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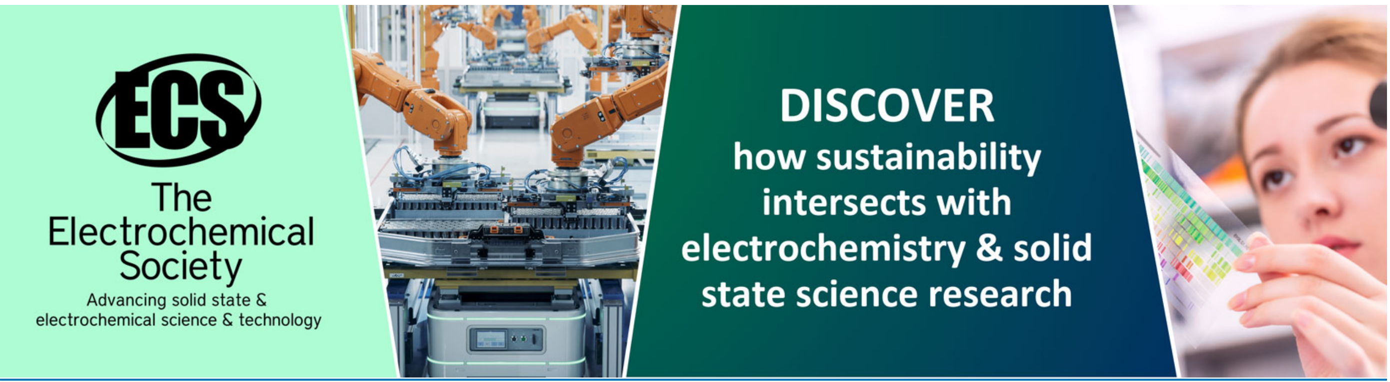

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Preparation of arc broadband piezoelectric composite vibrator and its transducer array

Miaojie Lv, Likun Wang, Chao Zhong and Lei Qin

Beijing Key Laboratory for Sensor, Beijing Information Science & Technology University, Beijing 100101, China

E-mail: lvmiaojie1991@163.com, wlikun1962@163.com, zclovelxm@163.com, qinlei@bistu.edu.cn

Abstract. This paper presents an arc broadband piezoelectric composite vibrator and its transducer array. The arc broadband piezoelectric composite vibrator was fabricated by 1-3 piezoelectric composite with matching layer and was prepared by the curved forming process. The vibration characteristics of a new vibrator were simulated via finite element analysis (FEA) and investigated by experiment. First, the acoustic impedance and thickness of the optimized matching layer were determined by theoretical analysis. Second, the arc piezoelectric vibrator was modeled and simulated in air conditions by the FEA method, and the variation law of resonant frequency was analyzed. Finally, the fabrication process of the arc broadband piezoelectric composite vibrator and its transducer array was studied, and the experimental sample was fabricated and measured. The bandwidth of the arc broadband transducer array was found to be up to 56.5 kHz. Results show that the experimental results were in accordance with the simulation results and have good directivity to realize the purpose of bandwidth and beam expansion.

1. Introduction

The multi-beam image sonar can detect, image, and recognize underwater targets and can be applied in underwater engineering, shallow landform mapping, and frogman operations [1, 2]. In practical applications, to obtain a large scope of observation, the transmitting transducer needs to have a wide beam and a high sound-source level and is generally used as an arc transducer. In addition, owing to the wide application of the transducer array, its signal processing system requires the transducer to have not only consistency but also a wideband characteristic. Thus, research on broadband technology has become the frontier field of underwater transducers, which can be summed up into two methods to expand the bandwidth. The first method reduces the mechanical quality factor of sensitive material. The most commonly used method adds flexible polymer into conventional piezoelectric ceramic, thereby increasing material consumption and reducing the Q value, such as the piezoelectric composite [3, 4]. The second method expands the bandwidth using modal coupling [5, 6]. A specific implementation method adds the matching layer to the surface of sensitive material. In response to these urgent needs, vigorous studies have been used to broaden the bandwidth of transducers. Some researchers have achieved remarkable results.

