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Dimension dependence of thickness resonance behavior of piezoelectric fiber composites

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HIGHLIGHTS

- PZT5 fiber/polymer 1–3 composites were fabricated by viscous polymer processing.
- Aperiodic fiber arrangement structures were confirmed.
- The aspect ratio t/d is critical to the resonance behaviors of the composites.
- Pure thickness resonance model was achieved.

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ABSTRACT

Aperiodic arrangement PZT5 fiber/epoxy resin 1-3 piezoelectric composites were fabricated by viscous polymer processing. The impedance spectra were used to discuss the radial and thickness resonance models dependent on the size of 1–3 composites. The aspect ratio t/d is found critical to the resonance parameters. As the aspect ratio t/d reducing, the mechanical quality factor Q_m would decrease, the frequency constant N_t and the acoustic impedance Z increasing. In general, the composites showed nearly a pure thickness mode with high anisotropy coefficient ($k_t/k_p \sim 1.38$–2.75) and low acoustic impedance ($Z \sim 9.5$–11.7 Mrayl) superior to those of monophasic PZT5 materials that have potential applications in medical ultrasonic transducers.

1. Introduction

1-3 piezoelectric composites present outstanding behaviors than traditional piezoelectric materials, such as low acoustic impedance Z, low dielectric constant ε', low hydrostatic piezoelectric coefficient, low mechanical quality factor Q_m, small radial mechanical electrical coupling coefficient k_p, good flexible, and so on, so they are widely applied in the fields of underwater acoustic, electro acoustic and ultrasonic [1–6]. As to 1–3 parallel structures that consisting of different elastic modes by ceramics and the polymer, the stress applied on the polymer can transfer to the ceramics, accompany with an arising magnification factor γ, which was defined partially by the elastic coefficient and contents of the two phases, as well as by the aspect ratio t/d of ceramic fibers (t is the thickness of 1–3 composites and d is the diameter of ceramic fibers). The value γ normally increased with the aspect ratio increasing. Meanwhile t/d also influenced other properties of the composites.

As the ceramic volume fraction is constant, normally, with increasing the aspect ratio, dielectric constant ε' would reduce, piezoelectric constant d_{33} increasing, hydrostatic figures of merits increasing, especially at lower t/d values. The enhancement of the hydrostatic figures of merits will be very slowly and reach an upper limit ultimately especially when t/d is above 50 [7]. On the other hand, when t/d is too high, a transverse resonance mode will arise and disturb the thickness one, lowering the thickness resonance frequency. Thus, the composites with egregious thickness present smaller thickness resonance frequency and then a low resolution of the transducer. Therefore, an optimized thickness (or t/d value) is demanded.

We mainly introduced the radial and thickness resonance modes of 1–3 PZT5/E − 51 piezoelectric composites by viscous polymer processing (VPP) with a fixed ceramic volume fraction of 30 vol% [8,9]. The radial and thickness mechanical electrical coupling coefficients k_p, k_t

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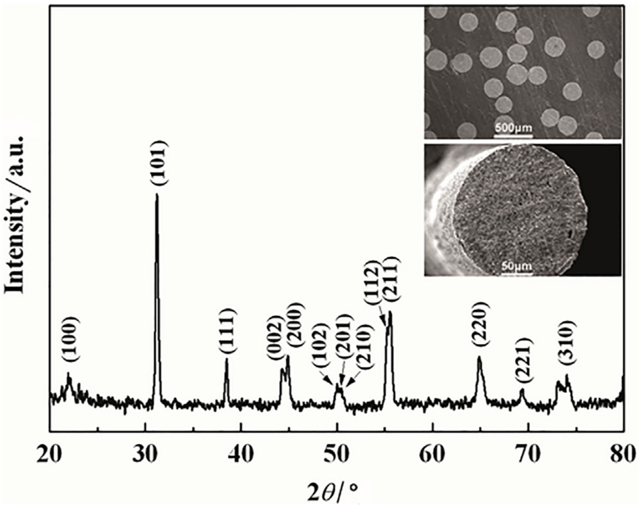

Fig. 1. XRD patterns of PZT5 ceramic fibers (the inserts are SEM images of 1–3 composites and PZT5 fibers).

