Evaluation of the ultrasonic transducer electrical matching performance

L. Svilainis, V. Dumbrava

Signal processing department, Kaunas University of Technology,
Studentu str. 50, LT-51368 Kaunas, Lithuania, tel. +370 37 300532, E-mail.: svilnis@ktu.lt

Abstract

Performance of electrical matching of an ultrasonic transducer to the excitation generator is analyzed. The analysis is based on a transducer measured impedance. Real power supplied to the ultrasonic transducer is one of evaluation criteria. The obtainable bandwidth as well as its product with a real power supplied are assigned as the alternative performance evaluation criteria. Effective bandwidth is adopted from radiolocation as one of criteria. Most popular matching circuits are analyzed using the mentioned criteria. Algorithms for matching network selection are presented.

Keywords: Ultrasonic transducer impedance, impedance matching, power factor

Introduction

The transducer electrical impedance affects an ultrasonic transducer noise performance, driving response, bandwidth and sensitivity [1-3]. These parameters can be modified by applying the electrical circuit in between the ultrasonic transducer and the excitation generator. Convenient approach to predict the result of such circuit introduction is to approximate the ultrasonic transducer by some electrical model [4]. In many instances optimal tuning circuit search is based on the Butterworth-Van-Dyke (BVD) model [5]. According to [6] BVD and Redwood models are derived by simplifying the Mason equivalent circuit and can be made by piezoelectric impedance modeling based on experimental results and electromechanical analogies. We consider BVD as the best lumped parameter equivalent circuit suitable for our purpose since they are fitting typical piezoelectric transducer impedance and are able to represent the transduction. The capacitance of the piezoelectric material is represented by \( C_m \). The mechanical system is described by a series resonant circuit \( L_m, C_m, R_m \). Changes in the mechanical boundary conditions are modeled by alteration of \( R_m \) and \( C_m \) while changes of inductance \( L_m \) describing the mass of the mechanical system, generally can be neglected. The \( R_m \) is an emission resistance [7]. The \( R_m \) can be split:

\[
R_m = R_{lm} + R_{xm},
\]

where \( R_{lm} \) is the part representing the losses in piezoceramic material and \( R_{xm} \) acoustic transmission into the medium. Assuming that losses in transducer are relatively small, the power supplied to \( R_m \) can be considered as the transducer acoustic emission.

The impedance \( Z_T \) of an ultrasonic transducer then can be expressed as [8]:

\[
Z_T = \frac{\omega^2 C_m L_m - j \omega R_{lm}}{\omega^2 C_0 C_m R_m + j \omega^3 C_0 C_m L_m - j \omega (C_0 + C_m)}.
\]

In such case the transducer will exhibit serial and parallel resonances:

\[
\omega_s = \frac{1}{\sqrt{R_m C_m}}, \quad \omega_p = \frac{C_m + C_0}{L_m C_m C_0}, \quad \omega_q = \frac{1}{\sqrt{C_m C_0}}.
\]

The series resonance frequency of such mechanical system is the optimal point of operation, because the oscillation magnitude is reaching its maximum value. For increase of emission efficiency matching circuits are used.

The aim of this work is to analyze the matching techniques performance based on the measured transducer impedance instead of BVD model.

Matching circuits

The power delivered to a load is maximized when the load impedance is equal to the generator intrinsic resistance \( R_g \). At the serial resonance the complex impedance of \( L_m, C_m \) series connection is zero and the equivalent transducer circuit is simplified to parallel connection of \( R_m \) and \( C_0 \) (Fig.1). It is evident that the power supplied to the transducer is tempered by the capacitance of the piezoelectric transducer \( C_0 \). This capacitance is loading the excitation generator output and is reducing the generator efficiency.

Fig. 1. Equivalent circuit at mechanical resonance

Ideally an element with the value \(-C_0\) should be placed in parallel to the transducer. Two simple methods exist to compensate for this capacitance: parallel or serial connection of inductance [9]. It should be noted that compensation is available only at a single frequency. But for many applications such compensation is sufficient.

Parallel compensating inductor (Fig.2). If matching performed at the mechanical resonance frequency, then \( L_m, C_m \) series connection is zero and only \( R_m \) and \( C_0 \) are used for calculation.

