ULTRASONIC GENERATOR-TRANSDUCER COMBINED PERFORMANCE ENHANCEMENT

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Abstract

The methods to improve the generator power transmission to ultrasonic transducer performance enhancement are analyzed. This is important in portable equipment. Performance is analyzed using the transducer mathematical model, obtained from complex impedance measurement results as the frequency-dependent response. The matching circuits are analyzed as well as the transformer matching case. The matching circuitry type influence has been evaluated. The performance is analyzed by P-SPICE simulation. Various secondary parameters related to voltage step-up and available bandwidth have been calculated. The presented configuration can be used for ultrasonic transducer excitation using an arbitrary waveform generator output stage which is important in nonlinear medical ultrasound studies.

1. Introduction

In the power ultrasound applications such as the medical therapy, nonlinear ultrasound and resonant technique used in nondestructive testing (NDT), the equipment performance is defined by the transducer matching. In such applications the power delivery to the load is of primary importance. The performance of high resolution techniques is also dependant of matching. But here the transducer time response and bandwidth are most important.

The electronic circuits, filters and inter-stages design usually aims to match out the load to a resistive generator, which maybe the Thevenin equivalent of some other network, so that the transfer of power from the source to the load is maximized over a given frequency band of interest. Variety of publications dedicated to this problem can be found [1-3].

The goal of this paper is to analyze the several standard methods of ultrasonic transducer matching to excitation electronics using various performance evaluation criteria.

2. Transduction model

In order to evaluate the whole system performance, transducer, excitation electronics and matching circuits' models are included. Power delivery from generator to media is analysed. Simplified model structure is presented in Figure 1.

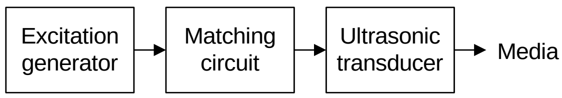

Figure 1. Transduction model

For model to be accomplished excitation electronics, transducer and matching stages have to be simplified to some extent and be presented as electronic equivalent model.

2.1. Ultrasonic transducer

Most of the ultrasonic transducer modeling techniques are based on the theoretical models. The Mason [4], Redwood [5], KLM [6] and other require the knowledge of the transducer's material properties and physical dimensions. Near the main resonant frequency piezoelectric ultrasonic transducer can be replaced by more simple equivalent circuit, described as *Butterworth-Van Dyke* (BVD) model [1]. (Figure 1).

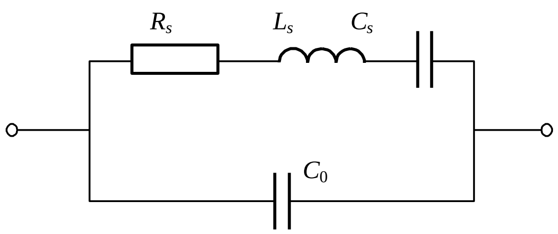

Figure 2. BVD model of transducer

We consider BVD as the best lumped parameter equivalent circuit suitable for our purpose since they are fitting typical piezoelectric converter impedance and are able to represent the transduction. The capacitance of the piezoelectric material is represented by C_0. The mechanical system is described by a series resonant circuit L_S, C_S, R_S. Changes in the mechanical boundary conditions are modeled by alteration of R_S, and C_S, while changes of inductance L_S describe the mass of the mechanical system. The R_S, can be split [2]:

$$R_s = R_0 + R_{xm}, \qquad (1)$$

where R_0 is the part representing the losses in piezo-ceramic material and R_{xm}- acoustic transmission into media. Since R_{xm} is the largest part, the power supplied to R_S can be considered as the acoustic emission.

The impedance Z_T of the ultrasonic transducer then can be expressed as:

$$Z_T = \frac{\left(R_s + j\omega L_s + \frac{1}{j\omega C_s}\right)\cdot\frac{1}{j\omega C_0}}{R_s + j\omega L_s + \frac{1}{j\omega C_s} + \frac{1}{j\omega C_0}}. \qquad (2)$$

System for ultrasonic transducer impedance measurement [7] was used to obtain the complex transducer impedance. Then impedance was approximated by BVD model. Results are presented in Figure 3.

