Vibro-acoustic design, manufacturing and characterization of a tonpilz-type transducer

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Tonpilz-type transducers are highly important for sonar systems to generate and receive sound waves. They are generally used for low frequency applications. This study covers designing, manufacturing and characterization of Tonpilz-type transducers which is intended to operate below 7 kHz in hull mounted sonar systems. Transducers are first designed using simple lumped parameter, equivalent circuit and finite element methods according to the acoustic specifications obtained from original prototypes. Two transducers are then specified by considering the predefined specifications and finally manufactured. The T1 and T2 transducers both have an operating frequency of 4.9 kHz with a mechanical quality factor of 3.5. Maximum TVR levels are 133.7 dB/1 lPa/V for the T1 and 137.3 dB/1 lPa/V for the T2. Maximum RVS values are 159.1 dB/1 V/lPa at 4.9 kHz for the T1 and 156.8 dB/1 V/lPa at 5 kHz for the T2. According to the accuracy of the results, FEM was the best one among the design methods. Acoustic parameters are highly satisfied for the T2 transducer when compared to the original prototype such that the operating frequency (f 0) is 30% lower, the TVR values are almost the same and the RVS is 3.2 dB/1 V/μPa higher. These results suggest that designed transducers can be successfully used in the currently-utilized hull mounted sonar systems due to their comparable acoustic parameters attained at much lower operating frequencies.

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1. Introduction

Sonar is used to define underwater acoustic technologies such as communication, detection and navigation in water. Sonar is separated into two types as active and passive sonar. Active sonar both emits sound waves and listens to them while passive sonar only listens to sound waves generated by other objects. In both systems, transducers are used for transmitting and receiving purposes. Among several types of transducers, Tonpilz transducers are the most common type which are used in low-frequency applications [1].

Underwater transducers have been an important research area for a long time. Because transducer design is a complex process, there have been many methods introduced in literature. The simplest modelling technique is the simple lumped parameter method (SLPM). In this method, the transducer is modelled as single degree of freedom spring mass system and the resonance frequency of the transducer can easily be calculated. The accuracy is not good, but it can be applied as an initial design step before applying more advanced ones [2].

Equivalent circuit method (ECM), first derived by Mason in 1938 [3], is another modelling method which combines electrical and mechanical parts of the transducer in one circuit. Based on this model, various ECM have been introduced in literature. Krimholtz et al. [4] presented alternative equivalent circuits with some advantages on particular types of piezoelectric transducers.

Several studies regarding Tonpilz transducers are available in literature. Miyama et al. [5] performed equivalent circuit analysis with multiple acoustic matching plates. Transmitting voltage response (TVR) and receiving voltage sensitivity (RVS) results calculated by ECM were compared to the experimental measurements and very good matching was obtained. On the other hand, the studies at improving the performance parameters are much in number in the recent years. Xiping and Jing [6] studied a Tonpilz transducer with a hole in its head mass to obtain a wider bandwidth. Kim and Roh [7] also applied a void head mass to widen bandwidth by using regression analysis and generic algorithm. Kai and De-shi [8] used a generic algorithm to optimize the structure of the transducer. They calculated better sound radiation...
power after optimization process. On the other hand, Butler [9] widened TVR bandwidth by designing two different mechanical structures to develop multi-resonant transducers. The flexural resonance is generally known as an undesired mode causing null response but Hawkins and Gough [10] used it to widen the bandwidth by lip-mounting. Saïjou and Okuyama [11] optimized the phase difference of Tonpilz transducers with a bending disk to widen bandwidth.

Non-linear goal programming algorithm was implemented by Combrugge and Thompson Jr. [12]. They introduced a systematic procedure instead of trial-and-error methods based on ECM. They stated that this procedure facilitated to design wide band and high acoustic power transducers. Optimization by using ECM were not sufficient but using finite element method (FEM) revealed more accurate results. Teng et al. [13] made comparison between ECM and FEM. Smith [14] discussed ECM and the boundary element method. The design methods for transducers were clearly defined and compared to each other by Çepni [2] and Çiçek [15]. Çepni also built a design methodology starting from SLPM and end with the experimental measurement to avoid wasting time while designing transducers.