Fig. 2. Equivalent circuit with parallel compensating inductance

The parallel \( L_{par} \) inductance value then is calculated as:
\[ L_{\text{par}} = \frac{1}{(\omega_s)^2 C_0}. \]  

(4)

It should be noted that inductor’s quality will affect the compensation results. Every real inductor can be treated as a serial connection of an ideal inductance and a losses resistance (refer Fig.3).

Fig. 3. Equivalent circuit of lossy inductor

The series connection of \( L_{\text{xs}} \) and \( r_{\text{loss}} \) can be converted to the parallel inductance \( L_{\text{xp}} \) and the loss resistance \( r_{\text{ploss}} \) [10]:

\[
Q_L = \frac{r_{\text{loss}}}{L_{\text{xs}}}, \\
L_{\text{xp}} = L_{\text{xs}} \left( 1 + \frac{1}{Q_L^2} \right),
\]

\[
r_{\text{ploss}} = r_{\text{loss}} \left( 1 + Q_L^2 \right).
\]

If \( L_{\text{xp}} \) is satisfying Eq. 4 then thanks to the parallel resonant tank \( C_0 \) and \( L_{\text{xp}} \) are resonated out and only the parallel connection of the inductor loss resistance \( r_{\text{ploss}} \) and the transducer emission resistance \( R_m \) remain. If high inductor quality is achieved (~100) then the mentioned effects can be disregarded and only the emission resistance \( R_m \) is remaining.

If other operation frequency is desired or \( R_m \) and \( C_0 \) values are not available, then the measured complex impedance can be used instead. Example of air-coupled ultrasonic transducer impedance measurement [11] results is presented in Fig.4.

Fig. 4. Measured electrical impedance of ultrasonic transducer

The arrow in Fig. 4 indicates the desired operation frequency. Since the impedance presented has a serial connection of real and imaginary parts, these have to be converted to the parallel connection:

\[
R_{\text{par}} = \text{Re}(Z_T) \left[ 1 + \left( \frac{\text{Im}(Z_T)}{\text{Re}(Z_T)} \right)^2 \right],
\]

\[
X_{\text{par}} = \text{Im}(Z_T) \left[ 1 + \left( \frac{\text{Im}(Z_T)}{\text{Re}(Z_T)} \right)^2 \right].
\]

(6)

Then

\[ L_{\text{par}} = \frac{1}{\omega_s X_{\text{par}}|_{\omega=\omega_s}}. \]  

(7)

The frequency \( \omega_s \) used in Eq. 7 can be replaced by other that the series resonance. Again, if the inductor used has a sufficient quality the only remaining part is the real part of the transducer complex impedance parallel equivalent \( R_{\text{par}} \) obtained from Eq. 6. Otherwise, the inductor quality has to be taken into account using Eq. 5.

The resulting input impedance \( Z_m \) for the same transducer as in Fig.4 impedance after parallel inductance matching is presented in Fig.5.

Fig. 5. Impedance after parallel inductance compensation

Note that at the desired frequency (indicated by the arrow) the imaginary part was fully compensated.

Serial compensating inductor (Fig.6). Here, the \( C_0 \) serial equivalent is creating the serial resonant tank with a compensating inductor.

Fig. 6. Equivalent circuit with series compensating inductance

Therefore, the transducer impedance at the mechanical resonance has to be converted to a serial form:

\[
R_{\text{ser}} = \frac{R_m}{1 + (R_m \omega_s C_0)^2},
\]

\[
X_{\text{ser}} = \frac{R_m^2 \omega_s}{\omega_s C_0 \left[ 1 + (R_m \omega_s C_0)^2 \right]^2}.
\]

(8)

The serial \( L_{\text{ser}} \) inductance value then is calculated as:

\[ L_{\text{ser}} = -\frac{1}{\omega_s X_{\text{ser}}}. \]

(9)

Again, if other frequencies are used or only impedance measurement results are available (refer Fig.3) then the imaginary part of the measured impedance is used:

\[ L_{\text{ser}} = -\frac{1}{\omega_s \text{Im}(Z_T)} \].

(10)
Such compensation results for the same transducer are presented in Fig.7.

![Fig. 7. Impedance after series inductance compensation](image1)

In this case the inductor quality will influence the remaining real part of the impedance. At the frequency where compensation is used only serial connection of impedance serial form real part and inductor losses resistance \( r_{\text{loss}} \) can be regarded as the excitation generator load.

