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The RF transformer application for ultrasound excitation: the initial study

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Abstract

Practical aspects of design and application radio frequency (RF) transformers in an ultrasonic system excitation channel are analysed. Design steps are discussed for those willing to design their own transformer an for excitation channel. Investigation has been carried out on what generator parameters can be obtained if instead of a purely active output stage the impedance matching RF transformer is used. It is assumed that a low output impedance active stage is coupled to a relatively high impedance ultrasonic transducer. An air coupled ultrasonic transducer has been used as a reference for the calculations. Several materials are considered for the RF transformer core and possible candidates and their properties for 10kHz to 10MHz frequency range are listed. The algorithm for performance investigation using only manufacturer parameters and the Matlab modeling has been presented. The experimental study has confirmed RF transformer suitability as a voltage step-up component for ultrasonic transducer excitation. The 0.1…10 MHz passband is achieved. The results obtained at different transmitted power levels (from 50μW to 0.5W) indicate there is only slight reduction in the bandwidth. The presented configuration can be used for ultrasonic transducer excitation using an arbitrary waveform generator.
Keywords: ultrasonic NDT, ultrasonic transducer excitation, transformer insertion loss, transformer model.

Introduction

The radio frequency (RF) transformers are extensively used in electronics – switched mode power supplies, control and automation circuits, telecommunication equipment and ultrasonics [1-4]. In common sense RF transformer application can be justified by three reasons: the need for the inductive element, direct current (DC) isolation and the impedance matching. The impedance matching allows for maximum power transfer, i.e. the signal voltage step-up. Source impedance modification, matching the amplifier noise optimal impedance, permits the signal to noise ratio (SNR) improvement [5, 6]. The transformer also allows the effective amplifier input DC biasing thanks to winding inductance. The influence of the transformer parameters on a preamplifier noise performance and their electrical parameters measurement was analyzed in [7].

In this paper we are analyzing the practical aspects of RF transformers design and application in a ultrasonic system excitation channel. The need for the high SNR at the receiving transducer requires to supply a high power to the exciting transducer. This task is complicated if a high impedance ultrasonic transducer is used. This is the case when the transmitting transducer possesses a high impedance or a relatively low impedance transducer is used for both transmission and reception of the signal. In such case a large voltage is required for excitation. Therefore, a quite attractive solution is increase of the transducer excitation voltage using a step-up transformer. Practical design steps are discussed for those willing to design their own transformer for an excitation channel.

The transformer model for excitation

An important component of every ultrasonic system is the high voltage pulse generator used for transducers excitation. Designing of a suitable generator with a (100-400)V output pulse is complicated. We shall investigate what generator parameters can be obtained if instead of a purely active output stage impedance matching the RF transformer is used. We assume that a low output impedance active stage is coupled to a high impedance ultrasonic transducer. The equivalent circuit diagram is presented in Fig.1.

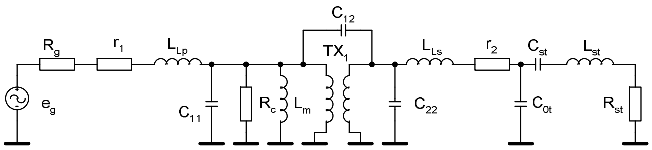

Fig. 1**. Transformer coupled excitation equivalent circuit**

The losses in the primary and secondary windings are presented by r_1 and r_2. The shunt resistance R_c accounts core losses. The coupling quality is defined by the leakage inductances L_{Lp} and L_{Ls}. The final core permeability is presented by the magnetizing inductance L_m. The lumped capacitances C_{11}, C_{22} and C_{12} are presenting the distributed capacitances resulting from the interwinding coupling.

The analysis of such circuit performance is complicated. Besides, the results will always be bind to a particular ultrasonic transducer. Furthermore, methods exist [8, 9] allowing to absorb or eliminate by resonance the imaginary part of ultrasonic transducer impedance. Therefore, we may simplify our analysis to a purely resistive load. The load will represent the real part of the ultrasonic transducer impedance. The simplified circuit for a low frequency region is presented in Fig.2. The equivalent circuit for a high frequency region is the same as presented in Fig.1, only L_{m} is removed and the transducer model can be replaced by R_{L}.

