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The influence of structural parameters on the actuation performance of piezoelectric fiber composites

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ABSTRACT

Piezoelectric fiber composites with interdigitated electrodes have attracted increasing interest in a variety of areas due to their unique performances. Viscous plastic processing technique was utilized for the fabrication of composite with customized feature sizes. The structural parameters, e.g., electrode finger spacing, fiber thickness, interlayer thickness and volume fraction of piezoceramic fiber, showed great influence on the free strain performance of composites, which were verified by both finite element analysis and experimental measurement. Electric field distributions along the longitudinal direction of piezoceramic fiber were used to discuss the actuation mechanism of piezoelectric fiber composites. The results revealed that narrower electrode finger spacing and thinner interlayer would be beneficial for improving the free strain performance. Smaller fiber thickness led to better free strain performance, owing to higher electric field strength and larger volume fraction of active zone in piezoceramic fiber. The free strain performance was enhanced nonlinearly with the increase of volume fraction of piezoelectric ceramic fiber.

1. Introduction

Piezoelectric materials are considered as the ideal candidates in smart and adaptive material systems due to the capability of sensing, actuation and control [1–4]. However, the drawbacks of traditional monolithic piezoceramic, e.g., vulnerable to accidental impact and hardly compliant to a curved surface due to the inherent brittle nature of ceramics as well as the high mass density restrict the applications of piezoceramic in many areas, particularly in areas such as curved or irregularly shaped surfaces and flexible or lightweight structures[5,6]. To overcome these limitations, an active fiber composite (AFC), which is composed of circular cross-section piezoceramic fiber, was originally developed at MIT [7], followed by the reputed macrofiber composite (MFC) invented at NASA Langley Research Center employing rectangular cross section fiber instead of circular cross-section fiber as a means of overcoming the small contact area between the electrode and the piezoelectric fibers was developed at NASA Langley Research Center [8]. The two kinds of structures are collectively referred to piezoelectric fiber composites (PFCs). PFCs are composed of active unidirectional piezoceramic fibers embedded in epoxy matrix and sandwiched between two interdigitated electrode (IDE). IDE patterns allowed PFCs to produce in-plane actuation utilizing d_{33} piezoelectric effect compared with the traditional monolithic piezoceramic, which utilized d_{31} piezoelectric effect to produce through-the-thickness actuation [3,9,10]. In addition, the combination of brittle piezoceramic fibers and elastic matrix provides the load transfer mechanism which increases robustness of the composites to damage and offers conformability and flexibility [11]. These benefits due to the unique structures have provided PFCs a wide variety of applications, e.g., structural health monitoring systems, actuation, energy harvesting, and vibration damping systems [12–15].

Although the application of IDE could provide many structural advantages, it also leads to distinctly inhomogeneous electric field distribution in PFCs [9,16], inducing nonuniform polarization and piezoelectric effect, which further influences the performance of PFCs. The finite element analysis was used to investigate the influences of geometrical parameters such as piezoceramic fiber thickness/diameter and orientation, electrode finger spacing and width on the performance of PFCs actuator with IDE to acquire the optimum structure of PFCs. Warkentin [17] reported that the IDE actuator based on the piezoceramic behaved more like the ideal case as both ratios of electrode spacing to electrode width and of electrode width to piezoceramic thickness increased. Rossetti [18] predicted larger ratio of electrode spacing to fiber diameter led to higher efficiency of actuation performance of PFCs on the basis of a constant electric field. Bowen et al. [19] claimed that PZT wafers could obtain the maximum strain when the optimum ratio of electrode finger width to substrate thickness was 0.5. Beckert [20] proposed that both decreasing the electrode finger width and increasing the electrode finger spacing could improve the

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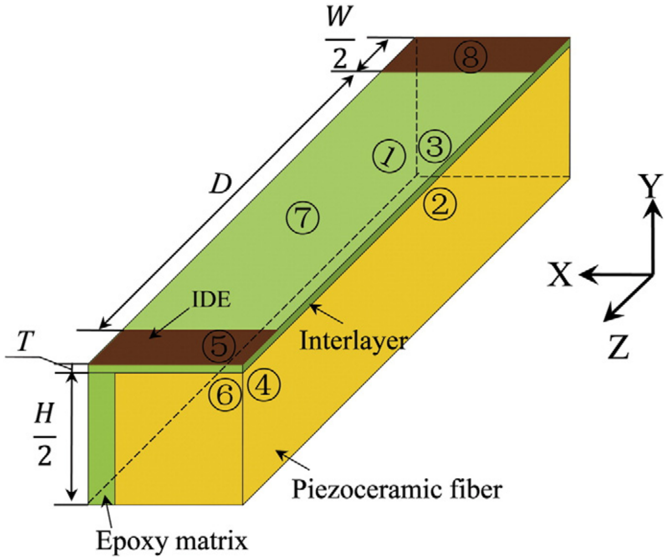

Fig. 1. Schematic structure of RVE for the modeling.

actuation performance of PFCs with circular fibers. Zhang [21] developed a linear electro-mechanically coupled finite element model and found that PFCs using d_{33} piezoelectric coefficient with different fiber angles produced larger actuation forces than that using d_{31} piezoelectric effect.