The use of “L” matching [12] allows matching both real and imaginary parts. It is implemented by placing two reactive components between the amplifier and the transducer (Fig.8).

![Fig. 8. Impedance after “L” matching](image2)

The transducer impedance at the desired frequency is converted to a serial form using Eq.8. Then, the corresponding reactances are:

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

\[
X_b = Q \Re(Z_T) - \Im(Z_T),
\]

where

\[
Q = \pm \sqrt{\frac{R_g}{\Re(Z_T)}} \left[ 1 + \left( \frac{X_g}{R_g} \right)^2 \right]^{-1}.
\]

Taking both \( Q \) solutions and swapping source and load positions four configurations are available. Note, that the generator can be treated here as having a complex intrinsic impedance. If the generator output is purely resistive then \( X_g \) can be omitted. The results are presented in Fig.9 of resulting input impedance when “L” matching is used for the transducer analyzed above.

The generator output impedance was assumed to be only real 50 \( \Omega \) resistance. Note, that the imaginary part has been compensated and the real part matched to the generator intrinsic impedance.

Application of transformer matching (Fig.10) is a popular technology in RF technique [13].

![Fig. 10. Idealized transformer matching circuit](image3)

The idealized transformer presented in Fig.10 is characterized only by turns ratio \( n \) and the magnetizing inductance \( L_m \). Such circuit is not complete. For extensive analysis a full transformer model should be used [14, 15]. The magnetizing inductance \( L_m \) is defining the lowest applicable frequency. In general it should be chosen so that the reactance at the mechanical resonance is ten times than larger the source impedance:

\[
L_m = \frac{10R_g}{\omega_s}.
\]

The impedance is transformed as \( n^2 \) therefore the required turns ratio is

\[
n = \frac{\sqrt{\Re(Z_T)}}{R_g}.
\]

Eq. 14 is maximizing the power delivered to a complex load. It should be noted that the imaginary part of the load will “tamper” the real part preventing the full available power delivery to the real part of the load. The techniques described above should be used to negate the imaginary part. The graphs in Fig.11 present the matching result or all mentioned techniques. The original impedance

![Fig. 11. Impedance changes after compensations](image4)
curves are labeled as “Orig”, the serial and parallel inductance matching are labeled “Ser” and “Par” correspondingly, “L” label is for “L” matching and “Tr” for transformer matching. The arrow indicates the desired operation frequency.

It should be noted that all techniques except the transformer matching have compensated an imaginary part. Only two techniques (“L” and transformer matching) convert the transducer impedance to desired 50 ohms.

The evaluation criteria

The graphs in Fig.11 are of little use since there is no evident advantage of any matching technique. Therefore we indicate the need for quantitative evaluation criteria. For instance in [9] it was indicated that decision when to use an additional inductance in series or in parallel can be based on the transfer coefficient at the operation frequency.

We define the following evaluation criteria:

- power delivered to a load at the operation frequency;
- -3dB bandwidth [16], effective bandwidth;
- power delivery to load efficiency [17];
- power factor;
- total efficiency.

The complex power delivered to a load can be calculated using the modified input impedance:

$$S_T = \frac{e_g^2 Z_{in}}{\left(R_g + Z_{in}^*\right)^2},$$  \hspace{1cm} (15)

where $Z_{in}$ is the input impedance after matching circuit was applied, $Z_{in}^*$ is the complex conjugate, $e_g$ is the generator open-circuit voltage. Assuming that losses in a matching circuit are negligible the real part of this complex power $S_T$ is equal to the power dissipated in the real part of the transducer acoustic impedance [18]. As it was mentioned before this power can be assigned to acoustic emission of the transducer [19]. The results of investigation are presented in Table 1.

Table 1. Matching circuit evaluation results

<table>
<thead>
<tr>
<th>Circuit</th>
<th>$P_T$ [mW]</th>
<th>$B_{3dB}$ [kHz]</th>
<th>$B_{eff}$ [kHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No matching</td>
<td>2.91</td>
<td>272</td>
<td>365</td>
</tr>
<tr>
<td>Series inductance</td>
<td>3.4</td>
<td>287</td>
<td>370</td>
</tr>
<tr>
<td>Parallel inductance</td>
<td>2.94</td>
<td>276</td>
<td>364</td>
</tr>
<tr>
<td>“L” matching</td>
<td>5</td>
<td>376</td>
<td>366</td>
</tr>
<tr>
<td>Transformer</td>
<td>4.68</td>
<td>355</td>
<td>375</td>
</tr>
</tbody>
</table>

The other criterium candidate we define is the -3dB bandwidth of real power $P_T$. The results presented in Table 1 can be obtained using graphs on Fig.12.