Liu Zhenjun et al. [7] proposed high-frequency underwater transducer curved arrays to improve the transmission voltage response and eliminate the coupling of the vibration mode of the length direction. The transmitting transducer adopted 1-3 piezoelectric composite. Receiver curved array consists of

181 elements. The transmitting voltage response reaches 161.4 dB, which is –3 dB bandwidth greater than 60 kHz. The sound-source level is up to 206 dB, and the receiver array sensitivity is approximately –197 dB. Benjamin [8] used 1-3 piezoelectric composite to fabricate doubly curved 2D conformal array and placed it in an acoustic test tank. The receiving voltage response is –174 dB for a selected element within the larger side-facing array.

Arc transducer array on the curved forming process requirements is relatively high and requires research focus. To expand the bandwidth and beam angle of the transducer, the multi-element arc piezoelectric vibrator base on 1-3 piezoelectric composite with matching layer is presented in this paper.

2. Design of multi-element arc composite piezoelectric vibrator

2.1. Structure of multi-element arc composite piezoelectric vibrator

According to the aforementioned method, the structure model of this design is proposed, as shown in figure 1. The 1-3 piezoelectric composite is selected as the sensitive material. Then, the matching layer is added to the surface of composites to fabricate the piezoelectric vibrator, and the 5-element arc piezoelectric composite array was prepared by the curved forming process to achieve the wide-band and wide-beam effect of the transducer. In figure 1, the A material is piezoelectric ceramic PZT-4; the B material is epoxy resin; the C material is the matching layer, which is formed by aluminum powder mixed into epoxy resin; the D material is silicone rubber, which is the decoupling material between the elements; *h* is the thickness of the piezoelectric composite; *t* is the thickness of the matching layer; and *w* is the thickness of the silicone rubber between the elements.

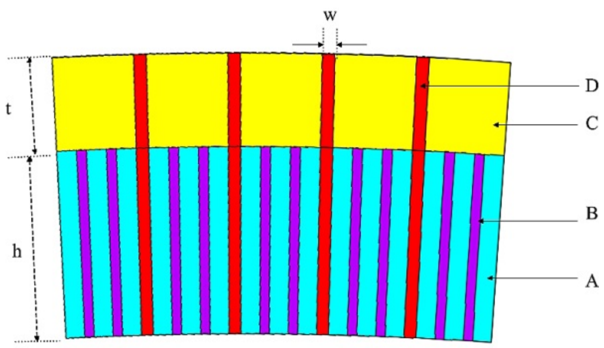


Figure 1. Structure diagram of arc vibrator base on piezoelectric composites

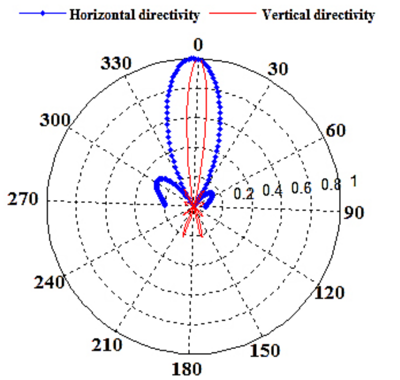


Figure 2. Directivity calculation results of 5-element arc piezoelectric vibrator

2.2. Directivity properties of multi-element arc composite piezoelectric vibrator

The directivity of the piezoelectric vibrator is one of the most important indicators in the design of transducer, and its directivity determines the beam angle of the transducer. The far-field directivity is classified into horizontal and vertical. The vertical directivity [9] of the multi-element arc piezoelectric vibrator array can be calculated according to the linear array directivity in equation (1), and the horizontal directivity [9] is calculated according to the circular array directivity in equation (2).

