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Torsional displacement of piezoelectric fiber actuators with helical electrodes

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ABSTRACT

A piezoceramic fiber wound with helical electrodes on its outer surface can be used as a torsional actuator. This paper explains the torsional actuator's working principles and points out that although such a mechanism can produce a large torsional strain, it will have a small axial strain. Detailed analyses are performed on the influences of the tubular fiber's wall thickness and the helical angle of the electrodes on the torsional strain. With the aid of the finite element analysis method, the electric field distribution in the actuator is illustrated. Theoretical analyses point out that to obtain the largest torsional strain, a 45° electrode helical angle is needed for an actuator with an ideal thin wall thickness, but the angle becomes smaller than 45° if the wall thickness cannot be ignored. Results of some deliberate experiments prove these analyses.

1. Introduction

Piezoelectric ceramic materials such as lead zirconate titanate (PZT) are now being widely used in solid-state actuators and sensors, which are fabricated for numerous applications such as precision positioning, noise and vibration sensing and cancellation, ultrasonic motors, and many others [1,2]. In many of those applications, a high torsional displacement with high blocking torque is required. This is evident in impact rotating motors, in robotics to achieve micro-positioning, in CD drivers, and in architectures for amplifying small piezoelectric strains such as coiled helix actuators [3]. Piezoelectric torsional actuators have actually been studied for many years. Net shape-formed helical torsional actuators made of helical bimorph strips were successfully fabricated by Pearce et al. in 2002 and used to form a super-helix structure that can produce a considerable linear displacement [4]. Similar spiral piezoceramic actuators were reported by Mohammadi et al. in 1999 [5]. Another type of torsional piezoelectric actuator, utilizing the d_{15} piezoelectric effect to produce shear strain directly, was developed from multi-layered and assembled piezoceramic cylinders by Chulho Kim et al. and Takeshi Morita et al. in 1998 and 1999 [6,7]. The manufacturing processes of these actuators are all rather complex and seem difficult to be used in miniature torsional actuators.

For this research, a new type of torsional actuator using piezoceramic fiber with helical electrodes is studied (Fig. 1). While L is the effective length, D is the outer diameter, t is the wall thickness for tubular fiber, and p is the axial distance between the two electrodes (the pitch is defined as $2p$ when there is only one pair of electrodes). With a pair of parallel electrode wires wound around its surface, forming a helical structure and likely interlacing similar to the interdigitated electrodes (IDEs), a tubular or solid PZT element can be easily transformed into a torsional actuator. The operating principle and experimental results for the prototype actuators are presented in this paper. It is also proven that an actuator with such a structure has an excellent integrated performance, especially when the actuator is in small size.

2. Torsional and axial strains of an actuator with helical electrodes

The torsional displacement of such actuators mainly comes from the longitudinal line's (axis z) shear strain in the radial direction (axis x), as shown in Fig. 2. When the actuator is put to use, one end should usually be fixed to a stable object called the firm-end and another end called the free-end can move freely. If the tubular fiber is cut along the longitudinal section and spread into a planar form, as shown in Fig. 3, then the actuator will look like a piezoceramic layer covered with parallel electrode lines on its outer surface. The electrode lines are arranged as alternating positive and negative electrodes, which are the same as the IDEs. Fortunately, a piezoelectric film with surface IDEs has been well understood [8,9], and this can help us in establishing a reasonable electromechanical model for the primary analyses of such kind of actuator.

In the following analyses, it is assumed that the whole fiber body is homogeneous and axially symmetric. First, the actuator made of a tubular fiber with very thin wall will be analyzed as

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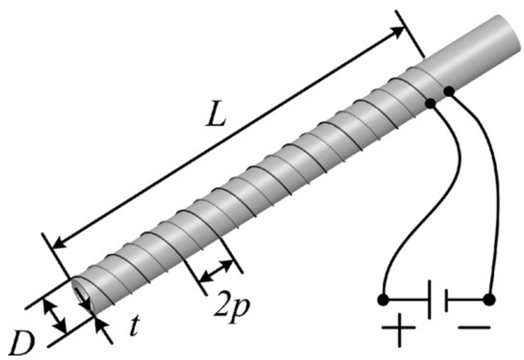

Fig. 1. The structure of the proposed torsional piezoelectric actuator.

it possesses a character that allows deformation in the radial direction (along axis x) negligible. Usually, when the wall thickness is thin enough, the distance of adjacent electrodes for this actuator is so large that the electric field between the electrodes can be regarded as a uniform pattern, which is parallel to the fiber surface and perpendicular to the electrode lines. Under this condition, the d_{33} coefficient will induce an in-plane strain parallel to the electric field, while the d_{31} coefficient will generate another in-plane strain perpendicular to the electric field. It is clear that, for a small part cut from the tube as Fig. 2 shows, the strains from d_{31} and d_{33} both have nonzero shear components in the tangential and longitudinal orthogonal lines. These shear components will cause a deflection of original longitudinal lines. This is the real reason why the fiber actuator produces relative torsional displacement between the two ends.

