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Fabrication and properties of 1-3-2 multi-element piezoelectric composite

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Abstract A design method is presented for 1-3-2 type multi-element piezoelectric composite so as to provide basis for the development and study of transducer and transducer array. The composite samples have been fabricated by a twice dice-filling process from lead zirconate titanate (PZT-4), epoxy resin and silicone, the properties of the composites have been measured and investigated physically. The results show that the piezoelectric, dielectric and electromechanical coupling properties of the composite exhibit a good consistency, while it has a high thickness electromechanical coupling factor K_t and a wide bandwidth of pulse-echo signal. The impedance plot of every element indicates good behavior that all elements show excellent frequency consistency, and on the other hand the chance of coupling of lateral resonance and thickness resonance is very small, and with a clear thickness resonance mode at around 100 kHz. Silicon has extremely decoupling properties which can efficiently block the transmission of the acoustic vibrations and eliminate coupling effect among elements. And the farther the distance between the incentive element and receiving element is, the smaller the response signal become, while the response signal decay rate exhibits the trend of increase, the largest up to 95%.

Keywords Piezoelectric composite · Multi-element · Consistency · Coupling performance

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1 Introduction

Transducer and transducer array are the key components of sonar system [1, 2], which are used to switch electrical signal with sound signal effectively to process pulse signal and control information. So, it is critical important to choose suitable materials applied to transducer and transducer array. Piezoelectric composites have attracted a great deal of attention and been widely used in the field of transducer structures due to its excellent integrated properties [3, 4]. Among them, the 1-3 piezoelectric composite is the most extensive material. But its fabrication is complex, and furthermore it deforms easily with heating and mechanical impact, thus it cannot satisfy the high stability requirement. 1-3-2 piezoelectric composite is a special type of 1-3 piezoelectric composite, which combines the structural characteristics of both parallel 1-3 connectivity and series 2-2 connectivity composites. A variety of advantages of 1-3-2 piezoelectric composite has been identified, such as low density, high hydrostatic piezoelectric response, high electromechanical coupling factor and improved impedance matching [5, 6]. And more significantly, it has a higher structural stability than 1-3 piezoelectric composite [5], so that it is not affected easily by environmental temperature and outside mechanical impact.

1-3-2 piezoelectric composite is typically used as independent element to prepare transducer array according to a certain formation. However, transducer array prepared by this method cannot get an excellent consistency and stability, and the method is too complicated. Thus, it cannot satisfy the request of high consistency when it is used in transducer and transducer array. In this paper, a new concept of 1-3-2 multi-element piezoelectric composite is proposed to solve this problem. 1-3-2 multi-element piezoelectric composite is fabricated by filling decoupling materials into

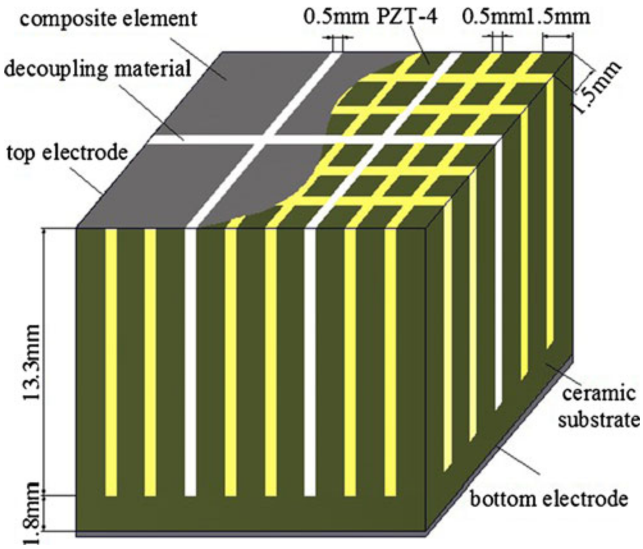

Fig. 1 Structure of 1-3-2 multi-element piezoelectric composite

the grooves between every element, which equates to a simple transducer array that every element can launch sound waves independently[7, 8]. What's most important is it has remarkable consistency, low coupling performance, and it can improve the transmitting efficiencies and receiving sensitivity of transducer array significantly.