Low-medium frequency transducers have been commonly used in many countries’ frigates and ships. This study offers a new design and manufacturing of a Tonpilz-type transducer which operates below the operating frequency of those transducers with satisfying acoustic parameters as well as keeping the same outer dimensions. In other words, new designs can easily be replaced with the currently-used ones at the original hull structures but operated at lower frequencies to detect sound much further distances. Three design methods (e.g., SLPM, ECM, FEM) are used in design methodology and then the results are compared with both experimental and original transducer’s results. There are so many studies using design methods in literature but there is a lack of information considering all methods together in order to find optimum transducer parameters according to predetermined design criteria and limitations, and finally compare them with the in-water acoustic measurement results.

2. Methodology

Transducer design started with defining the design criteria and initial parameters. There was limited information about low-medium frequency transducer (hereafter referred to as Original Prototype or OP) used at hull mounted sonar system, and available information was given for transducers with matching circuits and in array configuration. Therefore, in order to obtain acoustic parameters without matching circuits, two OP transducers were fabricated and analyzed first in order to find optimum transducer parameters according to predetermined design criteria and limitations, and finally compare them with the in-water acoustic measurement results.

2.2. Obtaining rough dimensions by using simple lumped parameter method

SLPM introduced by Sherman [1] is based on representing transducer by one degree of freedom spring-mass system as shown in Fig. 1. This model is used generally as a starting point of the design processes to have an idea before using the advanced modelling techniques. Here, head and tail masses are represented as equivalent mass, piezoceramics as spring. It is assumed that mass is ideal rigid mass and spring has only stiffness. The other parts of transducer are neglected in this model. In Fig. 1, the term \( M_s \) is analogous to effective mass of head and tail masses, the term \( K_o \) is analogous to the stiffness of piezoceramic stack, and the force, \( F \), to driving voltage and \( x \) is position of the mass.

For a single degree of freedom system, the equation of motion can be written as:

\[
M_e \frac{d^2x}{dt^2} + R_e \frac{dx}{dt} + K_o x = F
\]

\( R_e \) is effective resistance and represents the radiation terms of the medium. The effective mass and resistance, \( M_e \) and \( R_e \) can be expressed as follows [11]:

\[
M_e = \frac{M_h M_t}{M_h + M_t}
\]

\[
R_e = \frac{R_c}{\left(1 + \frac{M_t}{M_h}\right)^2}
\]

where \( M_h \) is mass of head mass,\( M_t \) is mass of tail mass and \( R_c \) is radiation resistance of the medium. From the equation of motion, the natural and angular natural frequencies can be determined as follows:

\[
\frac{d^2x}{dt^2} + \frac{R_e}{M_e} \frac{dx}{dt} + \frac{K_o}{M_e} x = F
\]
With the determined thickness of the head mass, the length of the head mass, and the length of the tail mass, the cross-sectional area can be found using the equations given in Section 3.3. The cross-sectional area of the tail mass was calculated as 85 mm² and 12 mm. Stress rod was omitted in this method, but its area was calculated using known density and volume of the piezoceramics as 0.29 kg.

Thickness of the head mass, side length of the surface, and mechanical properties of steel as 0.22 × 10⁶ N/m² were known. Radiation terms, K_c and M_t, for rectangular active surfaces were calculated with respect to frequency using the equations given in [16] and [17].

Stiffness of the stress rod was calculated from dimensions of it and mechanical properties of steel as 0.22 × 10⁶ N/m². Radiation terms, K_c and M_t, for rectangular active surfaces were calculated with respect to frequency using the equations given in [16] and [17].

For the design criteria and overall dimensions of the other parts, the rough dimensions calculated in this step were used directly in this step. The tail mass (Mt), head mass (Mh), and stiffness of the piezoceramic stack (K_c) were already known from SLP. Clamped capacitance, stiffness of the stress rod, radiation mass and radiation resistance and mass of piezoceramic stack (Mc) were to be calculated. Clamped capacitance was found by using the equation below [1]:

\[
C_0 = \frac{\eta_{pc} d_{13}^3 A_{pc}}{\alpha_{pc}} \left( 1 - \kappa_{33}^2 \right) = 2.38 \text{nF}
\]

In this equation, \( A_{pc} \) is the cross-sectional area of the piezoceramics (6.4 × 10⁻⁴ m²). The number of piezoceramics in the stack, \( n_{pc} \), was chosen to be 6 which resulted in 10 mm thickness (\( t_{pc} \)) for each ceramic. Mass of piezoceramic stack was calculated by known density and volume of the piezoceramics as 0.29 kg.