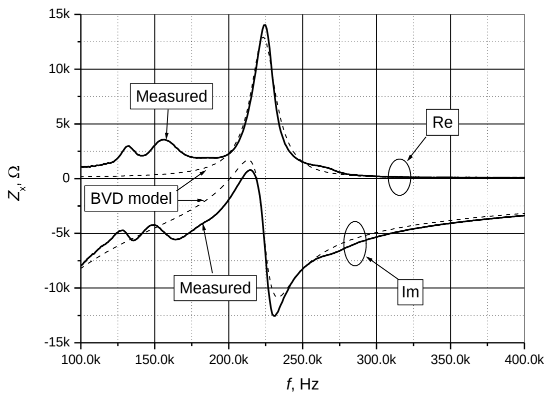

Figure 3. Measured impedance approximation by BVD model

The parameters of BVD model obtained by least mean square fitting to measured impedance are presented in Table 1.

Table 1. Transducer parameters

R_S, Ω	C_S,pF	L_S, mH	C_0, pF
5333	21.3	29.8	77.1

From Figure 3 it can be seen that transducer exhibit serial and parallel resonance:

$$\omega_s = \frac{1}{\sqrt{L_s C_s}}, \quad \omega_p = \frac{1}{\sqrt{L_s \frac{C_s C_0}{C_s + C_0}}}. (3)$$

The series resonance frequency of such mechanical system is the optimal point of operation, because the oscillation magnitude is reaching its maximum value. At this complex impedance of L_s, C_s series connection is zero and equivalent transducer circuit is simplified to parallel connection of R_s and C_0.

2.2. Matching circuits

In general two approaches can be used for matching [8-11]:

- LC circuit(s)
- RF transformer

LC circuit is used to neutralize the imaginary part of ultrasonic transducer input impedance and (or) to transform the impedance.

In LC resonant implementation, as indicated in [1] the additional inductor should resonate with clamping capacitor C_0 in order to remove it from the circuit (Figure 4).

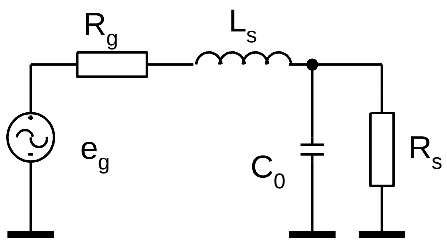

Figure 4. LC resonant matching

Serial L_s or parallel L_p inductance value then is calculated as:

$$L_s = L_p = \frac{1}{(\omega_s)^2 C_0}. \qquad (4)$$

In [1] It was indicated that decision when to use additional inductance in series or in parallel can be arrived by solving the transfer coefficient. For serial case it is:

$$K_s = \frac{\rho/R_g}{1+R_s/R_g}, \qquad (5)$$

and for parallel case:

$$K_p = \frac{1}{1+R_s \cdot R_g/\rho^2}, \qquad (6)$$

were ρ is characteristic impedance of resulting resonant tank. From (5) and (6) it is seen that $K_s>K_p$, when $\rho>R_g$ and $K_s<K_p$, when $\rho<R_g$. For $\rho=R_g$ case both solutions are equivalent.

The LC resonant circuit has highest sensitivity when operating close to mechanical resonance. High sensitivity of LC resonant circuit is serious disadvantage [2] since output filter is suitable only for particular transducer. Due transducer heating, aging and loading mechanical resonance is changed. In order to account for these effects L_s is chosen to resonate slightly below unloaded transducer resonance.

The LLCC resonant implementation (Figure 5) is similar: resonant frequency is chosen close to the mechanical resonance of ultrasonic transducer.

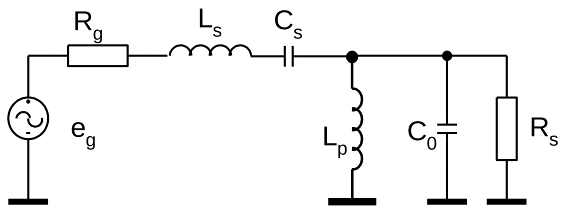

Figure 5. LLCC resonant matching

Equation (4) is used for L_s and L_p calculation and C_s is chosen equal C_0. In practical operation filter will be detuned, source [2] explains how to control the peaks position.

