Finite element and experimental study of composite and 1-D array transducers

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ABSTRACT

This paper reports a combined finite element and experimental study of composite and 1-D array transducers. The main properties characterized are the electrical impedance and beampattern. In order to calculate the beampattern of a transducer immersed in water, the pressure distribution and the normal velocity at the interface of water and transducer were calculated by using ANSYS\textsuperscript{®}. These results were then input into the Helmholtz integral to calculate the beampattern. The impedance curve was obtained by performing harmonic analysis using ANSYS\textsuperscript{®}. Related experiments were also conducted to verify these calculated results, good agreement was achieved between the experiments and simulations. Because of the similarity between the structures of 2-2 composite and 1-D array, the same FEA modeling procedure for 2-2 composites was extended to study a 1-D array. Particularly, the cross talk level and directivity of each element in an array were studied.

Keywords: FEA, composite, array, beam pattern, impedance, Helmholtz integral, ANSYS\textsuperscript{®}

1. INTRODUCTION

Lateral modes in piezocomposites limit the application of piezocomposites. These lateral modes are caused by the periodic structure of piezocomposites\textsuperscript{(1-7)}. Both the T-matrix and multisource T-matrix studies showed that lateral modes can be suppressed by introducing irregularities into either ceramic phase or polymer phase\textsuperscript{8,9}. In our previous studies, FEA was used to study composite transducers\textsuperscript{10,11}. The beampattern was calculated directly by using FEA, few experiments were conducted at the time. When calculating the beampattern of a transducer directly using FEA (ANSYS\textsuperscript{®}), the model is too large since one needs to include a large volume of water medium. In this paper we report a new way of calculating the beampattern. Considering the similarity of the structures between 2-2 composites and 1-D arrays, this new method is also extended to study 1-D arrays. In array designs, there are still many problems need to be addressed, such as crosstalk and angularity of each element of arrays.

2. BEAMPATTERN CALCULATION

The beampattern is an important factor in transducer design. The lateral resolution (beam width), the resolution in elevation direction (slice thickness), sidelobe level and grating lobe level can all be retrieved from the beampattern. A commonly used method to calculate the beampattern is to take a cosine Fourier transform of the space distribution of the vibrating intensity. For example, the beampattern in the far field of a uniformly vibrating rectangular transducer in an infinite rigid baffle is a sinc function. However, there are limitations to this approach. First, it is valid for farfield only; second, the baffle of the transducer is assumed to be an infinite rigid one, which does not correspond to reality. In ultrasonic imaging, the nearfield is of great interest, but the beampattern in the nearfield cannot be obtained by simply performing a cosine transform. We must calculate the general form of the Helmholtz integral.

Calculating the beampattern in the medium is to find the complex radiated pressure $p(x)$ in the fluid region exterior to a closed vibrating surface $S$. This problem follows from Green’s Theorem that the acoustic pressure, $p$, and the normal velocity, $v$, satisfy the integral formula\textsuperscript{12}

$$p(x) = \int_S \left\{ p(\sigma) \frac{\partial G(x,\sigma)}{\partial n_\sigma} + i\omega\rho v(\sigma)G(x,\sigma) \right\} d\sigma$$

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$$p(x) = \int_S \left\{ p(\sigma) \frac{\partial G(x,\sigma)}{\partial n_\sigma} + i\omega\rho v(\sigma)G(x,\sigma) \right\} d\sigma$$
where, \( S \) is the vibrating surface, \( x \) is an arbitrary point exterior to \( S \), \( \sigma \) is a point on surface \( S \), \( \frac{\partial}{\partial n} \) denotes differentiation in the outward normal direction, \( p(\sigma) \) is the pressure at \( \sigma \), and \( v(\sigma) \) is the normal velocity at point \( \sigma \). \( G(x, \sigma) \) is the green function,

\[
G(x, \sigma) = \frac{1}{4\pi} \frac{e^{-ik|x-\sigma|}}{|x-\sigma|} 
\]

\( k = \frac{\omega}{c} \)

The beampattern may also be directly calculated using FEA by adding the medium to the model. A large volume of water in front of the transducer greatly increases the computation task. Large model may also cause error accumulation. Fig. 1 shows the difference between the two methods. One can see that the two methods agree with each other very well in the region near the transducer; however, the result from FEA oscillates in the medium beyond the focal point. Our new combined method, FEA plus Helmholtz, gives good results in both the near field and the far field.

![Fig. 1 The axial pressure distribution obtained using FEA and FEA plus Helmholtz integral, respectively.](image)

3. STUDY OF 2-2 COMPOSITE TRANSDUCERS

Finite element analysis (FEA) and experiments have been performed to study 2-2 composites with both low and high ceramic volume percentages. The electrical impedance and the beampattern were measured using an impedance analyzer and a hydrophone water tank system, respectively. Dicing and filling technique was employed to build the designed 2-2 composites. Spurr epoxy, which has 4 components, was used as the filler for the kerfs and the PZT-5H elements were diced by using a K&S computer controlled diamond saw.