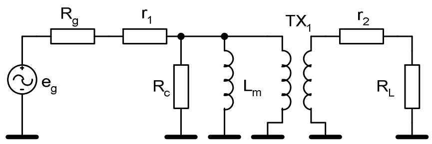

Fig. 2. **Low frequency region equivalent circuit**

The primary coil magnetizing impedances should be sufficient to prevent shunting of the signal source. Using Fig.2 we evaluate the lowest passband (-3dB) frequency:

$$f_L = \frac{R_{src} R_{ld}}{2\pi L_m} \cdot \frac{1}{\sqrt{R_{ld}^2 - R_{src}^2 - 2R_{src}R_{ld}}}, \qquad (1)$$

where:

$$R_{ld} = \frac{R_c \dfrac{(R_L + r_2)}{n^2}}{R_c + \dfrac{(R_L + r_2)}{n^2}}, R_{src} = R_g + r_1$$

From Eq.1 one can obtain the necessary magnetizing inductance value L_m:

$$L_m = \frac{R_{src} R_{ld}}{2\pi \cdot f_L \sqrt{R_{ld}^2 - R_{src}^2 - 2R_{src}R_{ld}}}. \qquad (2)$$

The secondary winding impedance together with the leakage inductance and the parasitic load capacitor together with the load capacitance form a low-pass filter that dictates the higher cutoff frequency of the circuit. Therefore, a trade-off exists between the turns ratio of the transformer and the bandwidth of the circuit (R_s is fixed). When the turns' ratio is increased, this usually is done increasing the secondary windings number. This will increase the parasitic capacitance and leakage inductance, lowering the highest cutoff frequency. If those parasitic components are absorbed into matching circuit, this would increase the bandwidth even at an increased number of secondary turns.

The core material properties analysis

If the transformer is dedicated for low frequency applications high permeability ferrite materials should be considered [10-13]. The possible candidates and their properties for 10kHz to 10MHz frequency range are listed in Table 1. Transformer properties can be varied by using different magnetic core materials. The general composition of ferrites is Fe_2O_4 combination with the divalent transition metals such as manganese (Mn), zinc (Zn), nickel (Ni), cobalt (Co), copper (Cu), iron (Fe) or magnesium (Mg). The most popular combinations are manganese and zinc (MnZn) or nickel and zinc (NiZn). The compounds can easily be magnetized and have a rather high intrinsic resistivity. These materials can be used up to very high frequencies without laminating, as is the normal requirement for magnetic metals.

Table 1. **Candidate ferrite material properties**

Brand	61	43	3F3	J	T38	H5C3	Magnaperm
Manufacturer	Fair Rite	Amidon	Ferroxcube	Magnetics	EPCOS	TDK	Metglas
Initial permeability, μ_i	125	850	2000	5000	10000	15000	72000
Volume resistivity ,Ω-cm	10^8	10^5	10^2	10^2	$0.15\ 10^2$	$0.1\ 10^2$	$0.14\ 10^{-3}$
Loss factor, tan $\delta/\mu_i\ 10^{-6}$	32@2.5MHz	20@1MHz	4.5 @0.1MHz	15 @0.1MHz	7.0 @0.1MHz	15 @10kHz	-
Resonant circuit freq, MHz	0.2…10	0.01…1	0.001…2	0.001…1	0.001…0.25	0.001…0.15	0.0001…0.01
Wideband circuit freq, MHz	10…200	1…50	0.5…30	1…15	0.001…1	0.001…1	0.0001…0.5
Material	NiZn ferrite	MnZn ferrite	MnZn ferrite	MnZn ferrite	MnZn ferrite	MnZn ferrite	Co all. 2714A

Ferrite is a semiconductor with a DC resistivity in the crystallites. NiZn ferrites have a very high resistivity (30 Ωm) and are most suitable for frequencies over 1 MHz. MnZn ferrites (10^{-3} Ωm) exhibit higher permeability (μ_i) and saturation induction levels (Bs) and are suitable up to 3MHz. Since there is an isolating layer between the crystals, the bulk resistivity is much higher: 0.1 to 10 Ωm for MnZn ferrites and 10^4 to 10^6 Ωm for NiZn and MgZn ferrites.

