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Effect of structural parameters and stability of constituent materials on the performance of 1–3 spherical crown piezocomposite and transducer

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ABSTRACT

Transducer is the main instrument for signal transmitting and receiving. As the core component of the transducer, the preparation and performance of piezocomposite directly affect the efficiency of the transducer. The novel 1–3 spherical crown piezocomposites with resonance frequency higher than 320 kHz was prepared via arrangement-casting technique. And the effect of structure parameters on properties of piezocomposite was studied in this paper. The results showed that PZT aspect ratio had a significant effect on the resonance frequency of the piezocomposite. Resonance frequency varied from 322 kHz to 457 kHz as the PZT aspect ratio increased from 0.57 to 0.74. While resonance frequency slightly increased from 347 kHz to 368 kHz as the PZT volume fraction varied from 27.0% to 70.6%. Resonance frequency of piezocomposites were merely dependent on the temperature varying from −20 °C to 60 °C, revealing a great thermal stability. The -3 dB opening angle of the transducer was respectively 42° and 39° in horizontal and vertical directions. And the increasing PZT volume fraction was beneficial for enhancing the peak value of transmitting voltage response from 157 dB to 164 dB with -3 dB bandwidth of 42 kHz.

1. Introduction

Sonar is one of the most common pieces of equipment for detecting and positioning underwater targets by sound waves [1–3]. The transducer as the core component in sonar, directly affects the detection accuracy of sonar. And the performance of transducer depends on the properties of piezocomposites, such as the large electromechanical coupling coefficient and the strong acoustic matching ability [4–6]. 1–3 piezocomposite has widely been used in transducer of sonar since its high piezoelectric strain constant and low acoustic impedance [7,8].

As the requirements of transducers have been developing continuously, designed transducers to not only have a high resonance frequency, but also are used for wide beam transmission. Nevertheless, the transducer fabricated by 1–3 planar piezocomposite cannot achieve these requirements due to its narrow bandwidth and low sound source level [9–13]. Therefore, 1–3 piezocomposites with special shapes have attracted much interest.

An arc transducer was firstly reported on the use of curvilinear PZT arrays in imaging sonar, the radius of arc transducer was 110 mm with the resonance frequency was 375 kHz [14]. Lv et al. prepared transducer fabricated by 1–3 arc wide-band composites and the -3 dB bandwidth of transducer fabricated by composite was 56.5 kHz [15]. Liu et al. fabricated high frequency arc transducer array and the horizontal directivity of the transducer was greater than 10° while vertical directivity was less than 10° [16]. Desilets et al. had developed a ring transducer with the maximum diameter of 90 mm and -3.3 dB bandwidth of transducer was about 10.2 kHz [17]. Jia et al. developed a cylindrical transducer composed of tangentially polarized piezocomposite in order to obtain high electromechanical coupling coefficient [18]. Brown et al. developed a cylindrical piezoelectric transducer for an underwater acoustic navigation system using two orthogonal dipoles driven in phase quadrature to create an acoustic spiral wave which had coefficient amplitude and phase that varies linearly with azimuth angle [19].

In this paper, 1–3 spherical crown piezocomposites were prepared firstly and piezoelectric, dielectric and conductance characteristics of composites were studied. The effects of structural parameters on the performance of composite were also investigated via finite element modeling (FEM) and verified by experimental results. And the effect of temperature on the performance of high temperature resistant epoxy was investigated

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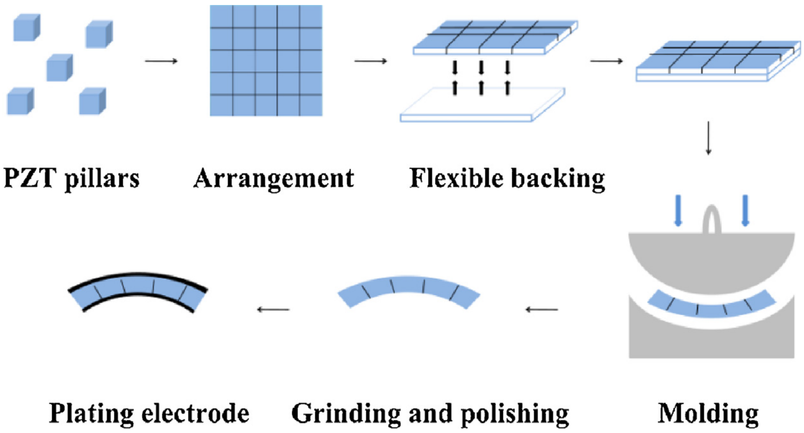

Fig. 1. Flow chart of preparation process of 1–3 spherical crown piezocomposite.