In order to obtain formula descriptions of the torsional displacement and electromechanical performance of the fiber actuators with helical electrodes, it is necessary to define a uniform coordinate system and several parameters of piezoceramic material and actuator geometry. Two coordinate systems are adopted in our analyses, namely xyz-coordinate and 123-coordinate (Fig. 4). Three axes in the xyz-coordinate denote the radial, tangential, and longitudinal directions, respectively, while three axes in the 123-coordinate denote the primary direction of electric field (axis 3), the direction of helical electrodes (axis 1) and the normal line direction (axis 2, radial direction). The positive direction of helical electrodes is defined as any point on the electrodes, from the firm-end to the free-end of the fiber along the electrodes. We define the angle between the positive direction of axis y and axis 1 as the helical angle of the electrodes, which is denoted as β and may either be a sharp angle or a blunt angle. The helical angle of the electric field is denoted as α, which is equal to $\beta - 90^{\circ}$. The outer radius of the fiber is denoted as r_0. Other structure parameters can be found in Figs. 1 and 2.

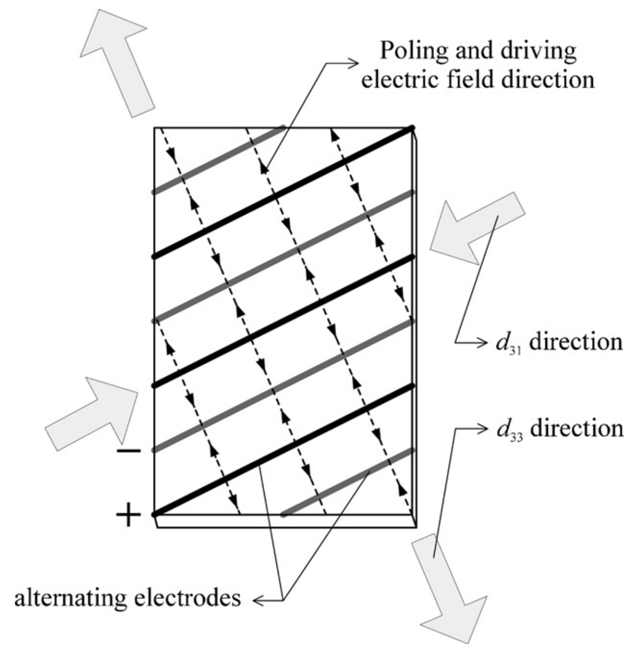

Fig. 3. Planar form of the torsional actuator made of tubular fiber. Imagine that a thin cut is made along the tube's longitudinal direction and the tube is spread into a plane, so the actuator looks like a planar actuator with IDEs.

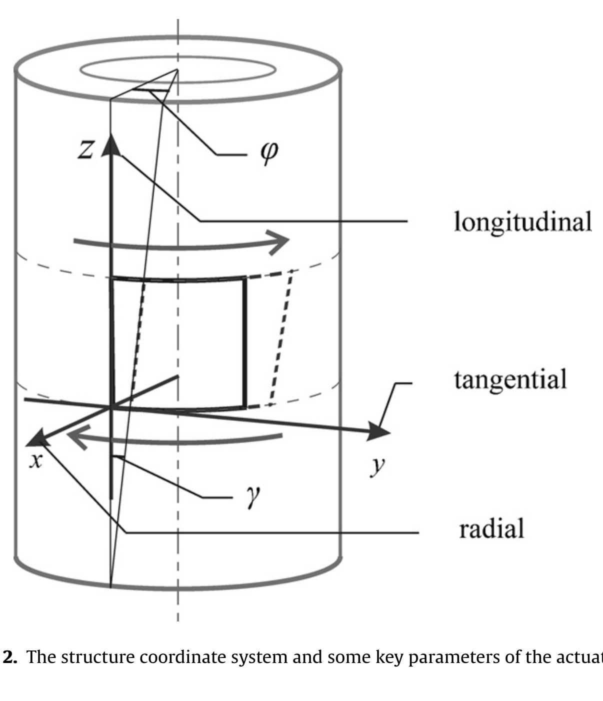

Fig. 2. The structure coordinate system and some key parameters of the actuator.

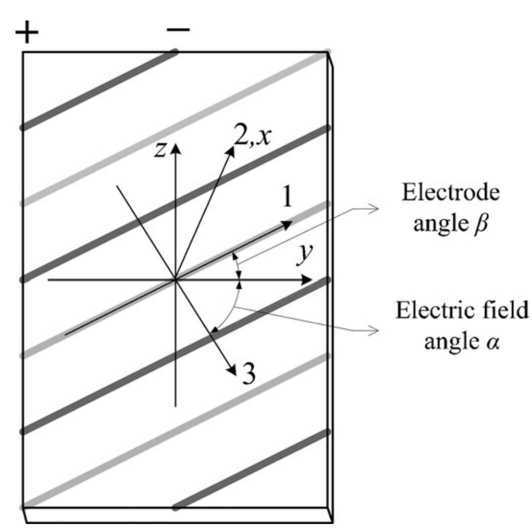

Fig. 4. Relationship between the structure coordinate system (x, y, z) and the material coordinate system (1, 2, 3). Axes x and 2 are along the radial direction. Axes y and z are along the tangential and longitudinal directions, respectively. Axis 1 is along the electrode lines. Axis 3 is along the poling and driving electric field direction.