$$D(\theta) = \frac{\sin(\frac{\pi l}{\lambda}\sin\theta)}{\frac{\pi l}{\lambda}\sin\theta} \tag{1}$$

In equation (1), l represents the vertical height of the radiating surface and λ represents the wavelength of the transducer in water.

$$D(\theta)=\frac{1}{2m+1}\sqrt{\{\sum_{k=-m}^{m}\cos[\frac{2\pi r}{\lambda}\cos(\theta+k\alpha)]\frac{\sin[\frac{\pi d}{\lambda}+\sin(\theta+k\alpha)]}{\frac{\pi d}{\lambda}+\sin(\theta+k\alpha)}\}^2+\{\sum_{k=-m}^{m}\sin[\frac{2\pi r}{\lambda}\cos(\theta+k\alpha)]\frac{\sin[\frac{\pi d}{\lambda}+\sin(\theta+k\alpha)]}{\frac{\pi d}{\lambda}+\sin(\theta+k\alpha)}\}^2} \quad (2)$$

In equation (2), $2m+1$ denotes the number of elements, d denotes the center distance of the element, r denotes the radius of the arc radiating surface, and α denotes the round central angle corresponding to a single element. The horizontal directivity of the arc array is mainly determined by the parameters such as frequency (wavelength), radiating surface radius, and its corresponding round central angle.

In this study, the horizontal and vertical directivities of the transducer are calculated using MATLAB. For the transducer design with a center frequency of 100 kHz, a 5-element arc piezoelectric composite array with radius r = 300 mm, α = 1°, and l = 73.6 mm was selected. The horizontal and vertical directivities at f = 100 kHz are calculated using equations (1) and (2), as indicated in figure 2, which shows a normalized graph in which the vertical directivity –3 dB opening angle is 10° and horizontal directivity –3 dB opening angle is 25°.

3. Finite element simulation

The commercial finite element simulation package ANSYS was used to model mainly the piezoelectric vibrator harmonic response analysis and modal analysis. First, the model of one array element is established and the matching layer is added to the surface of sensitive material. By adjusting the thickness and sound velocity of the matching layer, the dual-mode vibration can be induced between the composite layer and the matching layer so that the transducer bandwidth can be extended. The matching layer parameters can be obtained by theoretical analysis. Second, the ANSYS software was used to establish the model of the 5-element piezoelectric composite vibrator in the air, and the resonant frequency of the multi-element vibrator and admittance variation were studied.

3.1. Finite element simulation of piezoelectric composites

To widen the bandwidth of the transducer, this study uses the method of adding the matching layer on the surface of the 1-3 piezoelectric composite. In figure 3, the piezoelectric vibrator model PZT-4 is chosen as the piezoelectric material, epoxy resin is filled between the piezoelectric pillars, l is the length of the element, a is the width of the element, h is the thickness of the element, and t is the thickness of the matching layer.

