Finite Element Modeling of Ultrasonic Transducers

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Abstract

Ultrasonic transducers are the most important part of an ultrasonic testing system which significantly affect the precision and accuracy of the measurements. Piezoelectric transducers are the most common ultrasonic transducers which include three major components: the piezoelectric disk, backing material, and matching layer. The optimal combination of these three components is traditionally done by trial and error. Analytical models used for this purpose have their own pros and cons and are not capable of predicting the complete performance of the transducer. Finite element modeling is an alternative method that can be used for designing ultrasonic transducers. This paper presents a finite element model for a 4 MHz ultrasonic transducer excited by a spike signal in pulse-echo mode. The model considers an ultrasonic transducer composed of a piezoelectric disk, a matching layer, and a backing material. The main advantage of this model in comparison to earlier models is the incorporation of piezoelectric elements instead of mimicking the piezoelectric effect by applying forces or displacements. In the developed model, the input is an electrical signal and the output is an electrical voltage. This makes this model very similar to the way a real ultrasonic transducer operates. The simulation results are compared with results obtained from experiments and very good agreement is observed.

Keywords: Ultrasonic testing, Transducer, Finite element method, Piezoelectric

1- Introduction

An ultrasonic pulse-echo measurement process involves the generation of ultrasound by the transducer, propagation of these ultrasonic waves into the medium and then reception of these waves by the transducer again. The pulser sends the electrical pulse via a cable to an ultrasonic transducer. The transducer converts this electrical pulse into mechanical vibrations which could then propagate as an ultrasonic pulse into the material. The transducer also converts the returned ultrasonic pulse into an electrical pulse before transmitting it into the receiver. In ultrasonic measurement instruments, the transducer is a crucial part, which can significantly affect the precision of the system.

In the past, the development of ultrasonic transducers was usually done by trial and error. This would take a lot of time and cost a lot. It is difficult or even impossible to verify that the inadequate response of a transducer is due to design or construction problems. However, if a numerical model is used for designing the transducer, the transducer response is known in advance.

Researchers have already made efforts in modeling and simulating ultrasonic wave propagation to obtain further understanding of this process [1]. The models commonly used to simulate the mechanical and electrical behavior of piezoelectric transducers by incorporating simplifying assumptions. The geometries of practical transducers are often two or three-dimensional. However, the most popular models, such as Mason's or KLM models are only one-dimensional [2-5]. Comparison of a simulation with a related measurement proves that one-dimensional models can be rather inadequate when applied to practical transducer geometries [6].

In designing and examination of ultrasonic piezoelectric ceramic transducers, accurate simulation tools such as the finite element method (FEM) can be valuable tools. Application of the finite element method is one possible way to get a realistic transducer simulation and to visualize the real acoustic wave propagation into the medium. FEM is an efficient way to obtain the desired solution of a complex partial differential equations (PDE) which cannot be accurately studied using analytic methods [7]. Limitations of one-dimensional analytical models such as geometric constraints for accurate simulation and inability to simulate interaction with other objects can be avoided by using the finite element method.

Finite element capabilities in simulation of piezoelectric structures were identified in late 1970s [8-10]. Since then, much work has been done in improving the modeling of piezoelectric problems [11, 12]. Piezoelectric materials and transducers are used in various industries and equipment such as microphones, speakers, pressure sensors, ultrasonic motors and so on. Transducer structures vary according to their applications. Three-dimensional formulation of ultrasonic transducers, analytical methods of piezoelectric materials, estimation of natural frequencies and the corresponding eigenvalues, and limitations of various formulations were investigated by using the finite element method. It was shown that the standard one-dimensional models are available only in certain cases [13-16]. Kocbach reviewed the influence of material and geometry parameters on vibration, response functions, and radiated field of
transducers in transmission mode without considering the backing material [17]. Medina carried out simulations on ultrasonic transducers in transmission mode and observed that the simulated signals are noisier than those obtained from experiments [18]. Aanes studied the benefits and limitations of finite element modeling of transducers [19]. Only one piezoelectric crystal was modeled and electrical conductivity was compared with experimental measurements. Nygren introduced the material damping into the transducer but was not able to obtain the desired results [20]. Imperiale developed a code for the finite element model of an ultrasonic transducer by using domain decomposition technique [21]. Bilgunde studied the impact of changes in time period and the mesh size on his FEM model. He compared his simulation results in terms of received echo time with experimental results. Echo time was selected as the output parameter because transducer components information were taken from the literature and compared with experiment [22]. Over the years, much work has been done by using simplifying assumptions where not all three components of the transducer are modelled or just considering the transducer as a transmitting element [23-25].