Although the above-mentioned studies on simulation of PFCs were carried out, there were few reports taking into consideration the agreement between finite element results and experimental results. The aim of present work is to validate finite element analysis about the effect of electrode finger spacing, fiber thickness, interlayer thickness and volume fraction of PZT fiber on the free strain performance of PFCs by experimental results. Further investigation on electric field distribution in PZT fiber with variation of geometric parameters and the mechanism of electric field effects on free strain performance were presented and discussed.

2. Experimental procedure

The PFCs used in present study were fabricated by viscous plastic process method with an active area of 28 mm × 8 mm and an electrode finger width of 0.06 mm [22]. The piezoceramic material used for the fabrication of PFCs was soft PZT-51.

The standard electrical resistance foil strain gages with the active area of 2.0 mm × 2.4 mm (Jinan Sigmar Tech Co., Ltd., China) bonded to the center of the top and bottom of mechanically unconstrained PFCs [22,23] were used to obtain both longitudinal and transverse strain simultaneously. The set of test system was controlled by a computer using NI-LabView interfaces. A sine-wave voltage generated by a function generator (National Instruments) was amplified by a voltage amplifier (Smart Material Corp.) and then applied to the PFCs. Monitoring of the strain gage data and control of the amplifier voltage were made using an acquisition card and LabView software. The actuation experiments were conducted at a frequency of 0.1 Hz and a typical voltage input range of −500 V to +1500 V [23]. Moreover, the average value of thirty stable cycles was obtained and used for further evaluation. These data were used to characterize the free strain performance under unloaded operating conditions.

Table 1
Material properties used for the finite element investigation.

Material property	PZT-51 [24]	Matrix [25]	Units
ρ	7600	1170	kg m^{-3}
e_{31}	−10	0	m V^{-1}
e_{33}	24	0	m V^{-1}
e_{15}	17	0	m V^{-1}
$c^E{}_{11}$	6.02×10^{10}	10.18×10^{10}	N m^{-1}
$c^E{}_{33}$	6.09×10^{10}	9.392×10^{10}	N m^{-1}
$c^E{}_{12}$	-17.42×10^{10}	-6.416×10^{10}	N m^{-1}
$c^E{}_{13}$	-13.85×10^{10}	-6.776×10^{10}	N m^{-1}
$c^E{}_{44}$	2.11×10^{-11}	1.84×10^{10}	N m^{-1}
$\varepsilon^T{}_{11}$	2200	3.4	–
$\varepsilon^T{}_{33}$	2136	3.4	–

Table 2
Boundary conditions of displacement (d) and electrical potential (U) applied to the RVE.

Face number	Mechanical condition	Electrical condition
①	$d_x = 0$	$D_x = 0$
②	$d_y = 0$	$D_y = 0$
③	$d_z = 0$	$D_z = 0$
④	Coupled d_x	$D_x = 0$
⑤	coupled d_y	$U = -500$ V
⑥	coupled d_z	$D_z = 0$
⑦	coupled d_y	$D_y = 0$
⑧	coupled d_y	$U = 1500$ V

2.1. Modeling

A finite element analysis with ANSYS was established for the simulation of free strain performance of PFCs. In order to minimize computational complexity, a unit cell comprising all relevant parameters was defined. Due to the symmetry, the so-called representative volume element (RVE) could be defined as one quarter of a single fiber between two IDE fingers and its surrounding matrix, as shown in Fig. 1. The thin polyimide film, which incorporated IDE, was not included in the model as an extra material. The electrode was not modeled explicitly, but it was represented instead by an electric constraint, assuming constant potential on the electrode finger region of the PZT fiber surface. The electrical load in the model was represented by the control voltage applied between neighboring electrode fingers. Based on the uniform field model, a simplified approach was used with the assumption of homogeneous piezoelectric properties throughout the piezoelectric fiber. The properties of PZT and epoxy matrix used for the finite element investigation were listed in Table 1. The fiber thickness, electrode spacing, electrode finger width, volume fraction of piezoceramic fiber and interlayer thickness between electrodes and PZT fibers in the model were represented by H, D, W, T and V, respectively. The applied mechanical and electrical boundary conditions to RVE were detailed in Table 2.

3. Results and discussion

3.1. The influence of electrode spacing

The free strain test system was used to test the free strain performance of PFCs along the longitudinal and transverse axis of PZT fiber vs. applied actuation voltage spectra with different electrode spacings at the fiber thickness of 200 μm and PZT fiber volume fraction of 80%, which were shown in Fig. 2. The results demonstrate nonlinear hysteretic behavior between the free strain of the PFCs and the actuation voltage, which was typically observed in piezoceramic actuators. PFCs actuators with high levels of free strain capability and actuation anisotropy also demonstrated great suitability to the design of tailored smart structures. It also can be seen that PFCs with the electrode spacing of 500 μm demonstrated optimal free strain performance, when the free strain in the longitudinal and transverse directions reached 1900 με and 930 με, respectively. Further increase of the electrode spacing to 700 μm and 1000 μm, the free strain value decreased to 1618 με and 1461 με, and to 819 με and 750 με in two orthogonal directions, respectively. It can be inferred that the actuation performance of PFCs enhanced by 1.3 and 1.24 times as the electrode spacing decreased from 500 μm to 700 μm and 1000 μm. In order to study the correlation