In this study, a design method of multi-element piezoelectric composite has been proposed on the basis of composite principle and piezoelectricity theory. The composites have a PZT-4 rod volume fraction of 55.29% and cross-sectional dimensions of 1.5 mm×1.5 mm. The piezoelectric, dielectric and electromechanical coupling properties have been measured and the consistency and coupling performance were analyzed systematically.

2 Experimental methods

2.1 Composites preparation

PZT-4, epoxy resin and silicone were used to fabricate 1-3-2 multi-element piezoelectric composites by twice dice-filling technique. The structure of 1-3-2 multi-element piezoelectric composite was shown in Fig. 1, it includes composite elements, decoupling material, ceramic substrate, top and bottom electrodes.

Figure 2 shows the fabricating procedure of 1-3-2 multi-element piezoelectric composite. The WSQ50 diamond cutter was used to cut the PZT-4 ceramic with saw blade thickness of 0.5 mm. Initially, the PZT-4 ceramic was cut in two mutually perpendicular directions, as shown in Fig. 1 (b). After the first cutting, the specimen was cleaned in an ultrasonic cleaning machine, and the epoxy resin (the ratio of epoxy resin and curing agent was 4:1) was poured into the ceramic grooves. After curing, the two-phase composite with ceramic/ epoxy resin was formed. And then, the two-phase composite was cut in the second time along the perpendicular direction, as shown in Fig. 1(d). After cleaning, the silicone (the ratio of silicone and curing agent was 1:3%) was poured into the grooves, and cured 24 h at room temperature. The upper and lower surfaces of the composite were polished until the silicone cured. After polishing, a silver paint was applied on the surfaces of the composites for measurement. Following these processes, multi-elements composite with three phases (ceramic/epoxy/decoupling material) was obtained. The finished sample is shown in Fig. 3.

2.2 Performance testing

Model ZJ-3A d_{33} Quasi-static Measuring Instrument was used to measure the piezoelectric strain factor d_{33}. Resonant frequency f_s, anti-resonance frequency f_p, corresponding impedance R, capacitance C and dielectric loss $tan\delta$ of the composites were measured using an Agilent 4294A Impedance Phase Analyzer. Thickness electromechanical coupling coefficient K_t, mechanical quality factor Q_m and piezoelectric voltage factor g_{33} were calculated by Eqs. 1, 2, 3 and 4, respectively.

3 Results and discussion

3.1 Piezoelectric and dielectric properties

1-3-2 multi-element piezoelectric composite is an array with a specific type whose every element is a bi-phase piezoelectric

Fig. 2 Flow chart of fabricating 1-3-2 multi-element piezoelectric composite

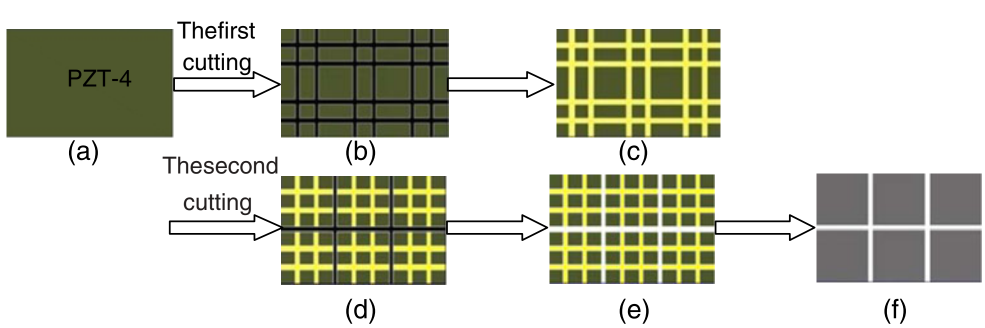

Fig. 3 1-3-2 multi-element piezoelectric composite

composite composed of piezoceramic and polymer. The dielectric constant ε_r and piezoelectric voltage factor g_{33} was calculated by Eq. 1, 2.

$$\varepsilon_r = Ct/\varepsilon_0 A \quad (1)$$

$$g_{33} = d_{33}/(\varepsilon_r \times \varepsilon_0) \quad (2)$$

Where t and A are thickness and electrode area of the specimen, respectively, ε_0 is the vacuum permittivity whose value is 8.85×10^{-12}F/m, and the capacitance C was measured at 1 kHz.