In order to ease the calculations, flexural frequency was used as the initial step. It is usually requested to be much higher than the resonance frequency of the transducer because it causes sharp decrease in TVR. It was chosen to be 15 kHz which was more than the double of requested operating frequency and for square surfaces it was calculated by [1]:

\[
f_{flex} = \frac{1.12 c_l t_h}{\lambda^2 (1 - \nu^2)^{3/2}}
\]

where \( \nu \) is Poisson’s ratio, \( t_h \) is thickness of the head mass, \( c \) is the sound speed in the material assigned to head mass and \( \lambda \) is side length of surface. Thickness of the head mass, \( t_h \), was calculated as 18 mm, based on predetermined 96 × 96 mm² dimensions. Then, mass of the head mass was calculated as 0.46 kg. A practical value of tail to head mass ratio is described in literature and recommended to be taken as 4 [1]. By using this ratio, mass of tail mass was calculated as 1.84 kg.

From Eq. (2), effective mass was calculated as 0.37 kg. When natural frequency was taken as 7 kHz, effective stiffness was found to be \( K_c = 0.7 \times 10^8 \text{N/m} \) from Eq. (4) and Eq. (5). The area of piezoceramics was taken as \( A_{pc} = 6.4 \times 10^{-4} \text{m}^2 \). Then, length of piezoceramic stack was found \( l_c = 60 \text{mm} \) by using area and density of piezoceramics. Considering the design criteria and overall length of the tonpilz as 120 mm, length of tail mass was assumed to be \( l_t = 120 - l_c - t_h = 42 \text{mm} \). Area of tail mass was calculated as \( A_{lt} = 5.56 \times 10^{-3} \text{m}^2 \) by its mass, density, and length. Considering the area, outer and inner diameters of the tail mass were selected as 85 mm and 12 mm. Stress rod was omitted in this method, but its dimensions were calculated by using design limitations and dimensions of the other parts. The maximum diameter of the stress rod was inner diameter of tail mass; therefore, it was chosen as \( d_o = 12 \text{mm} \). The length of the stress rod was selected as \( l_o = 110 \text{mm} \) by considering physical limitations and dimensions of the other parts. The rough dimensions calculated in this step is seen in Fig. 2. The calculated dimensions in this step were rough dimensions and some of the parts were omitted. Therefore, it was not important to find an actual design of the transducer for this step because the main purpose was to specify initial parameters to be used in equivalent circuit method.

### 2.3. Equivalent circuit method (ECM)

This method uses electrical circuits to define the transducer. After rough dimensions were obtained by SLP, the transducer was modeled by using ECM. The electrical circuit representation of the designed transducer is shown in Fig. 3.

K_c and K_r represent the stiffnesses of the piezoceramic stack and stress rod, respectively. K_r and M_t are radiation resistance and radiation mass of the medium. Parameters obtained in the first step were used directly in this step. The tail mass (Mt), head mass (Mh) and stiffness of the piezoceramics (K_c) were already known from SLP. Clamped capacitance, stiffness of the stress rod, radiation mass and radiation resistance and mass of piezoceramic stack (Mc) were to be calculated. Clamped capacitance was found by using the equation below [1]:

\[
C_0 = \frac{\eta_{pc} d_{13}^3 A_{pc}}{\alpha_{pc}} \left( 1 - \kappa_{33}^2 \right) = 2.38 \text{nF}
\]

In this equation, \( A_{pc} \) is the cross-sectional area of the piezoceramics (6.4 × 10⁻⁴ m²). The number of piezoceramics in the stack, \( n_{pc} \), was chosen to be 6 which resulted in 10 mm thickness (\( t_{pc} \)) for each ceramic. Mass of piezoceramic stack was calculated by known density and volume of the piezoceramics as 0.29 kg.

Stiffness of the stress rod was calculated from dimensions of it and mechanical properties of steel as 0.22 × 10⁶ N/m². Radiation terms, K_r and M_t, for rectangular active surfaces were calculated with respect to frequency using the equations given in [16] and [17].