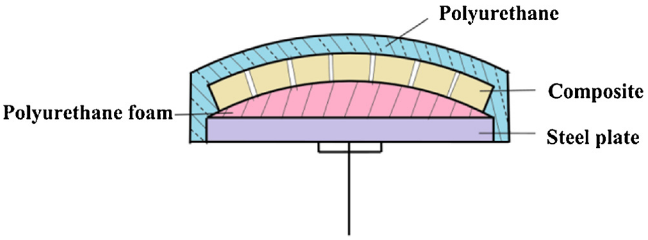

Fig. 2. Schematic diagram of spherical crown transducer.

to obtain the thermal stability of composite and transducer in different environmental temperatures. Then the spherical crown transducers were assembled and the underwater acoustic performances, such as the directivity and the transmitting voltage response were measured.

2. Experimental procedures

Piezoelectric ceramic PZT-4 (Weifang Jude Electronics Co., Ltd., China) was used to be functional phase and epoxy DW-3 (Shanghai Huayi resin Co., Ltd., China) was chosen to be matrix to fabricate 1–3 spherical crown piezocomposite. The arrangement-casting method was used to fabricate the composite. The fabrication process was illustrated in Fig. 1. Firstly, PZT pillars were arranged to be a square array in a horizontal flexible backing (Double sided tape, MinnesotaMining and Manufacturing Company, America). Then the PZT array was placed into a spherical crown mold and epoxy was poured into the mold to fill the gaps between PZT pillars. Firstly, piezocomposite was heated at 80 °C for 1 h, and vacuum technology was used to ensure the discharge of the internal bubbles in the epoxy. Secondly, a ramp temperature to the piezocomposite until 120 °C at a speed of 3 °C/min for 2 h and pressure of 5 MPa were applied to obtain the required shape of piezocomposite. Then, the temperature continuously increased to 150 °C for 2 h until the epoxy was fully curried. Finally, the piezocomposite was cooled to the room temperature. During the fabrication process, the shrinkage of epoxy was very weak, so the variation of volume had little effect on the shape of piezocomposite. Subsequently the nickel electrode was prepared by electroless plating using oxidation reduction method on composite's curved surfaces [20]. Finally, a spherical crown transducer was assembled using a 1–3 spherical crown piezocomposite. The schematic configuration of transducer was shown in Fig. 2. The piezocomposite and the polyurethane foam were served as the functional phase and the backing layer in this transducer respectively. Meanwhile polyurethane RC0801(Shanxi Chemical Research Institute, China) and steel plate 304 with a size of 60 mm × 60 mm × 8 mm (Suzhou Svetlje machinery processing Co. Ltd., China)on the surface were to ensure the integration of structure and form a waterproof layer with a thickness of 3 mm. The structural parameters of PZT pillars in the transducer were listed in Table 1.

The piezoelectric strain coefficient d_{33} was measured by a d_{33} meter (The Institute of Acoustics of the Chinese Academy of Sciences, ZJ-3 A). Dielectric loss $tan\delta$, permittivity ε_r, capacitance C and conductance G were obtained by impedance analyzer (Agilent Technologies, Agilent 4294 A). The d_{33} and ε_r obtained were used to calculate piezoelectric voltage coefficient g_{33}, according to

$$g_{33}=d_{33}/\varepsilon_0\cdot\varepsilon_r \tag{1}$$

where ε_0 is the permittivity of free space of 8.85×10^{-12} F/m and ε_r is the relative permittivity of composite. Then the acoustic performances of transducer including the horizontal and vertical directivity at a fixed frequency of 300 kHz and the transmitting voltage response were measured at an anechoic pond (China Shipbuilding Industry Corp 726, China).

3. Results and discussion

3.1. Effects of volume fraction of PZT pillar

The dielectric loss $tan\delta$ was the average value of D measured at1 kHz and relative permittivity ε_r was calculated by Eq. (2)

$$\varepsilon_r = C\cdot t/\varepsilon_0\cdot A \tag{2}$$

where A and t were area and thickness of composite with electrode respectively.

Fig. 3 shows the variation of ε_r and $tan\delta$ of 1–3 spherical crown composite as a function of the volume fraction of PZT. As can be seen, ε_r increased from 360 to 780 with the increase of the PZT volume fraction from 27.0% to70.6%. However, ε_r of the composite was obviously smaller than that of PZT since the ε_r of epoxy was 9.43 which was extremely small compared with that of PZT of 1200. So the effect of epoxy was weak enough to be ignored. It could be inferred that the permittivity of composite could be expressed by Eq. (3) [21]:

$$\varepsilon_{1\text{-}3} = \alpha\cdot\varepsilon_p+(1\text{-}\alpha)\varepsilon_e\approx\alpha\cdot\varepsilon_p \tag{3}$$

where the subscripts *1–3*, *p* and *e* represented1–3 composite, PZT and epoxy respectively. Therefore the theoretical permittivity of composite varied linearly with the volume fraction of PZT. And the results of experimental permittivity showed a great coincidence with the theoretical results as shown in Fig. 3, which confirmed the feasibility of Eq. (3).