The aim of this paper is to develop a finite element model that could be used as a designing tool for optimizing the performance of custom made ultrasonic transducers. We use the complete transducer model including the piezoelectric disk, backing layer, and matching layer in both transmit and receive modes. To validate the model, experimental measurements are conducted on an in-home constructed piezoelectric transducer.

2- Transducer General Description
An ultrasonic transducer is a layered structure as shown in Figure 1. The basic components of the transducer are the piezoelectric disk, backing material, and matching layer.

2-1 The Piezoelectric Disk
The piezoelectric disk is a crystal which converts the electrical energy into mechanical (ultrasonic) energy and vice versa. The crystal is a piezoelectric ceramic with two electrodes coated on its two opposite faces. Applying an electric impulse makes the ceramic vibrate at its resonance frequency [26]. The piezoelectric ceramic thickness determines its central frequency. The constitutive matrix equations relating the mechanical and electrical quantities that are the basis for the derivation of the finite element model are:

\[ T = C^e S + eE \]  
\[ D = eS + \epsilon^e E \]

where \( T \) is the tensor of mechanical stress \( (\frac{N}{m^2}) \), \( S \) is the tensor of mechanical strain, \( E \) is the electric field vector \( (\frac{V}{m}) \), \( D \) is the vector of dielectric displacement \( (\frac{C}{m}) \), \( C^e \) is the stiffness matrix for constant electric field \( (\frac{N}{m^2}) \), \( \epsilon^e \) is the permittivity matrix for constant mechanical strain \( (\frac{C}{m}) \), and \( e \) is the piezoelectric matrix \( (\frac{C}{m}) \) [27].

![Figure 1. Schematic design of a typical ultrasonic transducer.](image)

2-2 Backing Material
In order to support the piezoelectric disk, a backing material is used at the back of the piezoelectric disk. The backing material absorbs the back-transmitted energy and controls the vibration of the disk. To minimize the internal reflections, the acoustic impedance of the backing material matches that of the piezoelectric crystal. A typical backing material consists of a mixture of tungsten powder and epoxy [28]. To have an appropriate backing layer, several design considerations need to be considered such as appropriate attenuation coefficient and impedance of the backing material that would result in the desired bandwidth of the transducer [29].

2-3 Matching Layer
One or more front layers can be used to improve the power transmission between the piezoelectric disk and the propagating fluid. These layers also act as wear protection plates for a piezoelectric element. The addition of more than
one matching layer increases the complexity to manufacture the transducer. However, this also increases the efficiency of the transducer and results in the improvement of both bandwidth and sensitivity. Collin [30], based on transmission line theory, mentions that the optimal acoustic impedances for one matching layer ($Z_m$) is between impedance of the piezoelectric ceramic ($Z_{piezo}$) and impedance of medium ($Z_{med}$):

$$Z_m = \sqrt{Z_{piezo}Z_{med}}$$

For the design of a wide-band transducer, Desilets et al. in [5] modify the choice of front layer using the KLM theory:

$$Z_m = \frac{1}{n}(Z_{piezo}Z_{med}^2)$$

3- Transducer Modeling

The models are done with finite elements simulating a transducer radiating waves in a medium. The models are developed in ABAQUS v6.12 software. In the case of circular transducer, the model has been considered an axial symmetric geometry in order to reduce the computational time of simulations, Figure 2. In the model X axis is parallel to the transducer face, and Y axis is in the direction of wave propagation. The total time of propagation was 25 µs with 0.01 µs for the time sampling.