The transformation ratio can be calculated as follows [1]:

\[
N = \frac{d_{13} A_{pc}}{d_{33} t_{pc}} = \frac{289 \times 10^{-12} \text{c}^2}{6.41 \times 10^{-4} \text{m}^2} = 1.2
\]

![Fig. 2. Section view of a Tonpilz transducer with parameters obtained in SLP.](image-url)
When 1 Volt alternating voltage was applied to the electrical circuit shown in Fig. 3, the current passing through $M_h$ referred to the velocity of the active surface. After this current was calculated by analyzing the circuit, one could obtain the pressure in the far-field distance by using equation below [18]:

$$|P(r)| = \frac{\rho c u a b}{2 \pi r}$$  \hspace{1cm} (9)$$

where $\rho$ is the density of the medium, $c$ is the sound speed in the medium, $k$ is the wave number, $u$ is the velocity of the active surface, $a$ and $b$ are the side lengths of the active surface and $r$ is the far-field distance. After far field pressure was calculated, transmitting voltage response (TVR) and receiving voltage sensitivity (RVS) were calculated as follows [1]:

$$TVR = 10 \log \left( \frac{P_{rms}}{P_{ref}} \right) = 20 \log \left( \frac{P_{rms}}{P_{ref}} \right)$$  \hspace{1cm} (10)$$

$$RVS = TVR + 20 \log |Z| - 20 \log (f) - 294 \text{ dB}$$  \hspace{1cm} (11)$$

where $P_{rms}$ is root mean square pressure obtained in the far field, $P_{ref}$ is the reference pressure which is 1 $\mu$Pa for water and $Z$ is electrical impedance of the transducer.

In Fig. 3, passive elements such as glue, electrodes and isolators between piezoceramics were not included for simplicity. They were needed to be added to the circuit as capacitances in parallel to the capacitance of piezoceramics. After they were added, the total capacitance of piezoceramic stack can be calculated as follows:

$$C_{cs} = \frac{1}{K_{cs}} + \frac{1}{K_g} + \frac{1}{K_{el}} + \frac{1}{K_s}$$  \hspace{1cm} (12)$$

where $K_{cs}$, $K_{el}$, $K_s$ are stiffnesses of glue, electrodes and isolators, respectively. Finally, two electrical circuits excluding and including these passive elements (glue, electrodes and isolators) were modelled and called as basic ECM and improved ECM, respectively.

The analysis was run at different values of tail (1.84, 1.4 and 1 kg) and head (0.36–0.86 by 0.1 kg increment) masses and the optimum results were found at: $M_t = 1.84$ kg and $M_h = 0.46$ kg. These range of values were used because they were maximum and minimum masses that be obtained in limited dimensions. By these values, the natural frequency was found at 5.8 kHz and quality factor was found as 4. Finally, the dimensions of the main parts were determined according to the calculated parameters. The cross-sectional view of the transducer for the values obtained in the second step can be visualized in Fig. 4.

2.4. Finite element method (FEM)

FEM was used to compare the results and to improve the parameters by changing the dimensions and numbers of piezoceramics. First, transducer was constructed by using a CAD pro- gramme. Second, the main transducer parts such as head, tail, piezoceramics, stress rod and nut were modeled. The glue and electrodes between ceramics were skipped in this model.

After a 3D model was obtained, COMSOL Multyphysics 5.2a was used for further analysis. The physics interfaces; pressure acoustics, electrostatics and solid mechanics, were selected. The study type was selected as frequency domain because the transducer characteristics needed to be determined with respect to the frequency. Transducer model was transferred to COMSOL, and then, water and a perfectly matched layer (PML) domains were defined in front of the active surface. The materials for each part and for the domain were assigned. After piezoelectric polarization was defined in +Z direction (i.e., thickness polarization direction), 1 Vrms was applied to the positive surfaces and the other surfaces were grounded.

The analysis was run in a range of frequency from 3 kHz to 13 kHz with a step size of 0.1 kHz. The analysis was performed for 6 and 8 piezoceramics and in a range of 19–24 mm for inner radius ($r_{pc}$) and 22–27 mm for outer radius ($r_{pco}$), respectively. TVR and mechanical quality factor ($Q_m$) of the transducer for different size and number of piezoceramics were calculated. Two transducers were selected as optimum among 26 trials with acoustic performances within the limits of the design criteria. Table 1
shows the physical dimensions and parameters of the two selected transducers (T1 and T2) in this step. Here, \( f_p \) is operating frequency where TVR peaks, \( f_{p,RVS} \) is the frequency where RVS peaks.

