A Doubly-Curved Piezoelectric Composite with 1–3 Connectivity for Underwater Transducer Applications

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Abstract. Aim to increase the horizontal and vertical beam width of the high frequency transducer simultaneously, we present a doubly-curved 1-3 piezoelectric composite element. It consists of 54% piezoelectric ceramic volume fraction and two phases polymer matrix. The finite element analysis (FEA) is used to evaluate the dynamic response of composite. Electroacoustic response in water was measured for the doubly-curved composite being considered as underwater transducer. An underwater transducer was fabricated using the doubly-curved 1-3 piezoelectric composite element. The -3 dB full angle beam width of transducer is approximately 106° and 36° in the horizontal and vertical plane respectively. Both the FEA simulations and experimental results show the potential of a broad covered area of the composite transducer in underwater environment.

1. Introduction
Piezoelectric materials have been extensively applied in transducers [1, 2] and smart structure [3, 4]. Due to its excellent piezoelectric properties and easier to fabricate than single crystals, piezoelectric ceramics are currently commonly used in underwater acoustic transducers [5-7]. However, a drawback of piezoelectric ceramics is the higher acoustic impedance than water [8]. Also, being brittle and stiff, piezoelectric ceramics are difficult to conform to doubly-curved surface. They also have many hybrid resonance modes for monolithic piezoelectric ceramic. Which affect the electromechanical properties of transducers. In order to alleviate those problems, by combining a piezoelectric ceramic and a polymer matrix with the concept of “connectivity” developed by Newnham [9], an array of piezocomposites has been designed and fabricated. The piezoelectric ceramics exhibited excellent piezoelectric properties, the softer polymer phase can reduce the acoustic impedance and allows the composites to more flexible, so it can conform to doubly-curved surface [8]. Piezoelectric composite with 1-3 connectivity consists of piezoelectric ceramics connected in one dimension embedded in a polymer matrix. The softer polymer makes the piezoelectric ceramic pillars in a strong $k_{33}$ mode, such a composite can yield a high $k$ approach the $k_{33}$ of the piezoelectric ceramic.

Recently, high frequency transducers have been widely used in underwater detection and imaging with high resolution [5]. In an underwater environment, a broad beam width can enhance the detection
range of transducer. The existing cylindrical transducer presents an open emission pattern in the horizontal plane [1], so it can achieve an omnidirectional coverage in horizontal plane, but the vertical beam width is relatively narrow. It is required to increase vertical beam width of the transducer to achieve a large coverage in underwater environment. Being flexible, piezoelectric ceramic/polymer composites can be easily conformed to doubly-curved shape for increasing the beam width of high-frequency transducer. Simultaneously, low acoustic impedance and high coupling factor were obtained for transducer.

Our research designed a doubly-curved 1-3 piezoelectric composite to increase the horizontal and vertical beam width of the transducer simultaneously. In next section, the design of the doubly-curved composite is detailed. The harmonic analysis using finite element method is performed to evaluate the resonant mode of composite and acoustics fluid-structure interaction (FSI) analysis is applied to predict the beam width of composite transducer. Finally, a doubly-curved composite transducer is presented, and the experimental results of transmitting voltage response and beam directivity index of composite transducer in water are shown in the Section III. These experimental results are shown that the doubly-curved 1-3 piezoelectric composite is a promising material for fabricate broad beam transducer.

2. Design and Development of Doubly-Curved 1-3 Composite Transducer

2.1. Design of doubly-curved 1-3 piezoelectric composite

Considerable data have been reported on the electromechanical properties of 1-3 composite. Earlier work by Smith et al. [10] demonstrated composite's properties vary with the ceramic volume fraction, samples with volume fraction ranging from 50% to 80% could reach a high electromechanical coupling factor, but the acoustic impedance could increase linearly as ceramic volume fraction. The high acoustic impedance of ceramic cause acoustic impedance mismatch with that of water and body tissues (1.5 Mrayls). Therefore, the doubly-curved 1-3 composite with volume fraction of 54% was selected to investigate. For the cylindrical transducer, it can present an open emission pattern in horizontal plane [1]. To increase the vertical beam width, the proposed composite design as a doubly-curved structure as is shown in figure 1, \( \theta_a \) and \( \phi_a \) are the bending angle in the colatitudinal and circumferential direction in the spherical coordinate system [11]. The outer radius of composite is \( R \). The \( t \) and \( t_e \) refer to the radial thickness of composite and epoxy resin. Hence, resulting thickness of silicone rubber equals \( t-t_e \). The PZT-5H is chosen as piezoelectric phase, and the epoxy resin and silicone rubber are chosen to prepare the polymer matrix. In the composite, piezoelectric ceramic columns are poled along the radial direction of the composite.

![Figure 1. Schematic of a doubly-curved 1-3 composite (light blue: piezoelectric ceramic columns, green: epoxy resin, red: silicone rubber).](image)

2.2. Numerical study

In this subsection, we devoted to the finite element analysis (FEA) using the commercial FEM package ANSYS (ANSYS, Inc., Canonsburg, PA). This numerical calculation is performed to study the beam width varies with the magnitudes of the bending angle of the curved composite. To simplify the modeling, the FE model was established using the 2-dimensional element. The proposed curved composite is bending by monolithic piezoelectric composite plate with the same dimensions, so the arc
length of the different composite is set as a fixed value (46 mm) in the simulation. For the thickness of polymer, \( t \) and \( t_e \) are considered to be constants as designed \((t=5 \text{ mm}, t_e=3.5 \text{ mm})\). Aronov et al. studied the spherical shell transducers for underwater acoustics. The analytical and experimental results showed the increase of the bending angle were effective in terms of improving the beam width of transducer [12]. For comparison purposes, eight curved composites are defined with different bending angle (i.e., the central angle), as shown in figure 2. Table 1 summarizes the eight configurations.