Table 1 gives the piezoelectric and dielectric properties of pure PZT4 and 1-3-2 multi-element piezoelectric composite. It can be seen that the fluctuation of values of dielectric constant ε_r, dielectric loss $tan\delta$, piezoelectric strain factor d_{33} and piezoelectric voltage factor g_{33} for different elements is very small, so the piezoelectric and dielectric properties of the composite have significant consistency. That probably due to the composite is cut in the same matrix and with the same dimension and every element is a bi-phase piezoelectric composite composed of piezoceramic and polymer.

It can also be seen that comparing to that of pure PZT4, the ε_r and $tan\delta$ values of all elements are smaller and the g_{33} values are bigger, which is helpful for 1-3-2 multi-element piezoelectric composites to be used as transducer array in the sonar system. The piezoelectric strain factor of polymer is smaller than piezoceramics, so the d_{33} values of all elements are smaller than pure PZT4, however, the overall performance of composite is improved.

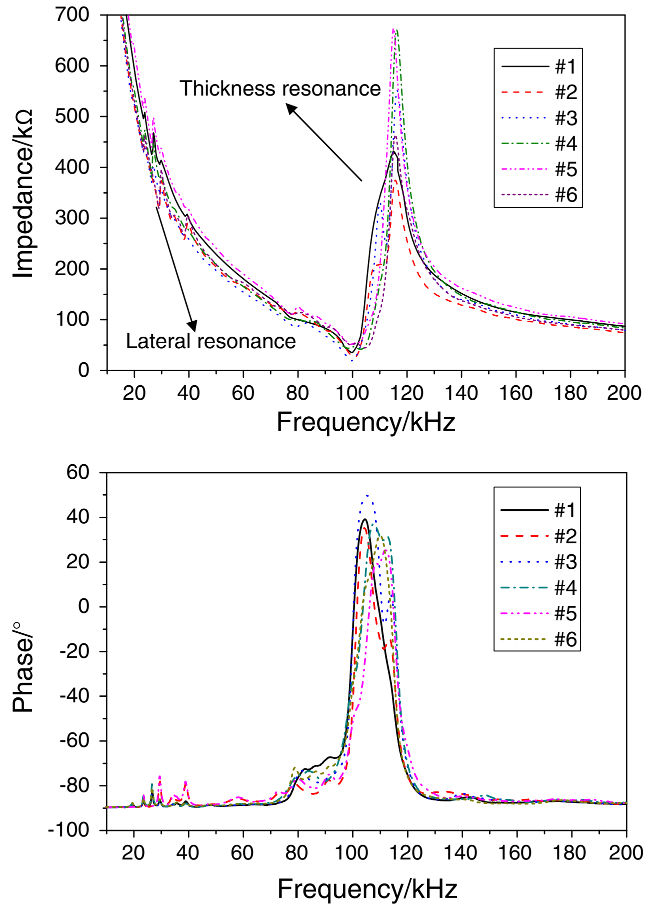

Fig. 4 Impedance magnitude and phase spectra of 1-3-2 multi-element piezoelectric composite

3.2 Electromechanical coupling properties

The modulus of the electrical impedance and phase spectra of every element in air are measured as a function of frequency, using an Agilent 4294A Impedance Phase Analyzer, in the frequency range 40 Hz–200 kHz, as can be seen in Fig. 4. It can be observed that some peaks appear in the impedance and phase curves, a clear fundamental resonance (thickness resonance) mode at around 120 kHz has been found except for a weak lateral resonance at 30 kHz. This means that the thickness resonance mode clearly defined and well separated from the lateral resonance mode, which almost from the impact of lateral resonance. It can also be observed that each element indicates a wide bandwidth of pulse-echo signal. These

Table 1 Piezoelectric and dielectric properties

Element	PZT4	#1	#2	#3	#4	#5	#6
ε_r	999	739	846	796	802	823	709
$tan\delta$	0.02	0.0066	0.0071	0.0058	0.0062	0.0071	0.0077
d_{33} / PC·N^{-1}	210	182	185	190	178	189	185
g_{33} / mV·m·N^{-1}	23.8	29.1	25.8	27.8	27.8	26.6	30.0

properties are vital to improve the signal noise ratio and resolution of piezoelectric transducer and transducer array.