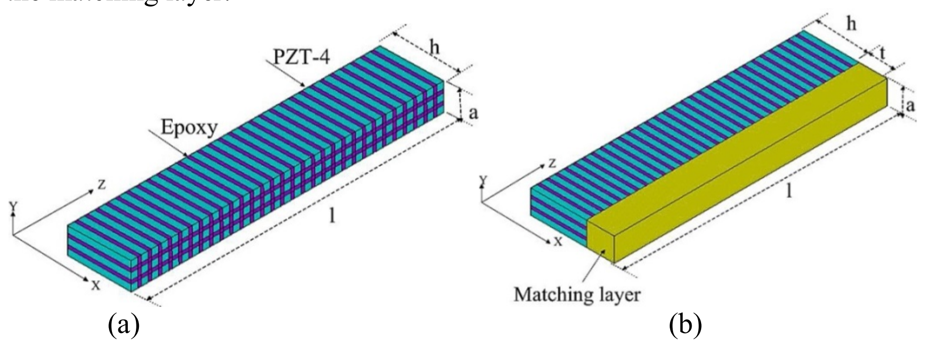
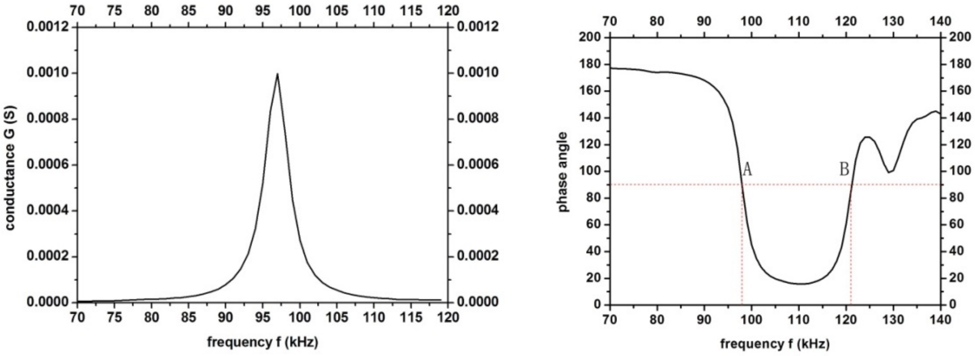


Figure 3. Piezoelectric vibrator structure diagram: (a) no matching layer, and (b) with matching layer

3.1.1. Finite element simulation of piezoelectric composites without matching layer. First, the harmonic response characteristics of the element are simulated in air. The structural parameters of the piezoelectric vibrator in figure 3(a) are as follows: width a = 6.4 mm, thickness h = 15 mm, and length l = 73.6 mm. The ceramic column width is 1.6 mm, the epoxy resin column width is 0.8 mm, and the ceramic volume percentage is 44.4%. The relationship among the conductance amplitude, conductance phase angle, and frequency of the piezoelectric vibrator can be obtained by simulation, as shown in figure 4, where point A corresponds to the resonant frequency (f1 = 98 kHz) of the composite element and point B corresponds to the anti-resonant frequency (f2 = 121 kHz) of the composite element.

3.1.2. Design of matching layer. In this paper, the matching layer acoustic impedance characteristic and impedance matching are discussed, and the parameters of the matching layer are designed. The aluminum powder was used as filler, epoxy resin as toughening agent, and curing agent as a matrix to fabricate the matching layer.



(a) (b)

Figure 4. In the air: (a) conductance amplitude curve, and (b) conductance phase-angle curve

According to the theory of total transmission when the acoustic wave propagates in the medium, the acoustic impedance and thickness of the matching layer are obtained when the acoustic matching is satisfied, where the optimum matching layer thickness in theory is equal to a quarter of wavelength.

(1) Characteristic acoustic impedance of matching layer

The characteristic acoustic impedance of the medium is the main parameter to characterize the acoustic properties of the medium. Here, the formula for the acoustic impedance of the medium is introduced [10]. The impedance of the matching layer is Z, as shown in the following equation:

$$Z = \rho c, \tag{3}$$

where ρ is the matching layer density and c is the propagation velocity of the sound in the matching layer.

(2) Preparation of matching layer

A matching layer was prepared and measured. In this study, the measurement of the matching layer density ρ can be used to determine the measurement result according to the ratio between mass and volume. The acoustic impedance of the matching layer is measured mainly by ultrasonic method. The time between two echoes is measured by digital ultrasonic flaw detector echograph 1095, and then a Vernier caliper is used to measure the thickness of the sample to calculate the speed of sound c of the matching layer. The final matching layer acoustic impedance Z can be calculated by equation (3). The specific parameters of the matching layer are shown in Table 1.