2.5. Manufacturing and characterization of transducers

Transducers were analyzed with some assumptions and simplifications. Glue, electrodes and isolaters between ceramics and metal parts were omitted in the design methods but had to be considered for the real transducers. The housing metal protecting transducer parts from environmental effects and the rubber coating on head mass and housing were to be considered as well. Neoprene rubber was particularly applied to increase insulation resistance of the whole transducer against water.

Fig. 5 shows the steps followed in the fabrication steps. Fig. 5(a) shows the aluminum head masses covered by rubber and assembled stress rods. Piezoceramics were stacked in electrically parallel using a conductive epoxy glue. A 50 \( \mu \)m thick Cu-Be electrode was placed between two piezoceramics and they were glued together. A master was designed to align ceramics on top of each other in the stack. Two glass fiber reinforced epoxy insulators were used between piezoceramic stack and head and tail masses for electrical insulation.

The stacks were kept at 60 °C for 1 h to cure the glue and then removed from the master (Fig. 5(b)). After cabling, they were covered by outside epoxy-glass fiber cloth and inside polyurethane potting as shown in Fig. 5(c) to keep the alignment of the stacks in case of cracking during working as well as to prevent electrical short-cut in case of contact with water. Piezoceramic stacks were placed between head and tail masses and squeezed by stress rods tightened at 50 Nm torque. A non-conductive epoxy-glue was applied to the contact surfaces between metal parts and stacks before squeezing the rods. Fig. 5(d) shows the tonpilz parts assembled. Transducers were encapsulated by neoprene-coated cylindrical housings together with a tail cable. They were all-glued together with a rubber-based glue and then kept at 60 °C for 1 h to fully cure and seal the transducers. The finished transducer ready for acoustic measurements is shown in Fig. 5(e). In addition, two OP transducers were also fabricated in the same way. Note that T1, T2, and OP transducers were produced without matching electronic circuits to make clear comparison between theoretical and practical results.

The measurements of the transducers were performed in the acoustic test pool 6 m in length, 4 m in width and 4 m in depth. In the pool, there was a positioning system to precisely locate the transducers. Secondary methods [19] were used to calculate the acoustic performance. A reference transducer was located exactly in front of the transducer at a distance of 2 m in depth and 2 m from the top surface of the pool. In the TVR measurements, the sound generated by the transducer under alternating voltage was measured by a reference transducer. On the contrary to the TVR measurements, the reference transducer was used as projector and the fabricated transducers were used as hydrophones in the RVS measurements.

Table 1

Parameters of the transducers selected for manufacturing process.

<table>
<thead>
<tr>
<th>No</th>
<th>( r_{pc} ) (mm)</th>
<th>( r_{pi} ) (mm)</th>
<th>( t_{pc} ) (mm)</th>
<th>( t_{pi} ) (mm)</th>
<th>( n_{pc} )</th>
<th>( f_p ) (kHz)</th>
<th>TVR (dB)</th>
<th>( f_{p,RVS} ) (kHz)</th>
<th>RVS (dB)</th>
<th>( Q_m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>24</td>
<td>20</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>5.4</td>
<td>136.5</td>
<td>6.3</td>
<td>153.8</td>
<td>3.6</td>
</tr>
<tr>
<td>T2</td>
<td>25.4</td>
<td>22</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>5.2</td>
<td>138.5</td>
<td>6.1</td>
<td>154.9</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Fig. 5. (a) Head masses covered by neoprene rubber and stress rods assembled, (b) Piezoceramic stacks (c) covered by outside glass fiber and inside polyurethane, (d) Tonpilz parts after electrical and mechanical parts assembled, (e) Finished transducer.
3. Results and discussion

Two transducers, namely T1 and T2, were designed by SLPM, ECM and FEM methods consecutively according to design criteria specified in advance. Then, the transducers were manufactured and tested. Acoustic performance parameters of the transducers obtained from the design methods and experimental results were compared to each other and the relative deviations for each one was determined. In addition, acoustic results of the two OP transducers were also completed whether the pre-determined criteria were achieved or not in real conditions. All results were then discussed.