The data in Table 1 are sorted by initial permeability increase order. Unfortunately, the higher is the permeability, the higher are the core losses, associated with excessive heating. In order to have the comparative evaluation of the loss factor, it has been normalized by the permeability μi. The lowest losses exhibit the Fair-Rite type 61. These materials are by far the most widely used for RF applications because of their low loss, high saturation flux and a wide variety of shapes and sizes that are available. This material is not much suitable for our purposes due to demand for a high permeability. The same conclusion (too low permeability) can be applied to Amidom 43. Due to a high permeability demand, the Metglas material Magnaperm seems to be most suitable. It is manufactured with the cobalt-based Metglas amorphous alloy 2714A. These flat loop toroidal cores offer a unique combination of an ultra-high permeability, a high saturation flux density and extremely low core losses. This is a novel material and the manufacturer claims that it is suitable for high frequency applications [13]. Therefore, samples have been ordered and the material has been investigated for suitability for application in the 10 kHz to 10 MHz frequency range.

Ferroxcube 3F3 (similar to Fair-Rite type 77 and EPCOS N27), EPCOS T38 (similar to Magnetics and Amidon W) and Metglas material Magnaperm have been chosen for further investigation. In such a way majority of materials lusted in Table 1 are covered. The materials magnetic properties have been taken from manufacturer data sheets and converted into a digital file for further data processing.

A core influence on a coil is expressed by the complex permeability μ' (inductance) and μ'' (resistance). In general, the complex permeability μ' and μ'' are frequency, temperature, flux density and DC biasing dependant. Using μ' and μ'' series inductances and loss resistance:

$$L_S = \mu' L_0, R_S = \omega L_0 \mu'', \quad (3)$$

where L_0 is the parameter defining the coil configuration:

$$L_0 = \frac{4\pi N^2 10^{-9}}{C_1}[H], \quad (4)$$

where C_1 is the core configuration, N is the turns number. For a toroidal core this can be simplified to:

$$L_0 = 0.0461 N^2 h \cdot \lg \frac{OD}{ID}[H], \quad (5)$$

where OD is the outer diameter, ID is the inner diameter and h is the core height in mm. The series connection of L_s and R_s can be converted to parallel, yielding the magnetizing inductance L_m and the core loss R_c used in the transformer model [7]:

$$Q = \frac{2\pi f L_S}{R_S}, L_m = L_S\left(1 + \frac{1}{Q^2}\right), R_C = R_S\left(1 + Q^2\right). \quad (6)$$

The complex permeability graphics for 3F3, T38 and Magnaperm (abbreviation Mp is used) materials are presented in Fig.3.

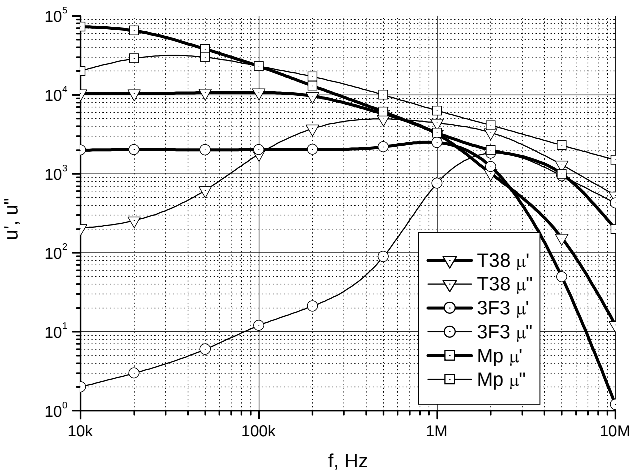

Fig. 3. **Complex permeability of the candidate materials**

By examining the data presented we see that μ' is constant (so is the inductance) and then starts decreasing. The μ'' is increasing (so are the losses) up to the certain frequency and then falls down. The frequency where both μ' and μ'' components get equal denotes the maximum frequency for the resonant circuit application (refer to resonant circuit frequency presented in Table 1).

