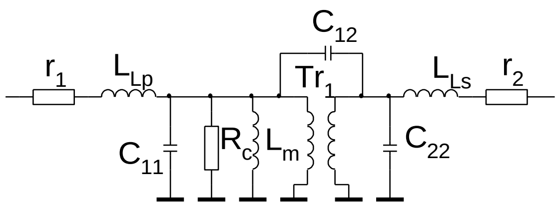

Figure 2. Complete transformer model

Resistance r_1 and r_2 are presenting the losses in the primary and secondary windings, respectively. The core losses are encountered through shunt resistance R_c. The coupling factor defines the level of leakage inductances L_{Lp} and L_{Ls}. The magnetizing inductance L_m represents the effects, associated with final core permeability. Lumped capacitances C_{11}, C_{22} and C_{12} are presenting the distributed capacitances.

3. Modelling results

In order to evaluate the importance and influence of circuit parameters, we now can investigate equation (5) noise components. The preamplifier with and without the transformer are studied.

3.1. Preamplifier noise

We have chosen three amplifiers as representatives of achievable limits. One (LMH6624, BJT amplifier) is presenting the lowest e_n, other (OPA657, FET amplifier) is exhibiting the lowest i_n and the third (AD8009) is a current feedback amplifier. To ignore the R_1 and R_2 noise, e_1 and e_2 has to be 1/3 of e_n contribution. According to the results [3], the optimal values are R_1=10Ω, R_2=1kΩ. The obtained NF for R_t=10 kΩ is presented in Figure 3.

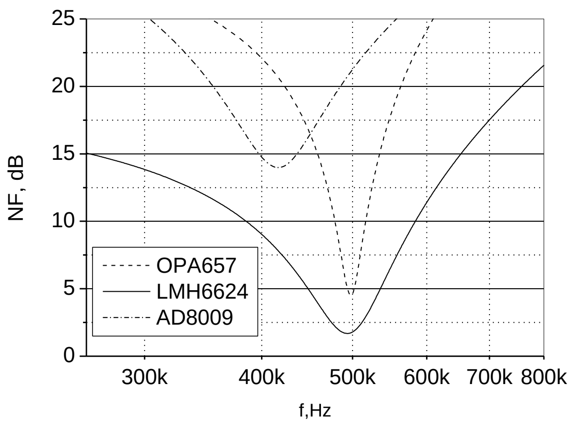

Figure 3. Preamplifier NF vs. frequency

It's clear that in the case analyzed LMH6624 exhibits lowest noise figure.

3.2. Preamp with transformer

We simplify the transformer model and split it depending on transducer output impedance case. In case of low transducer impedance only r_1 and r_2 are used since core losses can be neglected. In case of high transducer impedance, shunt resistance R_c represents the major concern, so it should be taken into account.

3.2.1. Winding losses model

If ultrasonic transducer exhibit low output impedance, only r_1 and r_2 are used and transformer core losses can be neglected. Now the preamp noise model incorporates the transformer *1:n* and it's winding losses.

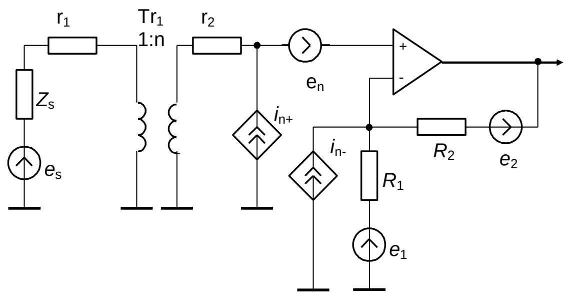

Figure 4. Model for winding losses

The noise spectral density and the signal level at the preamplifier input and output are evaluated as above. Turn to results in our publication [8] for complete explanation.

The noise figure is minimal for optimal transformation coefficient.

$$n_{opt} = \sqrt[4]{\frac{4kTr_2 + e_n^2 + i_{n+}^2 r_2}{i_{n+}^2 \left|Z_s + r_1\right|^2}} \quad . \qquad (8)$$

It can be seen from the equation above that the optimal turns ratio n_{opt} if winding losses should be taken into account is defined by r_1, and r_2. Usually $4kTr_2 << e^2_n >> i_{n+}r_2^2$ is satisfied, therefore r_2 can be omitted. Figure 5 is indicating the ratio n_{opt} change versus frequency for two transformer winding resistances.