Table 1. Parameters of matching layer

Mass fraction of aluminum powder (%)	Matching layer density (kg/m^3)	Matching layer sound velocity (m/s)	Matching layer acoustic impedance (MRayl)	Matching layer thickness (mm)
10%	1272	2496	3.2	6.4
30%	1383	2826	3.9	7.2
45%	1560	2942	4.6	7.5
60%	1732	3118	5.1	8.0

(3) Acoustic impedance matching of matching layer

According to the traditional theory of acoustic impedance matching requirements, the matching layer of acoustic impedance is between the piezoelectric composite and the water [11]. The acoustic impedance of the piezoelectric composite and water load is Z_3 and Z_0, respectively. The theoretical formula for the acoustic impedance of the matching layer is

$$Z = \sqrt{Z_3 \cdot Z_0} \quad , \tag{4}$$

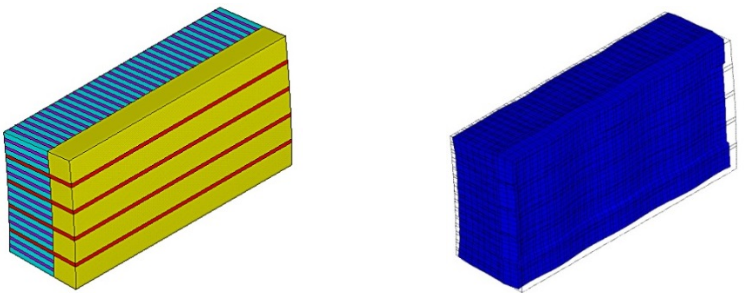
where the acoustic impedance Z_3 of the piezoelectric composite can be expressed as follows:

$$Z_3 = \rho_3 \cdot c_3 = (\rho_1 v_1 + \rho_2 v_2) \times (2 f_2 \cdot h) \quad , \tag{5}$$

where ρ_1 = 7500 kg/m3 is the density of the piezoelectric ceramic PZT-4; ρ_2 = 1050 kg/m3 is the epoxy resin density; v_1 = 44.4% and v_2 = 55.6% are the ceramic volume percentage and epoxy resin volume percentage, respectively; f_2 = 121 kHz is the anti-resonant frequency of the piezoelectric composite; and h = 15 mm is the thickness of the composite. These values were substituted into equation (5), where the acoustic impedance of the piezoelectric composite is calculated to be 14.2 MRayl and the acoustic impedance of the water load is 1.5 MRayl. Then, by equation (4), the acoustic impedance of the matching layer was calculated as 4.6 MRayl. As shown, the theoretical impedance of the matching layer is exactly the corresponding value when the mass fraction of the matching layer of aluminum powder in Table 1 is 45%. Thus, the optimized matching layer parameters are determined as follows: the mass fraction of aluminum powder is 45%, acoustic impedance is 4.6 MRayl, and matching layer thickness is 7.5 mm.

3.2. *Finite element simulation of multi-element arc piezoelectric composite vibrator*

The matching layer parameters have been determined by the preceding work. The piezoelectric composite model with matching layer as shown in figure 3(b) is established, and the array elements are gradually added. The modal analysis and harmonic response analysis were conducted by ANSYS software. Moreover, the admittance changes of the arc-shaped piezoelectric composites were observed when the number of elements changed from 1 to 5. The model diagram of the 5-element arc piezoelectric composite vibrator is shown in figure 5(a), where the array element is filled with silicone rubber material. The vibration mode as shown in figure 5(b) shows that the thickness of the vibration mode state is relatively pure.



(a) (b)

Figure 5. 5-element piezoelectric composites in air: (a) model diagram and (b) vibration mode diagram

The conductance curve is shown in figure 6. Through the preliminary simulation, two resonant peaks appeared due to the matching layer, which is in agreement with the theory. The frequency spacing and conductance difference of the two resonant peaks directly affect the coupling effect when it is under water.