The "L" matching [12] is implemented using by placing two reactive components between amplifier and the transducer (Figure 6).

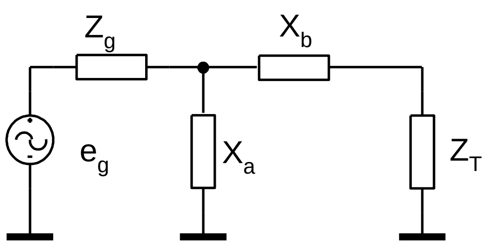

Figure 6. "L" matching structure

First, transducer impedance at mechanical resonance is converted to serial form:

$$R_T = \frac{R_s}{1+\left(R_s\omega_s C_0\right)^2},$$

$$X_T = \frac{R_s^2}{\omega_s C_0\left[1+\left(R_s\omega_s C_0\right)^2\right]}. \quad (7)$$

Then, corresponding reactance are:

$$X_a = -\frac{R_g^2 + X_g^2}{QR_g + X_g},$$

$$X_b = QR_T - X_T, \quad (8)$$

where

$$Q = \pm\sqrt{\left(\frac{R_g}{R_T}\left[1+\left(\frac{X_g}{R_g}\right)^2\right]-1\right)}. \quad (9)$$

Taking both Q solutions and swapping source and load positions four configurations are available.

RF transformer [11,13] is mainly used for impedance transformation therefore capacitive part of the load should be compensated using additional LC circuits. The magnetizing transformer [13] inductance L_m is defining the lowest applicable frequency. In general L_m is chosen that reactance at mechanical resonance is ten times larger the source impedance:

$$L_m = \frac{10R_g}{\omega_s}. \quad (10)$$

Transformer turns ratio is set:

$$n = \sqrt{\frac{R_s}{R_g}}. \quad (11)$$

2.3. Excitation electronics

Beside the transducer, also the excitation electronics play an important role in the system performance [14,15].

The application of the transformer as impedance matching element allows considering the push-pull B class amplifier as amplifier output stage [14] (Figure 7).

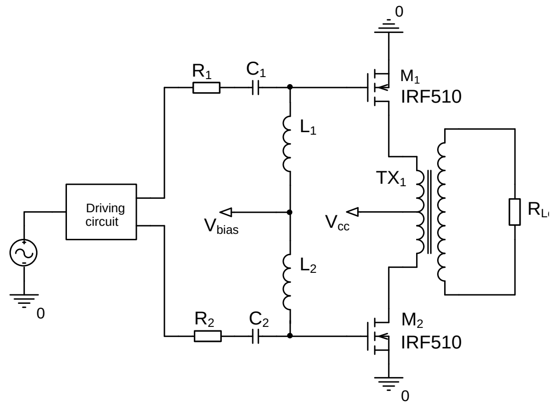

Figure 7. Push-pull output amplifier

In such setup active elements are operated at collector/drain voltages of twice the supply voltage. But the symmetrical power delivery and the ability to use same carrier type transistors make it attractive in ultrasonic transducer excitation. Therefore we will favor this topology over single-sided drive [15] or purely active amplifier stage [11].

3. Modeling results

The ultrasonic transducer and excitation generator combined performance have been studied. Assuming that low output impedance generator is matched to high input impedance load, introduction of the matching circuit should cause the voltage step-up. The voltage set-up ratio is proportional to impedances:

$$k_{up} = \frac{|Z_T|}{\sqrt{R_g R_s}}. \quad (12)$$

Modeling has assumed that excitation generator has pure active output impedance of R_g=50 Ω and transducer has parameters listed in the Table 1. Modeling results for transducer clamps voltage U_T for matching circuits mentioned above are presented in Figure 8.