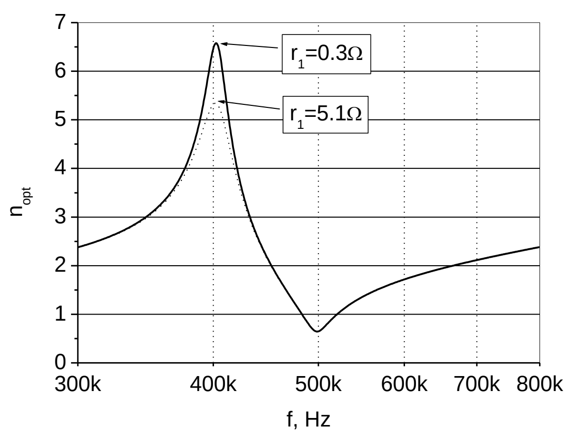

Figure 5. Optimal turns ratio n_{opt}

As can be seen from the Figure 5 n_{opt} is changing in wide range. In practice such transformer is not realizable.

Therefore only one value of *n* can be used. Then the noise figure variation versus frequency and transformation coefficient *n* contour plots get useful for choosing the right turns ratio (refer to Figure 6).

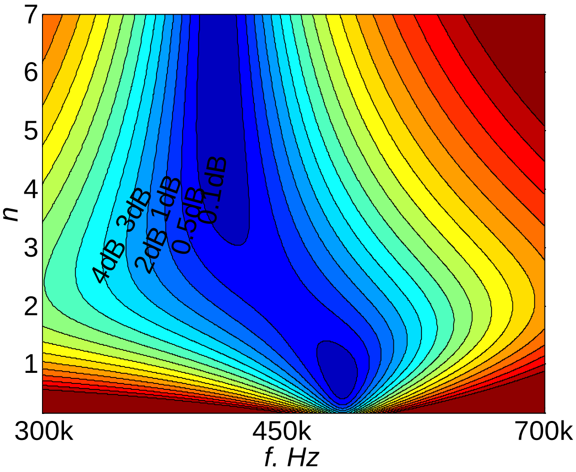

Figure 6. NF vs. frequency and turns ratio for low impedance transducer

Figure 6 indicates that noise figure is degraded due to non-optimal *n.*

3.2.2. Core losses model

If ultrasonic transducer has high output impedance, shunt resistance R_c represents the major concern, so it should be taken into account. Winding losses r_1 and r_2 can be neglected in such case. The resulting noise figure is presented in Fig.7 (for FET) and Fig.8 (for BJT).

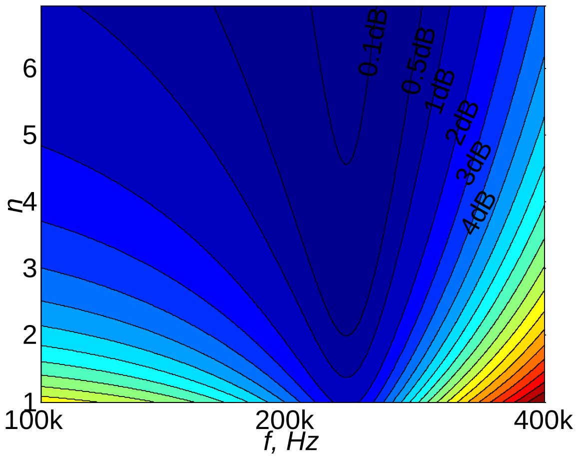

Figure 7. NF vs. *f* and *n* for high Z_s transducer used with FET amplifier

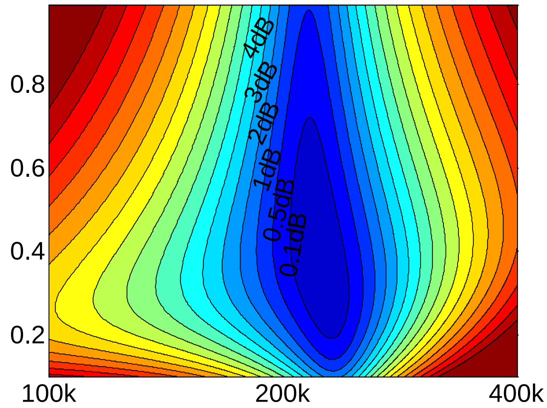

Figure 8. NF vs. *f* and *n* for high Z_s transducer used with BJT amplifier

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

4. Experimental investigation

The obtained theoretical results have been investigated experimentally. The noise figure measurement for signal source with complex output impedance is complicated. Therefore the signal, noise and SNR improvement have been measured in experimental verification.

4.1. The system

The system for signal propagation and absolute noise level measurement over the frequency range has been developed. The programmable DDS generator is used for the transmitting transducer excitation. The variable gain amplifier and A/D converter are used for data acquisition. The tested preamplifier is inserted immediately after the receiving transducer.