![Figure 2. Increase of bending angle of 1-3 composites.](image)

Acoustics fluid-structure interaction analysis was carried out to study the electroacoustic performance of composite in underwater environment. An FE model of composite transducer in the fluid was constructed, as shown in figure 3. To simplify the calculation, 1/2 fluid domain is modeled using the symmetry conditions [13]. The external parts such as acoustic backing layers were simplified [14]. The infinite boundary condition was applied to the spherical surface of fluid domain [14, 15]. Figure 3 shows that the eight numerical transmitting voltage response (TVR) of the eight composite in the frequency range 250 KHz-400 KHz. All the maximum transmitting voltage response, bandwidth values and beam width (at -3 dB) are summarized in table 1. As expected, the beam width is influenced by the bending angle of the composite. The greatest beam width is 120° which is obtained from sample 1. In general, the increase of the bending angle of composite can improve the beam width. However, it will also decrease the TVR of sample. For the curved piezoelectric composite, a trade-off then must be made between the TVR and the beam width, as illustrated in figure 4.

![Figure 3 FE model of the composite transducer in the fluid.](image)

| No. | R (mm) | bending angle (°) | maximum transmitting voltage response (dB) | \( BW_{-3 \text{ dB}} \) | beam width \(-3 \text{ dB} \) (°) |
|-----|--------|-----------------|------------------------------------------|----------------|-------------------------------|
| 1   | 20     | 132             | 153                                      | 296-351        | 120                           |
| 2   | 22     | 120             | 153.8                                    | 299-353        | 108                           |
| 3   | 30     | 88              | 155.5                                    | 277-362        | 74                            |
| 4   | 40     | 66              | 158.4                                    | 289-357        | 58                            |
| 5   | 50     | 53              | 160.2                                    | 285-350        | 42                            |
| 6   | 60     | 44              | 162.5                                    | 289-350        | 38                            |
| 7   | 70     | 38              | 164.2                                    | 284-344        | 30                            |
| 8   | 80     | 33              | 165.6                                    | 294-357        | 28                            |

Table 1. Geometrical specifications and numerical results of the eight doubly-curved composites.
These numerical results clearly show the possibility of a broad beam width of the doubly-curved 1-3 composite transducer in underwater environment.

3. Performance test of doubly-curved 1-3 composite transducer

Figure 5 shows the fabrication procedures of the doubly-curved 1-3 composite. The “dice and fill” method was used to fabricate the doubly-curved 1-3 composite. First, a PZT ceramic is cut along the length and width directions of the ceramic block, and a common base is retained. The thickness of PZT ceramic is $t$, and the thickness of common base is $t_e$. The rubber is then cast into the PZT ceramic pillars. After casting, the PZT ceramic sample is inverted, and the ceramic base is cut precisely along the grooves between the PZT ceramic pillars. The cutting depth is $t-t_e$. Then, fix the sample in a doubly-curved-shaped mould. After fixed the sample, pour the epoxy resin into the mould. After solidifying, polished the surfaces of the sample and cleaned by acetone. Finally, a doubly-curved 1-3 piezoelectric composite element will be complete, as shown in figure 6.

An underwater transducer was fabricated with the doubly-curved 1-3 piezoelectric composite as the driving element. Figure 7 shows the structure of the doubly-curved 1-3 composite transducer. The performance such as the transmitting voltage response and beam directivity index were measured at room temperature. The transducer was connected to an underwater acoustic measurement system (The Institute of Applied Acoustics, Hangzhou, China). The measured transmitting voltage response
(250KHz-350KHz) of the composite transducer is shown in the figure 8. The maximum transmitting voltage response is 163.5 dB. The -3dB frequency bandwidth of the transducer is 274kHz-307kHz.

![Figure 7. Structure of the doubly-curved 1-3 composite transducer.](image)

![Figure 8. The transmitting voltage response of the doubly-curved 1-3 composite transducer.](image)

The measured beam directivity index of the transducer is presented in figure 9. It can be seen that the -3 dB full angle beam width is approximately 106° in the horizontal plane. Moreover, the -3 dB full angle beam width is approximately 36° in the vertical plane. The results show that the doubly-curved composite transducer can achieve a broad beam width in the horizontal and vertical plane simultaneously in a relatively high operating frequency (300KHz).

![Figure 9. Experimental beam directivity index of the doubly-curved composite transducer.](image)

4. Conclusions
A doubly-curved piezoelectric composite with 1–3 connectivity has been successfully designed and fabricated. Finite element analysis is performed to evaluate the its electroacoustic performance in underwater environment. According to the results of FEA simulation, an underwater transducer using
doubly-curved 1-3 composite with volume fraction of 54% is fabricated. The outer radius of composite is 50 mm. The radial thickness of composite and epoxy resin are 5 mm and 3.5 mm. The bending angle of composite in the colatitude and circumferential direction are 120° and 53°. In the operating frequency (300KHz), the -3 dB full angle beam width of transducer is approximately 106° and 36° in the horizontal and vertical plane. Consequently, this composite is a promising geometry for making broad beam underwater transducer.

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