The effective bandwidth is adopted from radiolocation as other alternative criteria [20]:

$$B_{eff} = \frac{\int_{f_1}^{f_2} f^2 P_T(f) df}{2\pi \int_{f_1}^{f_2} P_T(f) df},$$  \hspace{1cm} (16)

The results obtained for the effective bandwidth are presented in Table 1. Notable, that series inductance and the matching transformer have produced slightly wider effective bandwidths. The effect can be explained when examining the graphs on Fig.12: both mentioned circuits have a higher real power level at high frequencies.

It is interesting to investigate efficiency of the power delivery to a load is expressed as a real power conveyed to the load ratio to the power available from generator:

$$\eta = \frac{4R_g Re\{S_T\}}{\left(4R_g Z_{in}^2\right)^{100\%}} = \frac{4R_g Z_{in}^2}{\left(R_g + Z_{in}^*\right)^2} 100\%. \hspace{1cm} (17)$$

The results of the power delivery to the load efficiency for all mentioned matching techniques are presented in Fig.13.

An other widely used criterion is the power factor which is defined as the real power ratio to the apparent power:

$$PF = \frac{Re\{S_T\}}{|S_T|} = \frac{Re\{S_T\}}{\sqrt{Re\{S_T\}^2 + Im\{S_T\}^2}}. \hspace{1cm} (18)$$

The results of the power factor evaluation for all mentioned matching techniques are presented in Fig.14. Analysis of the power factor and the real power delivery efficiency indicate that the same matching technique behave differently according to the analyzed criteria. For instance, the parallel inductance matching has a widest bandwidth according to the power factor, but it has the
same performance as in an unmatched case according to the real power delivery efficiency criterion. Therefore, it is suggested to use the total efficiency criterion:

\[ \eta = PF \cdot \gamma. \]  \hspace{1cm} (19)

Graphs of the total efficiency for the mentioned matching techniques are presented in Fig. 15.

Now differences between various matching techniques are clearly seen. The total efficiency for an unmatched transducer at the operation frequency (900 kHz) is 50%. When the series inductor matching is used, the total efficiency is increased to 58%. For a parallel matching inductance it is 64%. Application of only one reactive component does not match both real and imaginary impedance parts. Therefore, the total efficiency is lower. Use of “L” matching implies two reactive components. Therefore, the total efficiency is increased to 100% at the operation frequency. For a particular ultrasonic transducer, used for analysis in this paper, “L” matching components have been calculated using the swapped load and the source case:

\[ Q_{swp} = \pm \sqrt{\frac{\text{Re}(Z_T)}{R_g} \left[ 1 + \left( \frac{\text{Im}(Z_T)}{\text{Re}(Z_T)} \right)^2 \right] - 1}. \]  \hspace{1cm} (20)

\[ X_a = -\frac{|Z_T|^2}{-Q_{swp} \text{Re}(Z_T) + \text{Im}(Z_T)}, \quad X_b = -Q_{swp} R_g. \]  \hspace{1cm} (21)

Then values for the circuit presented in Fig. 16 are calculated as

\[ L_a = \frac{X_a}{\omega_k}, \quad C_b = \frac{1}{X_b \omega_k}. \]  \hspace{1cm} (22)

Such configuration has been chosen deliberately in order to have a high pass filter. If voltage step excitation is used such signal contains significant amount of low frequency components. The high-pass filter prevents those low frequency components to pass to a transducer.

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Conclusions

It is suggested to use matching performance evaluation based on the measured ultrasonic transducer impedance. Six matching performance evaluation criteria have been offered. Primary analysis indicates that a total efficiency criterion is sufficient for matching performance evaluation. It is suggested to use matching performance evaluation.

References


L. Svilainis,V. Dumbrava

Ultragarsinio keitiklio elektrinio suderinimo efektyvumo vertinimas

Reziumė