3.1. The electrical impedance

A. Regular 2-2 composites

A few regular periodic 2-2 composites were fabricated. Table I shows the specifications of the four regular composites constructed.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Ceramic volume(%)</th>
<th>kerf(mils)(microns)</th>
<th>Center frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>2 (50.8)</td>
<td>3.5MHz</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>5 (127.0)</td>
<td>3.5MHz</td>
</tr>
</tbody>
</table>
Fig. 2 is the computed and measured impedance curves for the No.1 sample. The first anti-peak is the thickness mode and the fifth anti-peak is its third harmonic. The second, third and fourth anti-peaks are lateral modes. In this case, the lateral modes are not strongly coupled with the thickness mode. The calculated impedance is almost the same as the measured impedance curve.

![Impedance spectrum of a regular 2-2 composite with 80% ceramic volume and 2 mil kerfs](image1)

Fig. 2 Impedance spectrum of a regular 2-2 composite with 80% ceramic volume and 2 mil kerfs

![Impedance spectrum of a regular 2-2 composite with 5 mil kerfs and 40% ceramic volume.](image2)

Fig. 3 Impedance spectrum of a regular 2-2 composite with 5 mil kerfs and 40% ceramic volume.

Fig. 3 is the computed and measured impedance curves for the No.2 sample. The three modes are the thickness mode, lateral mode, and the third harmonics of the thickness mode, respectively. The lateral mode strongly couples to the thickness mode in this case. One can see again that the FEA results match the measured results very well.

B. 2-2 composites with irregular kerfs

A 2-2 composite with three different kerfs have been constructed by dicing the ceramic with three different blades, the widths of the three different blades are 5, 4 and 2 mils, respectively. The spacing data can be programmed into a laptop computer which controls the diamond saw.
Fig. 4 Impedance spectrum of a sequential irregular 2-2 composite with 40% ceramic volume and 3 different kerfs (5,4,2 mils)

Fig. 4 is the calculated and measured impedance curves of a sequential irregular 2-2 composite with 40% ceramic volume and 3 different sized kerfs. There are basically two major modes shown in Fig. 4. The first is the thickness mode and the second one is its third harmonic. The measured results are almost the same as the calculated result.

Fig. 5 are the impedance curves of a 2-2 composite with 60% ceramic by volume and irregular ceramic width. There is only one major mode, i.e., the thickness resonance mode. One can see two small bumps in both the calculated and the measured results in the vicinity of the thickness mode which could be remnant of lateral mode. Since these two bumps are very small, the interference to the thickness mode is minimal. These two bumps also imply that the ratio of 5:4:2 irregularity may not be sufficient to suppress the lateral mode.

From the comparison of the four sets of calculated and experimental measured electrical impedance curves, it can be concluded that the FEA results are very accurate in evaluating the electrical impedance. In other words, the FEA simulation can practically replace the experiments to study the impedance spectrum.
3.2. Beampattern for 2-2 composite transducers

A hydrophone system was used to measure the transducer beampattern. Both the nearfield and farfield can be measured accurately by using this system.\textsuperscript{13} Fig. 6(a) is the calculated 2-D beampattern of a 2-2 40\% ceramic composite transducer with water loading. Fig. 6(b) is the measured result. The shapes of the two results are almost the same, but the calculated beampattern appeared to have much more details which did not show on the measured one due to the low sensitivity of the hydrophone.

Fig. 6 Beampattern of regular 40\% ceramic 2-2 composite transducer immersed in water. (a) Calculated using the combined method; (b) Measured beampattern using a hydrophone system.
Fig. 7 is the directivity pattern of a regular 2-2 composite transducer with 60% ceramic by volume. The kerf of the 2-2 composite is 5 mils. The measured directivity has lower sidelobe level, and the measured directivity is not symmetric. The asymmetry may be caused by the asymmetry of the transducer construction or by misalignment of the transducer. The calculated directivity pattern showed more details of the sidelobes while the measured one has much lower sidelobe level. This is caused by the low sensitivity of the hydrophone. Fig. 8 is the on-axis pressure distribution comparison. The agreement is satisfactory considering the non-optimized transducer and the sensitivity of the hydrophone.

![Directivity Pattern](image1)

**Fig. 7** A regular 2-2 composite with 5 mil kerf and 60% ceramic volume

![On-axis Pressure Distribution](image2)

**Fig. 8** On-axis pressure of a regular 2-2 composite with 5 mil (127 micron) kerf and 60% ceramic volume. The solid line is from calculation while the dotted line is measured data.

Fig. 9 is the directivity pattern of a sequential irregular 2-2 composite with different ceramic widths. The calculated directivity pattern and the on-axis pressure distribution by FEA and Helmholtz are almost the same as the measured ones as shown in Fig. 10.
Three sets of pressure distribution data have been compared in this section. Although some difference were found, the FEA plus Helmholtz results are basically the same as the experimental results. We therefore conclude that the FEA simulation can replace experiment to study the beampattern of transducers with good accuracy.