Design of the driving generator

Design of a driving generator assumed a relatively low voltage power supply. It was limited to +/- 12V power supply. Therefore, the expected output voltage can only reach 20V peak-to-peak (p-p). An external signal source can be up to 4Vp-p if only +5V single supply is used. Therefore, the voltage gain of the input stage should be 5 times. The output voltage can be raised twice using a dual bridge circuit up to 40V p-p. For this reason the input stage has the differential output. The current feedback amplifiers AD8016 were used in the output stage. The current feedback amplifiers were chosen because of capability of such topology amplifier to maintain the stability of a full power bandwidth. Apart of high slew rate, the amplifiers are capable of 600mA output current. The closed loop output impedance is below 0.3Ω up to 1MHz. For the sake of impedance control in series to the output external resistors of 10Ω have been added. The resulting driving generator structure is presented in Fig.4.

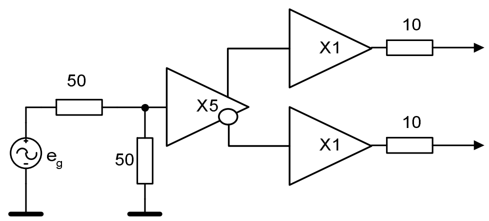

Fig. 4. **Driving generator structure**

Keeping in mind that both outputs have the 10Ω output resistance, the resulting output impedance of 20Ω will be used in further calculations.

The experimental investigation

We will investigate the RF transformer application for excitation of an ultrasonic transducer. In order to start the necessary calculations a particular transducer has to be chosen. An air coupled ultrasonic transducer has been used. Parameters of the transducer were evaluated using the Butterworth-Van Dyke model [8]. The parameters are presented in Table 2.

Table 2. **Ultrasonic transducer electrical parameters**

Parameter	Value
C_{0t}, pF	115
C_{st}, pF	26.4
L_{st},μH	22849
R_{st},Ω	2900
f_s, kHz	205
f_p, kHz	229

Assuming that the maximum power supplied to the transducer is the must, the generator and the load impedances should match. This condition also eliminates the signal reflection from the load. The transducer transmitting efficiency is highest at the series resonance. Assuming C_{0t} was eliminated using matching techniques [8], we use the transducer resistance R_{st} as the load value.

Keeping all this in mind the turns ratio for the transformer can be calculated:

$$n = \sqrt{\frac{R_{st}}{R_g}} = \sqrt{\frac{2900}{20}} \approx 12\,. \qquad (7)$$

Referring to Table 2, the transducer resonance is about 200 kHz. Choosing the lowest passband frequency to be half of this value, the primary winding magnetizing inductance L_m can be calculated using Eq.2. It should be about 15μH. Let us compare the cores chosen for investigation parameters. The core parameters are presented in Table 3.

Table 3. **Core parameters**

Brand	3F3	T38	Magnaperm
Outer diameter, mm	13	12.5	8
Inner diameter, mm	7.5	7.5	5.3
Height, mm	5	5	5
Inductance factor, μH/turns^2	0.9	5.11	28.3
Required primary turns	5	2	1

Analyzing the inductance factor we see that about 15μH is too low for the Magnaperm material core. Therefore we slightly increase the L_m value setting up to 28μH, which corresponds to 1 turn on the Magnaperm core. Three different transformers have been manufactured using the winding numbers and the cores indicated in Table 3. The transformer insertion loss has been measured using 2.9 kΩ resistor as a load and the driving generator discussed above. The 100 kHz to 10MHz frequency range have been used in order to evaluate the achievable bandwidth. The results obtained indicate that such an excitation is suitable not only for the transducer presented in Table 2, which operates in a low frequency range. Such an excitation can be used even for higher frequency transducers. Transducers, operated within the passband obtained, can be excited by an arbitrary waveform. The excitation by the arbitrary waveform would allow obtaining new measurement properties by compensating the transducer response, increase the accuracy of even perform the inverse filtering. Results are presented in Fig.5.

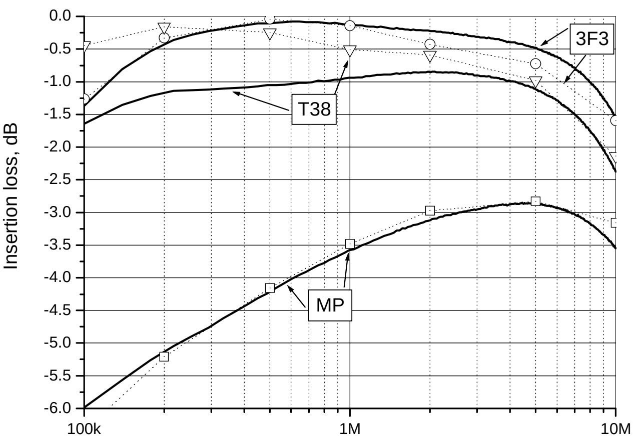

Fig. 5. **Insertion loss measurement and modelling**

We would like to point out that the insertion loss modeling has been done using the Matlab. The Eq. 3, 4, 5 and 6 have been used in modeling. The material properties presented in Table 1, the core parameters indicated in Table 3 and the model presented Fig.1 were used. The modeling results are also presented in Fig.5 by dotted lines.