3.1. Conductance

Conductance results were compared in Fig. 6. Conductance reveals the resonance frequency of the transducers. Because the operating frequency is usually close to the resonance frequency, conductance is used as the first step before measuring TVR and RVS. Resonance frequencies \( f_r \) of the transducers were measured at 4.6 and 4.9 kHz for the T1 and T2, respectively. They were well below 7 kHz which was one of the predetermined design criteria. The peak conductance values depend on the dimensions and number of piezoceramics. The most closely matching results were calculated by FEM whose details will be explained later. It should be stated that first modes of the transducers are calculated by all design methods, but the second mode is not seen in ECM. In the OP transducers, two modes were observed similar to the T1 and T2 results. This situation will also be discussed later.

3.2. Transmitting voltage response (TVR)

TVR results were compared in Fig. 7. TVR was one of the most important design criteria in this study because the operating frequencies and the mechanical quality factors were determined with respect to the TVR results. Operating frequencies were measured as 4.9 kHz for both transducers with a mechanical quality factor of 3.5. The operating frequencies calculated with design methods matched to great extent with the experimental measurements. Maximum TVR values and the values at other frequencies calculated by design methods and experimental results well-matched to each other as well. Maximum TVR (e.g., at the operating frequency) was measured as 133.7 dB/\( \mu Pa/V \) for the T1 and 137.3 dB/\( \mu Pa/V \) for the T2 transducers.
investigated. The displacement responses of the transducers at first and second resonance frequencies are shown in Fig. 9. The first mode was a piston mode where the transducer parts moving forward and backward together in the polarization direction. In the second mode, corners of the head mass moved in opposite direction to the centre, as inside and outside. This is the flexural mode of the head mass which in general adversely affects transducer performance. However, there are some reports [10] using the flexural mode to broaden TVR bandwidth, as is the case in our study. However, this is not the case in RVS.

Moreover, the head mass and all the other parts were modeled in ECM by their physical properties such as stiffness and mass. Their shapes and dimensions could not be modeled in these methods. Therefore, velocity of the head mass was assumed to be uniform in ECM. As a result, the second (flexural) mode could not be observed in basic ECM and improved ECM models.

There were some simplifications and assumptions made in the design methods which are possibly the reasons for the deviations between calculated and measured values. While designing a transducer, the transducer parts are always presumed to be uniformly connected to each other, which in fact is not totally possible in practice. In addition, in-water measurement environment was assumed to be ideal in the design methods, but it is not possible in the real measurement conditions (e.g., turbidity, temperature gradient, salinity, etc.). More importantly, prestress induced in transducer due to tightening torque by means of a stress bolt was also not modeled in the design methods. The torque creates a compression on the ceramics which adjusts the natural frequency and resulting acoustic performances. In FEM, passive parts such as electrodes, glue and isolators were not modeled. The constraints of the design methods and comparison to the measurements can be seen in Table 2. Rubber and prestress are particularly important because none of the models are able to incorporate them to the analysis.

Table 3 shows the relative deviations of the design methods when compared to the actual measurement results of the T1 and T2 transducers. Relative deviations given in Table 3 are referenced to the measurement results of the transducers T1 and T2. The OP results are given to compare actual acoustic measurements. The accuracy can be improved in the models by incorporating skipped parts such as glue, electrodes, prestress level, isolators or neoprene rubber coating. On the other hand, in order to get more accurate results in the RVS calculation, rather than using a reciprocity formula, transducer can be analyzed as hydrophone to directly measure RVS. Also, if the prestress occurred in the stress rod is modeled in FEM, the deviations would decrease to quite small levels. In ECM, there are more simplifications because of the nature of the method. Nevertheless, this method can also be improved by modeling neoprene rubber or prestress somehow in the circuit, which may reduce the relative deviations in ECM. Among the design methods used in this study, FEM is the best one to design a transducer based on minimum relative deviations, similar to the results reported in literature [2,13]. Although both the T1 and T2 transducers successfully satisfy the predetermined parameters (e.g., operating frequency $<7 \text{kHz}$, $Q_m \leq 4$, $\text{RVS} = -160 \pm 3 \text{dB}/1 \mu\text{Pa}$ and a TVR $= 138 \pm 3 \text{dB}/1 \mu\text{Pa}$), the T2 transducer matched to the design methods with better accuracy and reached to much higher TVR and RVS values than the T1 transducer. The acoustic parameters were highly satisfied for the T2 transducer when compared to the OP such that the operating frequency ($f_p$) was 30% lower, the TVR values were almost the same, and particularly the RVS was 3.2 dB/$1 \mu\text{Pa}$ higher. Therefore, it can be used instead of the OP in underwater applications due to its comparable acoustic parameters obtained at much lower operating frequencies.