As shown in figure 6, with the increase in the number of array elements, arc piezoelectric composite vibrator conductance value also increases linearly. The differences of the first and second resonant peak conductance values of the piezoelectric vibrator increasing with a different number of array elements are less than 0.5 and 0.23 mS, respectively, which is due to the parallel relationship between the array elements. When the number of array elements increases, the impedance of the piezoelectric vibrator decreases. As a result, the conductance value increases. Each array element is the same, so the admittance changes are also similar. The specific changes are shown in Table 2.

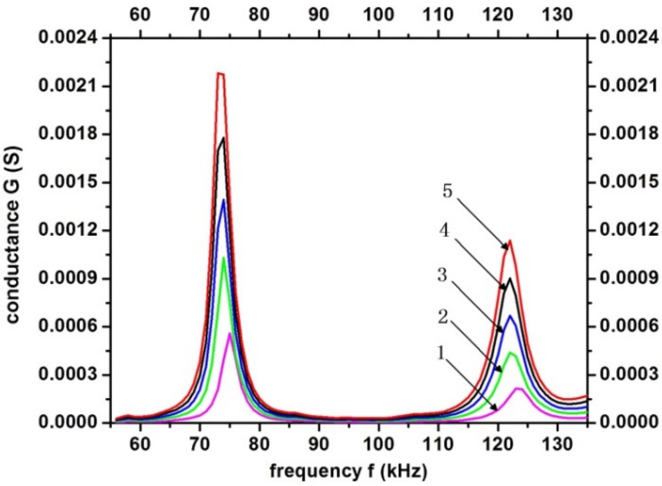


Figure 6. Frequency–conductance curves of different number of array elements

Table 2. Variation of resonant peak of piezoelectric vibrator with different number of array elements

Number of element	Resonant frequency of first resonant peak (kHz)	Resonant frequency of second resonant peak (kHz)	Conductance of first resonant peak (mS)	Difference of conductance between the two elements (mS)	Conductance of second resonant peak (mS)	Difference of conductance between two elements (mS)
1	75	123	0.56	\	0.21	\
2	74	122	1.03	0.47	0.44	0.23
3	74	122	1.39	0.36	0.67	0.23
4	74	122	1.78	0.39	0.90	0.23
5	73	122	2.18	0.4	1.14	0.24

4. Experimental measurement

4.1. Fabrication and measurement of multi-element arc piezoelectric composite vibrator

To verify the results of the finite element analysis, the piezoelectric vibrators with the same structure as the simulation are fabricated in this study. The fabrication process is as follows: The ceramic is cut and then filled with epoxy. The electrode is covered with silver paste. The matching layer is added. Secondary cut is performed. The silicone rubber is filled. Finally, the arc type mold is added.

The flow chart is shown in figure 7. The selected ceramic material is a PZT-4-type piezoelectric ceramic. The thickness of ceramic is 15 mm, the width is 36 mm, and the length is 73.6 mm.

First, the piezoelectric vibrator was measured in air. Their resonant frequencies are measured by an impedance analyzer (Agilent 4294A). The conductance curves are shown in figure 8. The resonant frequencies of the composites with one to five array elements are measured, and the conductance increases with the increase in the number of array elements, which is consistent with the simulation results. The dashed line in the figure shows the simulation curve of the 5-element arc composite vibrator. The simulation and experimental results fit well, and the fluctuation between the simulation conductance and experimental conductance is less than 0.4 mS. The two resonant peaks of simulation conductance curve appeared as 73 and 122 kHz, whereas the two resonant peaks of the experimental conductance curve are 73.8 and 117.6 kHz, respectively; the reason is that the parameters of the piezoelectric ceramics in the simulation have certain inconsistencies with the actual parameters.