4. FEA (ANSYS®) STUDY ON 1-D ARRAYS

The crosstalk, subdicing and baffle effects in a transducer array have not been thoroughly studied theoretically up to date. Because of the complexity, the FEA seems to be the only tool which could be employed to address these issues.

4.1 Angularity study of an element embedded in an array

Each element of an array is embedded in a finite dimension array, the baffle effect is neither a cosine function, nor a constant. It always has been assumed to be a cosine function in the transducer industry because of lacking more accurate modeling tools.
Fig. 11 is a 1-D array FEA model, it has a backing, 2 matching layers, fluid-structure interface and water medium. There are 32 elements in this array model. The kerf is 4 mil, the ceramic volume percentage is 60%, and the thickness of the ceramic is 1.12 mm. With this model, the directivity pattern of an element can be studied by exciting only one element.

If the 16th element in the array is fired, the pressure and normal velocity distribution can be obtained through harmonic analysis in ANSYS®.

In Fig. 12, the dashed line represents the \( \text{sinc}\left(\frac{kd}{2\sin(\theta)}\right)\cos(\theta) \) the solid line is the FEA result. The directivity pattern obtained from FEA is much more complicated than the simple product of sinc\(\left(\frac{kd}{2\sin(\theta)}\right)\cos(\theta) \). The directivity pattern may also depends on many other factors, such as the properties of the kerf filler and the geometry of the array structure. For example, the hardness of the filler material can have a strong influence on the directivity pattern. As shown in Fig. 13, the intensity of the sound field is higher when the kerf is filled with harder material. For a 2.2 composite with soft kerf filler, the kerf is vibrating out of phase with the ceramic, causing the vibrating intensity to become smaller than that of the array filled with harder material. On the other hand, the angular response becomes wider when the backing material is softer although the amplitude of angular response is smaller.
It is desirable to have a wide angular response for each element in an array, particularly for phased arrays. However, the crosstalk between elements makes the angular response narrower, or strongly angular dependent. As shown in Fig. 14, the amplitude variations are caused by the crosstalk with the neighboring elements. One can also see that when the two matching layers are not diced, the crosstalk is very strong and the angular response of the element is very narrow. If one matching layers is subdiced, the angular response becomes wider. There is a substantial improvement in the angular response when both matching layers are subdiced. This results explains the necessity to cut both the two matching layers.

4.2 Crosstalk in 1-D array

The crosstalk in arrays degrades the contrast resolution or cause artifacts, it is of great importance to reduce the crosstalk level in medical imaging. In this section, a new way to define the crosstalk is discussed. We will also discuss how to cut the kerfs in order to reduce the level of crosstalk between elements. The dimensions of this array is the same as the linear array studied above.
If we excite one element at the center of an array using a pulse, then record the impulse response of this element and its neighbors, the ratio of the responses of the neighbor elements to that of the excited element will be defined as the crosstalk level in this study.

The center element of the array shown in Fig. 11 is excited electronically, and the impulse responses of the center element and its four neighbors have been calculated. The outer matching layer was not cut while the inner matching layer was diced. From Fig. 15 (a) to Fig. 15 (c), the amplitude of impulse response of the neighboring elements gradually decreases as they are away from this element. Also the impulse response gradually delays because of the distance which the wave has to travel. Fig. 16 (dashed line) shows how fast the impulse response decreases from one element to its neighbors. The RMS value has been used as the measure for the impulse response. The ratio of the impulse response of the neighbor to the impulse response of the center element was calculated in dB scale.

![Graphs](image-url)  
*Fig. 15(a) The impulse response of the center element in an array. (b) The impulse response of the second neighbor of the center element in an array. (c) The impulse response of the third neighbor of the center element in an array.*
Fig. 16 shows the results for an array with only the inner matching layer diced and with both matching layers diced. One can see that the crosstalk level is much lower when both of the matching layers are diced. The crosstalk level for the nearest neighbor should be at least -30 dB or lower in order to avoid the artifacts, therefore it is not enough to dice only one matching layer. This is the reason why the current array designs have both matching layers diced.

Fig. 17 shows the comparison of the crosstalk level of an array without dicing on the matching layers (dashed line) and with dicing only on one of the two matching layers (solid line). Interestingly, cutting only one matching layer does not help much in this case. The explanation for this is that one non-diced matching layer can still strongly couple the adjacent elements. A lens is often put on top of the array to change the focus of the transducer. This lens may cause extra cross coupling unless the lens is made of materials which have very small shear modulus.
5. CONCLUSION

In this paper, we have demonstrated that finite element analysis (FEA) is a powerful numerical tool in ultrasonic transducer and array design. The theoretical results from FEA have been confirmed by related experiments for 2-2 composite transducers. A new way of combining the FEA and Helmholtz integral has been used in our study of the beampattern, which can overcome the difficulty of error accumulation in large size FEA model. The same method used in 2-2 composite transducer study has been extended to study 1-D arrays. The cross talk among adjacent elements in arrays can be coupled through matching layers and the backing. Cutting both matching layers are necessary to reduce the element cross-talk.

6. ACKNOWLEDGEMENTS

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7. REFERENCES