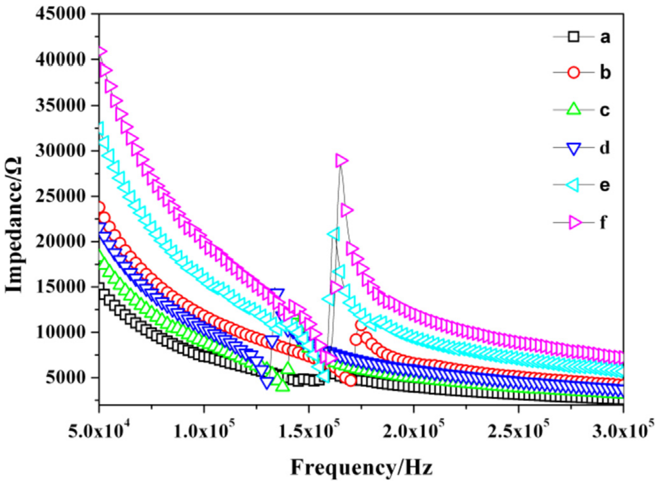

Fig. 2. Radial impedance spectra at the frequency of 50–300 kHz with different sample size (Diameter $D \times$ Thickness t): (a) 7.84 × 0.57 mm^2, (b) 6.58 × 0.74 mm^2, (c) 8.62 × 0.98 mm^2, (d) 8.88 × 1.26 mm^2, (e) 7.80 × 1.48 mm^2 and (f) 7.68 × 1.76 mm^2.

dependent on the fiber aspect ratio t/d were systematically discussed, as well as the anisotropy parameters.

2. Experimental procedure

PZT5 fibers were fabricated by viscous polymer processing (VPP) with commercial PZT5 calcined powders, polyvinyl alcohol (PVA) binder and glycerol. The gel fibers were then sintered at 1280 °C for 4 h to form ceramic fibers [10]. A bundle of fibers were inserted and arranged randomly in a glass tube of Φ10 mm, following by casting epoxy resin E−51 and curing to form 1–3 connecting structures. The composite rods were then cut and polished to slices with diameters of 6.58–8.88 mm and thicknesses of 0.57–1.76 mm. Air-dry silver paste was coated on both sides of the slices and then dried at 100 °C for 4 h to form electrodes. The electric poling was done perpendicular to the flake surface at the electric field of 2.5 kV/mm and temperature of 100 °C for 30 min.

The fiber phase was confirmed by using an X-ray diffractometer (XRD) (Panalytical X-pert Pro) with CuKα radiation. The microstructure was observed by a scanning electron microscope (SEM, Japan JSM-5610 LV Electron Microscope). The radial and thickness impedance spectra ($Z_m - f$) as well as the dielectric spectra of 1–3 composites were implemented on Agilent 4294A precision impedance analyzer from 40 Hz to 10 MHz. The capacitance at 1 kHz, the radial resonant frequency f_r and the anti-resonant frequency f_a, the series and parallel resonant frequencies f_s and f_p were sought out. The radial mechanical electrical coupling coefficient k_p was calculated and checked by GB standard [11]. While as the value of $\Delta f/f_r$ was lower than 0.001, k_p is calculated by $k_p{}^2 = 2.51 \times (f_a - f_r)/f_r$. The thickness mechanical electrical coupling coefficient k_t, mechanical quality factor Q_m, acoustic speed V^D and acoustic impedance Z can be calculated as following [12].

$$k_t = \sqrt{\frac{\pi}{2}\frac{f_s}{f_p}\mathrm{tg}\left[\frac{\pi(f_p - f_s)}{2f_p}\right]} \tag{1}$$

$$Q_m = \frac{1}{2\pi f_s R_1 C^T\left(\frac{f_p^2 - f_s^2}{f_p^2}\right)} \tag{2}$$

$$V^D = 2f_p l \tag{3}$$

$$Z = \rho V^D \tag{4}$$

where R_1 is equivalent resistance at 1 kHz; l the sample thickness and ρ the sample density. The density ρ of the composites (ceramics content of 30 vol%) was confirmed to be 2.81 g/cm^3 based on Archimedes principle.

3. Results and discussion

Fig. 1 shows XRD patterns of PZT5 ceramic fibers and the inserts are SEM images of 1–3 composites and fibers. Tetragonal phase of PZT5 ceramic fibers were confirmed and SEM images showed diameter of ~250 μm. Aperiodic arrangement was observed for 1–3 composites.

3.1. Radial resonance mode

When the bias voltage is applied in the electric poling direction (perpendicular to the composite surface), the radial resonance can occur in-plane that relates to the diameter of the plate and is called a radial mode. Because the diameter d is far larger than the thickness t of 1–3 composite plate, the radial mode has the lowest frequency among all vibration modes. Fig. 2 shows radial resonance impedance spectra of 1–3 composites dependent on the sample size. Table 1 gives data of the fundamental resonance frequency f_r and the anti-resonance frequency f_a. As the diameter D was close in Fig. 2(a), (e) & (f), f_r increased with increasing the thickness t, namely, increasing the aspect ratio t/d. As

Table 1
Resonance frequency f_r, anti-resonance frequency f_a and radial mechanical electrical coupling coefficient k_p.

Property parameters	Diameter $D \times$ Thickness t (mm^2)					
	7.84 × 0.57	6.58 × 0.74	8.62 × 0.98	8.88 × 1.26	7.80 × 1.48	7.68 × 1.76
f_r (kHz)	146	170	138	130	157	160
f_a (kHz)	151	174	143	134	162	165
k_p (%)	28	24	30	28	28	28