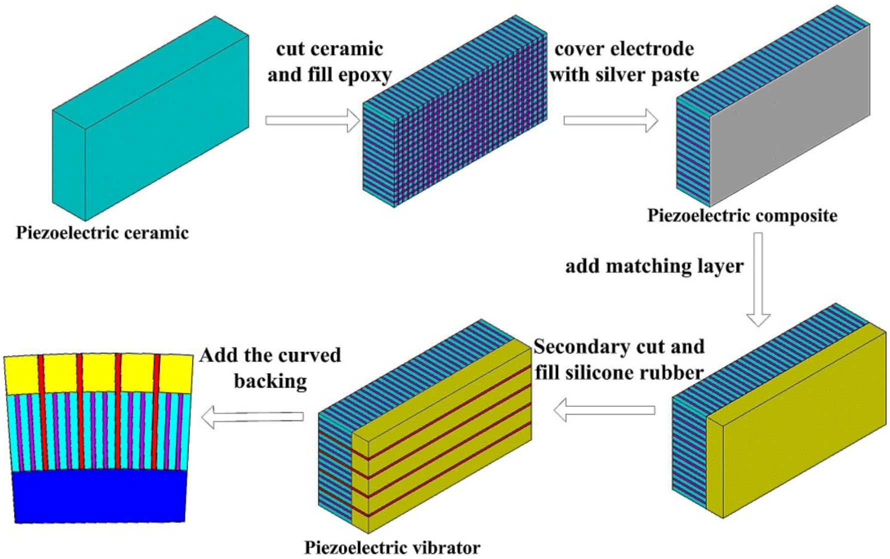


Figure 7. Fabrication flow chart of multi-element arc piezoelectric composite vibrator

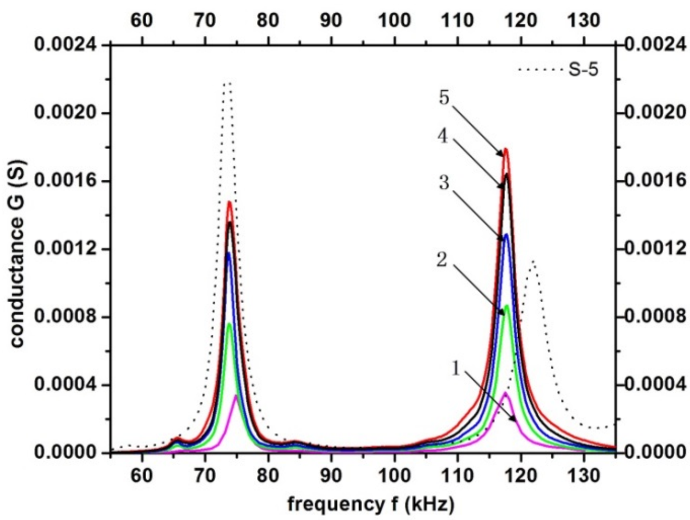


Figure 8. Comparison of simulation and experimental results of conductance curves

4.2. Fabrication and measurement of transducer

The 5-element arc piezoelectric vibrators with matching layer are then made into transducers. The structure is shown in figure 9. One end of the arc piezoelectric vibrator is designed with one sound-absorbing layer, which is made of rigid foam, and the other end is used as the emitting surface to emit sound waves. Then, polyurethane was poured and used as waterproof layer.

The transmitting voltage curves of the transducers can be obtained by the underwater acoustic measurement system. The transducer arrays with 1-, 3-, and 5-array elements were measured. The test results are shown in Table 3 and figure 10.