The results produced a good match for Magnaperm and 3F3 materials. The modeled losses for T38 material have some discrepancy from the measurement results in a low frequency region. Both the modeling and measurement results indicate that the Magnaperm material losses are too high, so we consider it not suitable for the range above 100kHz. We decided that the 3F3 material is best suited for our frequency range needs.

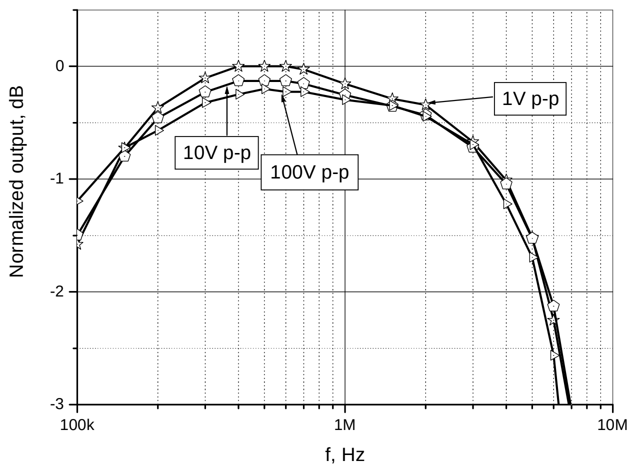

Fig. 6. **Normalized output voltage frequency response**

The investigation mentioned was performed at low signal levels. It is interesting to investigate whether these conclusions are valid at higher signal levels. The investigation was carried out at different output levels. The results are presented in Fig.6.

The sourcing generator voltage has been set at three different levels. Those driving levels suppose to give the output voltages of 1V p-p, 10Vp-p and 100Vp-p correspondingly. The measured output voltage was normalized by a corresponding factor. The results obtained indicate there is some slight reduction in the bandwidth at the high signal level in a high frequency region. The low frequency region remains unchanged or even acts opposite. Therefore, we claim that change in a transmitted power from 50μW to 0.5W does not influence the bandwidth significantly.

Conclusions

This initial study has confirmed suitability of a RF transformer as a voltage step-up component for excitation of ultrasonic transducers. The transducers exhibiting a relatively high input impedance have been examined. In order to confirm the same for low impedance transducers, an additional investigation is necessary.

The algorithm for investigation performance of a using only manufacturer parameters and the Matlab modeling has been presented. The match of modeling and experimental results confirmed validity of the algorithm.

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Radijo dažnio transformatorių naudojimas ultragarsiniams keitikliams žadinti : pradinis tyrimas

Reziumė

Nagrinėjami praktiniai radijo dažnio transformatorių projektavimo ir pritaikymo ultragarsiniams keitikliams žadinti klausimai. Pateikti signalinių transformatorių projektavimo etapai naudojantis gamintojų pateiktomis magnetinių medžiagų savybėmis. Pateikti tokių medžiagų parametrai nuo 10 kHz iki 10 MHz dažnių juostoje. Pateikti eksperimentinių matavimų ir modeliavimo *Matlab* paketu rezultatai. Parodyta, kad dažnio transformatorius gali būti naudojamas santykiškai didelės vidaus varžos radijo ultragarsiniams keitikliams žadinti. Eksperimentiškai gauta nuo 0.1 MHz iki 10 MHz pralaidos juosta. Eksperimentu parodyta, kad keičiant žadinimo signalo galią 10000 kartų (nuo 50 μW iki 0.5 W) praleidžiamų dažnių juosta kinta nedaug. Pasiūlytoji konfigūracija gali būti naudojama ultragarsiniam keitikliui žadinti sudėtingos formos signalu.

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