3.3. Receiving voltage sensitivity (RVS)

RVS results were compared in Fig. 8. RVS is an indicator of the transducer receiving sensitivity. Transducers are also required to receive sound. RVS better than $-160 \text{dB}/1 \mu\text{Pa}$ is sufficient for most transducer applications and that level was achieved at respective peak frequencies (e.g., $-159.1 \text{dB}/1 \mu\text{Pa}$ for the T1 and $-156.8 \text{dB}/1 \mu\text{Pa}$ for the T2).

It should be mentioned that the peak frequencies in the TVR (Fig. 7) and RVS (Fig. 8) plots are nearly the same in the measurements while, in the design methods, they are higher for the RVS results. In the design methods, RVS was calculated by reciprocity formula (Eq. (11)) after TVR was measured. In the actual measurements, however, RVS was directly calculated by using it as a hydrophone. The same situation was also observed by Miyama et al. [5]. They studied a Tonpilz transducer and calculated TVR and RVS by ECM and compared them to the actual measurements. They observed approximately %11 deviation between them.

The other important detail is a sharp decrease after the peak frequency is exceeded in the RVS results (Fig. 8) as compared to the TVR results (Fig. 7). The effect of second mode at nearly 12.4 kHz was not clearly observed in the RVS plots while it broadened the bandwidth in the TVR plots. The same effect was also observed in literature [20]. In order to detail possible reasons for this situation, the first and second modes of the transducers were
4. Conclusions

Low-medium frequency Tonpilz-type transducers are highly important for underwater sonar technologies to generate and receive sound waves. This study covers designing, manufacturing and characterization of Tonpilz-type transducers which is intended to be used in currently-utilized hull mounted sonar systems. Predetermined acoustic parameters were obtained from original prototype transducer measurements such that operating frequency was lower than 7 kHz, transmitting voltage response was $138 \pm 3$ dB/$\mu$Pa/V, receiving voltage sensitivity was $-160 \pm 3$ dB/$\mu$Pa/V, and mechanical quality factor was $\leq 4$. After defining the design criteria, rough transducer dimensions were determined by using Simple Lumped Parameter Method (SLPM).

Table 2
Comparison of the model constraints and the actual measurements.

<table>
<thead>
<tr>
<th></th>
<th>ECM (Basic)</th>
<th>ECM (Improved)</th>
<th>FEM</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main parts (Head, tail, stress rod, piezoceramics)</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Passive parts (Glue, electrodes, isolators)</strong></td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Neoprene rubber</strong></td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Water</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>3-D modelling of parts</strong></td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Uniform velocity assumption for head mass</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Prestress occurred in stress rod</strong></td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>RVS calculation</strong></td>
<td>From TVR (By reciprocity formula)</td>
<td>From TVR (By reciprocity formula)</td>
<td>From TVR (By reciprocity formula)</td>
<td>Directly measured</td>
</tr>
</tbody>
</table>

Fig. 9. (a) First mode (5.4 kHz) and (b) second mode (12.4 kHz) (flexural mode) of the transducer T1 modeled by FEM.
Table 3
Parameters calculated by using design methods and their relative deviations (%) with respect to the measurement results of T1 and T2. The OP results are given for comparison.