![Axisymmetric model](image)

As the model is axisymmetric, all components of the transducer have been modeled with axisymmetric plane elements. The models were shaped with square 2D elements of 4 and 8 nodes. For wave propagation problems, the spatial discretization must be defined such that it can resolve the shortest wavelength of interest. It is recommended to use 10 element per wavelength to get an adequate solution [15].

For the finite element modeling, the piezoelectric material is modeled as orthotropic (transverse isotropic) material. The ceramic used in the construction of ultrasonic transducers has symmetry in the XY plane and is polarized on Z axis. The PZT-5A ceramic used in this work, with 10 mm diameter, thickness of 0.54 mm, and central frequency of 4 MHz.

The piezoelectric crystal has not constraints or load, except for the electrical point of view. To create the wave, it is enough to excite the piezoelectric crystal and creating the potential difference between two faces above and below it. A spike excitation is applied on the upper surface of the crystal, while the bottom one is grounded. Excitation pulse is defined by using the following model [31]:

$$v_1(t) = \begin{cases} 0 & t \leq 0 \\ -V_0[1 - \exp(-\alpha_1 t)] & 0 \leq t \leq t_0 \\ -V_0 \exp(-\alpha_2(t - t_0)) & t \geq t_0 \end{cases}$$

where $V_0 = V_0/(1 - \exp(-\alpha_1 t_0))$ and the three parameters $t$, $t_0$, and $V_0$ are time (µs), maximum pulse time (µs), and maximum voltage (V). Figure 3 shows the pulse excitation obtained from the above equation.
To model the backing layer, epoxy material was considered by attenuation of 8.13 dB per meter. In order to eliminate interference echoes reflected from surface of backing material, the minimum thickness can be achieved by using following equation [32]:

\[ \alpha = \frac{20}{L} \log\left(\frac{P_0}{P}\right) \]  

where \( L \), \( \alpha \), and \( \frac{P_0}{P} \) are propagating distance (m), attenuation (dB/m), and ratio between transmitted and received wave amplitude.

For our case, acoustic impedance of piezoelectric disk is 33 MRayl, whereas, acoustic impedance of fluid (propagating medium) is 1.5 MRayl. So, based on Desilets theory, matching layer with the acoustic impedance 4 MRayl is required for the wideband transducer. In the existing transducer, Plexiglas is used as the front layer and has an acoustic impedance of 3 MRayl. This value is very near to the required impedance for the wideband transducer. Therefore, the existing selection is a good (not ideal) selection as the matching layer. The thickness of the front layer is set equal to quarter wavelength (\( \lambda/4 \)) to improve the transmitted wave into the propagating medium [33]. Table 1, Summarizes all material parameters used in the finite element model.

<table>
<thead>
<tr>
<th>Material</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy</td>
<td>Density (Kg/m³)</td>
<td>3674</td>
</tr>
<tr>
<td></td>
<td>Poison Ratio</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Elasticity Module (GPa)</td>
<td>6.7</td>
</tr>
<tr>
<td>Plexiglas</td>
<td>Density (Kg/m³)</td>
<td>1158</td>
</tr>
<tr>
<td></td>
<td>Poison Ratio</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Elasticity Module (GPa)</td>
<td>5.4</td>
</tr>
<tr>
<td>Water</td>
<td>Density (Kg/m³)</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>Bulk Module (GPa)</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Sound Velocity (m/s)</td>
<td>1500</td>
</tr>
</tbody>
</table>

Table 1. Summary of material parameters used in the models.

Contact between transducer components and contact between transducer and propagating medium were defined in such a way to allow the waves to be transmitted. Therefore, the nodes are tied to each other. In this case, the acoustic impedance of material is the only influential factor in the reflecting and transmitting of the waves. In the experiment, there is a sheet on the tank floor which is simulated with zero displacement of low end of fluid in the model. This boundary condition is used rather than modeling sheet because simulating the thin sheet needs to use finer mesh which increases the solution time.
4- Numerical Results
We have performed three simulations in order to study the effect of components and to complete our model: one with a piezoelectric disk, the other with a piezoelectric disk and backing material, and finally with all three main components (piezoelectric disk, backing material, and matching layer).