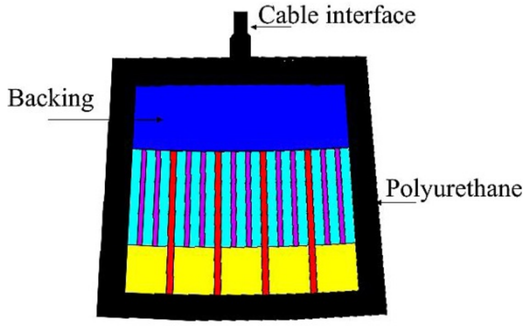
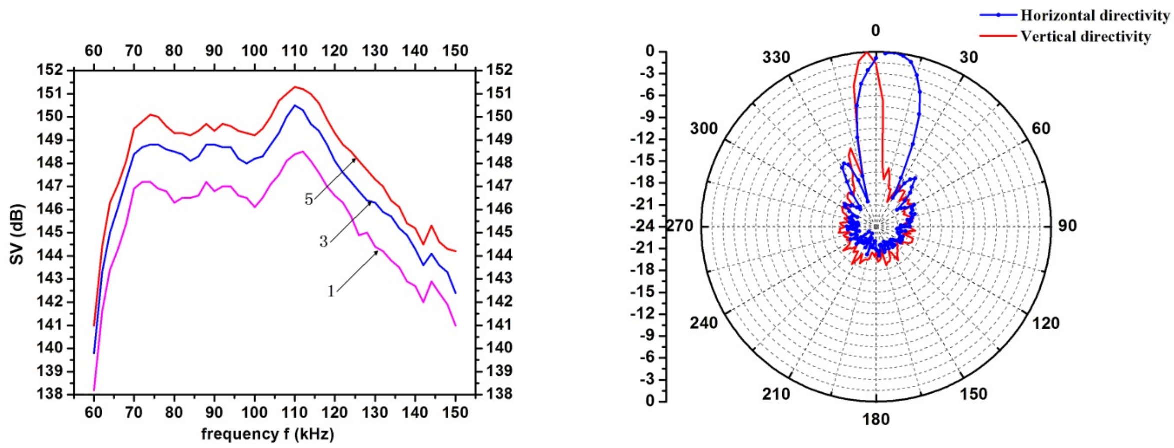


Figure 9. Schematic of transducer structure

Table 3. Performance parameters of transducer

Number of elements	Largest transmitting voltage response (dB)	Transmitting voltage response bandwidth (kHz)
1	148.5	56.5
3	150.5	54
5	151.3	56.5



(a) (b)

Figure 10. Multi-element transducer array: (a) transmitting voltage response curves and (b) directivity curves

As shown in figure 10 (a), the value of the transmitting voltage response increases as the number of array elements increases. As the number of array elements increases from 1 to 5, the transmitting voltage response increases by about 3 dB because the sound pressure at each point in the sound field is the superposition of the sound pressure generated by each array element, and the increase in the number of array elements causes the increase of the sound pressure to realize the increase of the transmission voltage response. The matching layer was then added to achieve the expansion bandwidth, where –3 dB bandwidth reached 56.5 kHz.

The directivity of the far field of the piezoelectric vibrator directly determines the wave beam angle of the transducer. Figure 10 (b) presents the horizontal directivity curve and vertical directivity curve of the 5-element transducer array at the center frequency (f = 95 kHz), where the vertical directivity –3 dB opening angle is 9° and the horizontal directivity –3 dB opening angle is 20°. Compared with the theoretical results, the vertical directivity of the opening angle is basically the same. The horizontal directivity opening angle decreased slightly because one end of the arc transducer array is a rigid foam backing and the other end is polyurethane, thereby affecting the propagation of the wave beam and resulting in a decrease in the directivity opening angle.

5. Conclusions

In this study, the 5-element arc broadband piezoelectric composite vibrator and its transducer array were designed and fabricated using the matching principle and curved forming process. First, the optimized parameters of the matching layer and the directivity of the transducer were calculated theoretically. Then, the resonant frequency of the 5-element arc piezoelectric composite vibrator was analyzed using the finite element software ANSYS. Finally, we conducted an experiment for verification. The results show that the experimental results agree well with the theoretical and simulation results. The transmitting voltage response of the 5-element arc transducer array reaches 151.3 dB, the bandwidth of the transducer is up to 56.5 kHz, the vertical directivity of the –3 dB opening angle is 9°, and the horizontal directivity –3 dB opening angle is 20°.

In the future we will expect to study 10-element and 44-element arc broadband piezoelectric composite vibrator and its transducer array, and study the characteristics of broadband and wide beam.

Acknowledgement

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