<table>
<thead>
<tr>
<th></th>
<th>ECM (Basic)</th>
<th>ECM (Improved)</th>
<th>FEM</th>
<th>Measurement</th>
<th>OP</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fr [kHz]</td>
<td>6.1 (41%)</td>
<td>5.5 (20%)</td>
<td>5.4 (17%)</td>
<td>4.6</td>
<td>6.6–6.8</td>
</tr>
<tr>
<td></td>
<td>f0 [kHz]</td>
<td>6.1 (24%)</td>
<td>5.5 (12%)</td>
<td>5.4 (10%)</td>
<td>4.9</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>fs-axl [kHz]</td>
<td>7.1 (45%)</td>
<td>6.6 (34%)</td>
<td>6.3 (28%)</td>
<td>4.9</td>
<td>7–7.2</td>
</tr>
<tr>
<td></td>
<td>Qm</td>
<td>3.8 (8.5%)</td>
<td>5 (42%)</td>
<td>3.6 (2.8%)</td>
<td>3.5</td>
<td>2.3–2.7</td>
</tr>
<tr>
<td>Max TVR [dB/1 μPa/V]</td>
<td>136.8 (3.6%)</td>
<td>136.7 (3.6%)</td>
<td>136.5 (3.4%)</td>
<td>133.7</td>
<td>138–138.3</td>
<td></td>
</tr>
<tr>
<td>Max RVS [dB/1 V/μPa]</td>
<td>−161.6 (1.5%)</td>
<td>−160.8 (1%)</td>
<td>−153.8 (3.3%)</td>
<td>−159.1</td>
<td>−160 to −160</td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>fr [kHz]</td>
<td>5.7 (16%)</td>
<td>5.2 (6%)</td>
<td>5.2 (6%)</td>
<td>4.9</td>
<td>6.6–6.8</td>
</tr>
<tr>
<td></td>
<td>f0 [kHz]</td>
<td>5.7 (16%)</td>
<td>5.2 (6%)</td>
<td>5.2 (6%)</td>
<td>4.9</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>fs-axl [kHz]</td>
<td>6.6 (32%)</td>
<td>6 (20%)</td>
<td>6.1 (22%)</td>
<td>5</td>
<td>7–7.2</td>
</tr>
<tr>
<td></td>
<td>Qm</td>
<td>4 (14%)</td>
<td>4.7 (34%)</td>
<td>4.7 (14%)</td>
<td>3.5</td>
<td>2.3–2.7</td>
</tr>
<tr>
<td>Max TVR [dB/1 μPa/V]</td>
<td>137.2 (0.07%)</td>
<td>137.7 (0.2%)</td>
<td>138.6 (0.9%)</td>
<td>137.3</td>
<td>138–138.3</td>
<td></td>
</tr>
<tr>
<td>Max RVS [dB/1 V/μPa]</td>
<td>−163.2 (4%)</td>
<td>−162.2 (3.4%)</td>
<td>−154.9 (1.2%)</td>
<td>−156.8</td>
<td>−160 to −160</td>
<td></td>
</tr>
</tbody>
</table>

Equivalent Circuit Method (ECM) was used to model head and tail masses considering mechanical properties and physical parameters. Final form was modeled in Finite Element Method (FEM) to fix head/tail ratio, ceramic dimensions and number of ceramics in the stack. By considering the predefined parameters, two transducers (e.g., T1 and T2) were selected and manufactured. The T1 and T2 transducers both had an operating frequency of 4.9 kHz with a mechanical quality factor of 3.5. Maximum TVR levels were 133.7 dB/1 μPa/V for the T1 and 137.3 dB/1 μPa/V for the T2. Maximum RVS values were −159.1 dB/1 V/μPa at 4.9 kHz for the T1 and −156.8 dB/1 V/μPa at 5 kHz for the T2. According to the accuracy of the results, FEM was the best one among the design methods. On the other hand, the solution time took much longer than ECM, which required that ECM was used first to decrease the analysis time before ECM analysis. The comparison of the results obtained from the design methods and experimental measurements indicated that calculated acoustic parameters were fairly good although there were some deficiencies to be improved in the design methods such as prestress in the stress bolt and passive elements like glue, electrodes and isolators.

The T1 and T2 transducers operating well below the operating frequency of the original prototype transducer and reaching comparable acoustic performances for underwater applications were successfully designed, manufactured and characterized. The acoustic parameters were highly satisfied for the T2 transducers when compared to the original prototype such that the operating frequency (fr) was 30% lower, the TVR values were almost the same, and particularly the RVS was 3.2 dB/1 V/μPa higher. Therefore, it can be used instead of the original prototype in underwater applications due to its comparable acoustic parameters attained at much lower operating frequencies.

Acknowledgements

Part of this research was funded by Ankara Yıldırım Beyazıt University (Turkey) Scientific research project no. 2771) and is greatly acknowledged.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time due to technical or time limitations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apacoust.2019.02.003.

References