4-1 Piezoelectric Disk
In the first part, the FEM model of the piezoelectric disk propagating in a water medium was performed. In this form, only the piezoelectric disk was simulated. Figure 4 shows the output signal of the piezoelectric crystal. The first echo shows vibration of piezoelectric crystal after excitation. The second echo is due to the wave that is transmitted in the water and been received by piezoelectric disk after reflection from the rear surface of water.

![Figure 4. Received signal by piezoelectric disk.](image)

4-2 Piezoelectric Disk and Backing Material
This time, we present another configuration to illustrate the effect of backing material on the response of transducer. Backing material is used to minimize internal reflections, controlling piezoelectric vibration and limit the pulse duration. We consider a backing material directly in contact with piezoelectric disk. Backing material with thickness of 15 mm and impedance of 6 MRayl was added to simulate the effect of backing material on transducer response. As expected (Figure 5.), signal amplitude has fallen due to absorption of wave energy by the backing material. Also, due to energy absorption, pulse length decreased which is highly desirable in the designing of ultrasonic transducer because it will result in increasing transducer resolution. The use of backing material produces a short response by reducing the ringing following the initial excitation of the piezoelectric disk.

![Figure 5. Received signal by piezoelectric disk with backing material.](image)
4-3 Completed model
In the last stage of modeling, matching layer with 3 MRayl impedance and thickness of a quarter wavelength was added to the model. The thickness of a quarter wavelength increases the amplitude. The selected Impedance, which is very close to proposed impedance for Desilets theory, shortening the pulse and thereby increase the bandwidth, Figure 6.

![Figure 6. Received signal by completed model.](image)

5- Experimental Validation
The transducer was developed in laboratory with the same characteristics as the FEM model. PZT-5A piezoelectric crystal used in transducer with 4 MHz nominal frequency. Matching layer and backing material attached directly to the front and rear of crystal. Figure 7 shows the final transducer image. The experimental setup was performed in water tank in pulse-echo mode, Figure 8. A Pulser/Receiver Panametrics 5072PR was used to generate excitation signal.

![Figure 7. In-house manufactured ultrasonic transducer.](image)  
![Figure 8. Experimental test setup.](image)

In this section, the simulation results will be compared with test results. Figure 9 shows a comparison of echoes obtained by the experiment and simulation. Two echoes are very similar but there are little differences in the ringing. For the best understand of the graphics all the curves are normalized.

The frequency response curve is extracted. Figure 10 shows the frequency response curve obtained by simulation and experiment. The center frequency and frequency bandwidth of 3.5 MHz and 28.57 percent, respectively, is obtained from the simulation, while the amount of 3.7 MHz and 24.32 percent, respectively, shown in experimental test. Good agreement can be seen between the simulation and experimental result. In simulation many parameters are assumed to be ideal and some parameters are simplified which may affect system performance. Therefore it could be expected that difference exist between simulation results and experimental measurement. The difference in the received signal and frequency response can be caused by the following factors:
- Errors in the manufacturing process.
- Ideal assumption of component connections, frequency and thickness of crystal, and … in simulation.
- Piece surface finishing, no parallel surfaces, and … are factors that may cause errors in experimental tests.
6- Conclusions

Many designers employ one dimensional analytic models to predict the behavior of ultrasonic transducers. However, due to certain limitations these models are not adequate for understanding the complete performance of an ultrasonic transducer. In recent years, finite element modeling has been considered for designing the ultrasonic transducers. The objective of modeling and simulation of transducers is to optimize the design parameters without going through time-consuming tests. It also makes it possible to easily evaluate new materials and study the output signal of the system.

In this paper, ultrasonic transducer simulation was carried out by using the finite element method. A 4 MHz ultrasonic transducer consisting of a piezoelectric disk, a backing material, and a matching layer was modelled. The modelled transducer was excited by a spike signal in pulse-echo mode. The FEM results were compared with experiments and good agreement was observed. This kind of simulation can be used as a powerful tool for predicting the behavior of ultrasonic transducers.

References