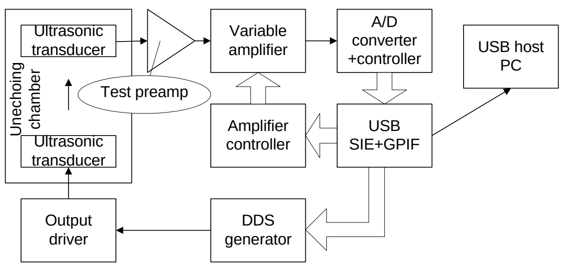

Figure 9. Measurement system

Data is collected and all the processing accomplished in host PC, connected via USB 2 interface.

4.2. Noise measurement

Noise measurement is done by taking the FFT of the signal at the tested preamp output (no excitation).

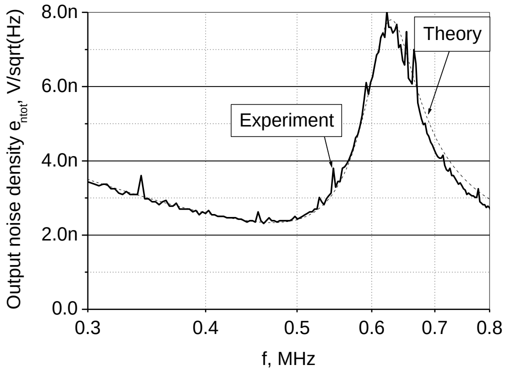

Figure 10. Measured vs. theory noise

Results in Figure 10 present noise spectral density at preamp input. The theory values are calculated using equation (5) divided by equation (4).

Same way the results for the transformer matching investigation have been obtained. Other type, air-coupled ultrasonic transducers have been used for next investigation. Same operational amplifiers have been used. Figure 11 is representing the results for experimentally obtained noise spectral density. Figure 12 is for measured signal spectral density. Figure 13 is for calculated SNR improvement when transformer matching is applied.

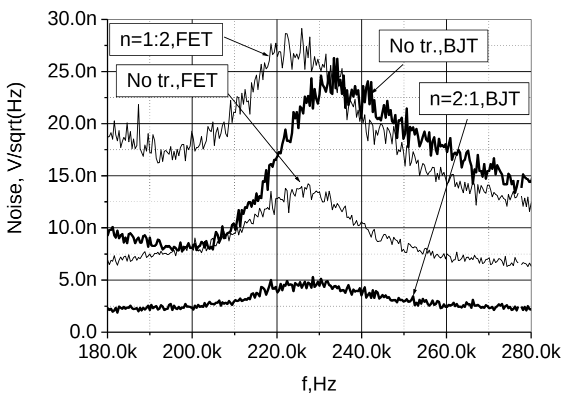

Figure 11. Measured noise

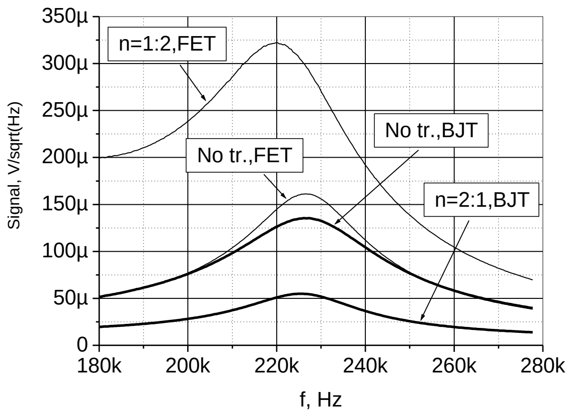

Figure 12. Measured signal

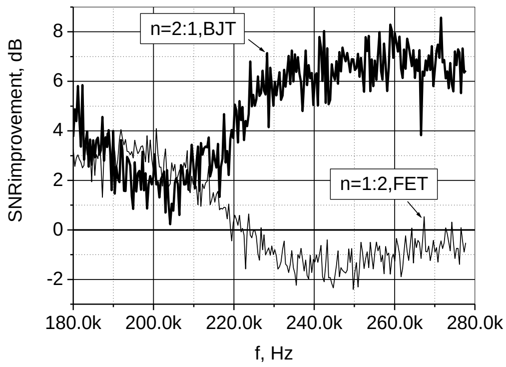

Figure 13. SNR improvement

5. Conclusions

The theoretical and experimental investigation confirmed the ability to improve the ultrasonic preamplifier noise performance basing the theoretical analysis. In the particular application analysed transformer application allows for 7dB SNR improvement. The improvement is confirmed using the measurement system described.

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