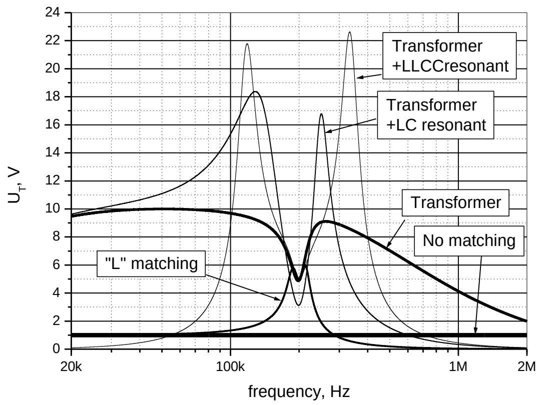

Figure 8. Transducer voltage U_T

Analysis of results presented indicates that almost all matching circuits have similar voltage step-up ratio at mechanical resonance. The only difference is the voltage behavior beyond the resonance frequency. Table 2 carries the voltage step-up ratios obtained for various matching conditions.

Table 2. Voltage step-up at resonance

Matching circuit	Step-up
No maching	0.99
Transfomer	4.9
Transfomer +LCrez	3.1
Transfomer+LLCCrez	5
"L" matching	5

Notable that for unmatched case the voltage on transducer clamps is not changing over frequency. Since power the matching goal is the maximum acoustic emission, it is interesting to analyze the voltage on acoustic emission representing resistor R_S. Graphs on Figure 9 are demonstrating the voltage U_{Rs} for various matching conditions.

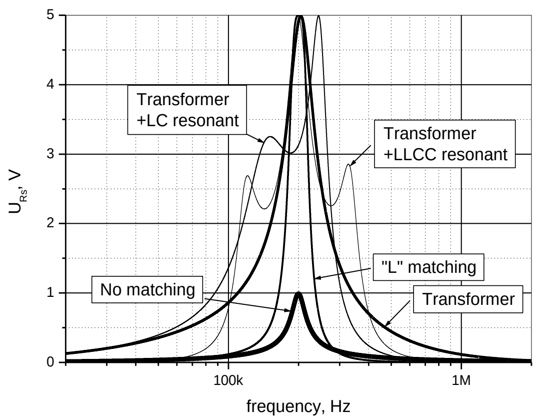

Figure 9. Emission representative U_{Rs}

Again, all the matching circuits produce similar voltage on emission resistor. Only one peak is aside main (Transformer+LC resonant) resonance. This circuit is deliberately detuned as recommended in [2]. Notable, that behavior over frequency range is different for all matching circuits. Therefore power on R_S was calculated and normalized to its peak. Results of normalized emission power are presented in Figure 10. After normalization it was expressed in dB.

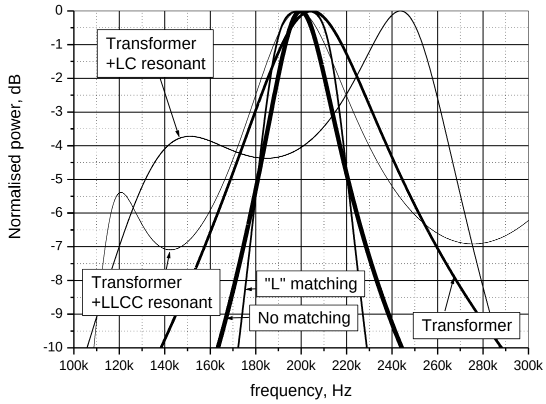

Figure 10. Normalised power on R_s

Using results on Figure 10 the -3dB bandwidth was calculated for various matching configurations. Results are presented in Table 3, column labelled B to indicate the bandwidth in kHz.

Table 3. Bandwidth and energy of *R*s

Matching circuit	B, kHz	E, J
No maching	27.2	8.24
Transfomer	51.9	370
Transfomer +LCrez	46.6	421
Transfomer+LLCCrez	45.7	462
"L" matching	32.8	180

It can be seen that transformer introduction in matching circuits has improved bandwidth response. But it is interesting to combine both bandwidth performance and the voltage step-up. Therefore integral of power on R_S was taken over whole frequency band. The generator voltage was unity. The result can be treated as energy which can be delivered to media (Table 3, row "E").

4. Conclusions

Investigation carried out indicates that if the matching at single frequency is needed then all matching circuits perform the same. But if bandwidth is under consideration transformer introduction allows for significant bandwidth increase. If both the power delivered and the available bandwidth is important then transformer and resonant LC or LLCC matching circuits should be considered.

Acknowledgments

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