From the resonance (f_s) and anti-resonance (f_p) frequency measured from the impedance peaks, the thickness electromechanical coupling coefficients K_t and mechanical quality factor Q_m of different elements were calculated by Eqs. 3, 4 and listed in Table 2.

$$K_t^2 = \frac{\pi}{2} \cdot \frac{f_s}{f_p} \cdot \tan\left(\frac{\pi}{2} \cdot \frac{f_p - f_s}{f_p}\right) \tag{3}$$

$$Q_m = \frac{1}{2\pi f_s RC\left(\frac{f_p^2 - f_s^2}{f_p^2}\right)} \tag{4}$$

Where R is the corresponding impedance that can be replaced by the minimum impedance value.

It can be seen that the thickness frequencies of all elements show an excellent consistency, which can make transducer array transmit multiple beams to scan and detect efficiently. It also can be seen the mechanical quality factor Q_m are much smaller than the pure PZT4 (48.6). The low Q_m value makes the piezoelectric composite materials suitable for producing wide broadband and narrow pulse transducer.

3.3 Coupling performance

The coupling performance between any two elements was measured by the signal generator and oscilloscope. Sine wave with frequency of 100 kHz and peak of 10 V was transmitted by the signal generator, which incent the element #1 vibration. At the same time, the response signals of element #1, #2, #3 and #4 were measured, as can be seen in Fig. 5. It is evident that the response waveform of received elements is still sine wave, however, the amplitude decrease. This is because silicon has functions of damping, soundproofing, sound-absorbing and decoupling, which can block the transmission of the acoustic vibrations among elements. It can also be observed that the farther the distance between the incentive element and receiving element is, the smaller the response signal become. Table 3 provides the decay rate of every element. It can be seen that the decay rate of every element is tremendous big, the maximum value of decay rate up to 95.0%, this property makes every element launch sound waves independently, without interacting.

Table 2 Electromechanical coupling properties of 1-3-2 multi-element piezoelectric composite

Element	f_s /kHz	f_p /kHz	Δf	K_t /%	Q_m
#1	99.78	115.06	15.28	53.69	15
#2	100.84	115.86	15.02	53.12	17
#3	99.87	115.08	15.21	53.58	22
#4	103.6	116.3	12.7	49.22	12
#5	105.11	115.86	10.75	45.73	13
#6	102.62	115.42	12.8	49.57	11

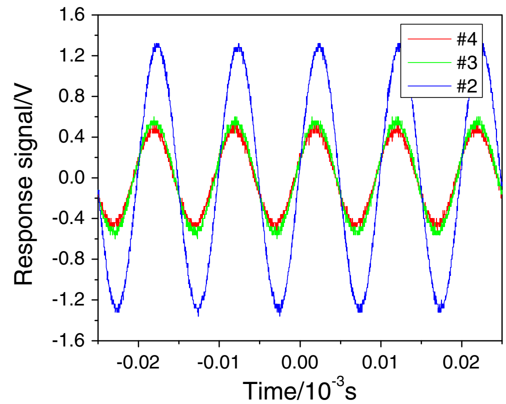

Fig. 5 Response waveform of each element

4 Conclusions

In this work, the electromechanical and coupling properties of 1-3-2 multi-element piezoelectric composites were measured, which fabricated using PZT-4 as the active component, epoxy resin as matrix and silicone as decoupling materials by a twice dice-filling technique. All elements of the composite exhibit a good consistency of piezoelectric, dielectric, frequency and electromechanical coupling properties. Compared with pure PZT4, ε_r and $tan\delta$ values of all elements are smaller and the g_{33} values are bigger. The electrical impedance and phase spectra of every element appear some peaks that the main peak is obviously higher than side peaks. That is the thickness resonance mode clearly defined and well separated from the lateral resonance mode, which make energy focus on the direction of thickness. The intercoupling effect among elements is extremely small, and with the distance between the incentive element and receiving elements increasing, the response signal amplitude rapidly decreases.

The properties of multi-element piezoelectric composites showed great potential for application in transducer and transducer array. In the near future, research will be carried out to apply 1-3-2 multi-element piezoelectric composites in sonar system.

Table 3 Response signal amplitude and decay rate of each element

Element	#1	#2	#3	#4
Distance/mm	0	4.56	9.12	10.20
Response voltage ΔV/V	20	2.72	1.24	1.00
Decay rate/%	0	86.4	93.8	95.0

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