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Displacement improvement of piezoelectric membrane microactuator by controllable in-plane stress

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ABSTRACT

Aiming to improve the displacement of the piezoelectric membrane microactuators, controllable in-plane tensile stress was introduced by applying a bias voltage on the idle part of PZT. The stress generated by the bias voltage was calculated by an analytical model based on the theory of plates and shells. Analytical result shows that tensile stress with a magnitude of 10 MPa can be generated under 100 V bias voltage. The stress is large enough to cause the change of piezoelectric coefficient d_{31} as well as the displacement of the actuator. Then the experimental results on the PZT thick film actuators demonstrated that d_{31} was remarkable increased for both the disc actuator and the ring actuator under an appropriate bias voltage, improving the displacement by 6% and 42%, respectively. Furthermore, the resonance frequency shifts were observed as a result of Young's modulus change under the bias voltage.

1. Introduction

A piezoelectric membrane microactuator typically consists of a passive layer, a piezoelectric layer (PZT thin film [1] or PZT thick film [2,3]), and a pair of electrodes. They are widely used in many engineering applications, such as micropump [4], droplet ejector [5], deformable mirror [6] and micro-transformer [7]. In order to improve the performance of the piezoelectric microactuators, the most common way is to optimize the structure parameters, such as the acutaor size, thickness, and electrode pattern [8–11]. From a viewpoint of material science, researchers usually focus on the improvement of the material properties [12]. Addtionally, a strategy of introducing in-plane stress can be utilized [13], by which the material properties including the piezoelectric coefficient d_{31}, Young's modulus and dielectric permittivity can be significantly affected.

As a well known example, Rainbow (reduced and internally biased oxide wafer) and Thunder (thin unimorph driver) actuators [14,15], with the lateral stress caused by the thermal expansion mismatch, can display displacement and load-bearing responses that are substantially greater than the traditional devices with the same dimensions. However this method is difficult to be utilized in the standard MEMS fabrication process. For MEMS devices, one method to form in-plane stress is deposition of various functional and structural layers with internal stress [16], which increases the fabrication complexity and is hard to control. Morris et al. [17] reported another method to generate in-plane stress by introducing a static air-pressure over a micro-machined piezoelectric diaphragm. This biasing pressure has been proved to be able to dramatically increase the quasi-static actuation and acoustic performance. However, producing air-pressure on actuators is inconvenient in practical applications.

In this paper, we present a convenient method to generate controllable in-plane stress to improve the displacement of the piezoelectric membrane actuators. The top electrode of the actuator is divided into a disc electrode and a ring electrode, while the continuous bottom electrode serves as the ground. One of the top electrodes with bias voltage is used to generate in-plane stress, while the other one is used to generate the displacement. In this method, no extra fabrication process is needed except handily adjusting the electrode pattern of the actuator. The stress can be controlled easily by the bias voltage. First, the in-plane stress in the piezoelectric microactuator was analyzed when a bias voltage was applied. Then the displacements of the disc actuator and the ring actuator were measured experimentally under different bias voltages. Furthermore, the change of Young's modulus under the bias voltage was investigated, which resulted in the frequency shifts of the actuators.

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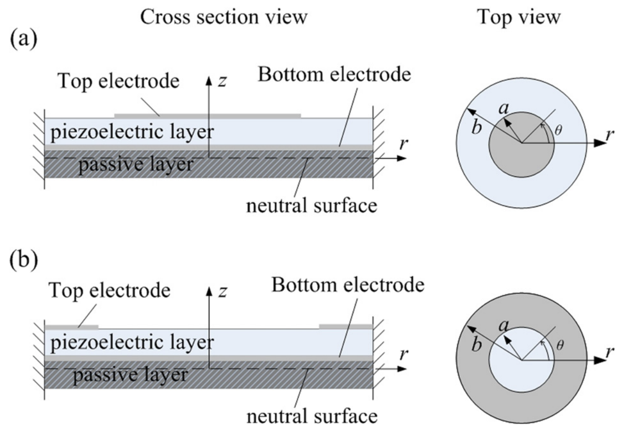

Fig. 1. Piezoelectric membrane actuators. (a) Disc actuator and (b) ring actuator.

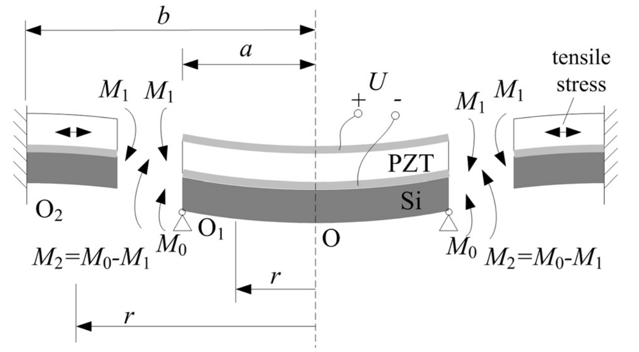

Fig. 2. Deflection model of disc actuator. a and b: radii of the disc electrode and the actuator, respectively; M_0: moment caused by actuation of PZT; M_1: moment between two parts; M_2: equivalent moment applied on the disc part.

2. In-plane stress analysis

2.1. Principle

Micro disc actuator and ring actuator are differentiated according to the pattern of top electrode as shown in Fig. 1. The PZT covered by a disc or ring electrode contracts and brings in a bending moment to flex the membrane out of its plane when a positive voltage is applied. The directions of the displacement of the ring actuator and the disc actuator are upward and downward, respectively. Meanwhile, tensile stress occurs in the idle part of PZT without the top electrode for both the actuators. Inversely, compressive stress occurs when a negative voltage is applied. In general, appropriate tensile stress increases piezoelectric coefficient d_{31}, while compressive stress decreases d_{31} [18–20]. The displacement of the actuator is directly proportional to d_{31}. Therefore, the idle part of PZT can be utilized to generate controllable in-plane stress in the drive part of PZT by applying a bias voltage, with assistance of an extra electrode. This controllable stress has a possibility to improve the actuator performance along with d_{31}.

2.2. In-plane stress model

So far, the quantitative relationships between stress and d_{31} are still unclear. The stress analysis helps to understand the effect of stress on d_{31} qualitatively. Some analytical models based on the theory of plates and shells have been developed to predict the displacement of a disc actuator and a ring actuator [8,21,22]. The deformations of a disc actuator and a ring actuator are the same except the direction.

As shown in Fig. 2, the disc actuator is divided into two parts: a disc part (simply supported at $r = a$) and a ring part (fixed supported at $r = b$). According to the theory of plates and shells, the deflections of these two parts relative to the supporting point O_1 and O_2 are calculated using the following equations, respectively [23]:

$$w_1(r) = \frac{M_0(b^2 - a^2)(a^2 - r^2)}{4D_e b^2}, \quad (0 \le r \le a) \tag{1}$$

$$w_2(r) = \frac{M_0 a^2[(r^2 - b^2) - 2b^2 \ln \frac{r}{b}]}{4D_e b^2}, \quad (a < r \le b). \tag{2}$$

The moment caused by actuation of PZT M_0 is expressed as [24]:

$$M_0 = \frac{D_e d_{31} U/h_{pzt}}{(h/2) + (2/h)(1/E_{pzt}h_{pzt} + 1/E_{si}h_{si})(D_{pzt} + D_{si})} \tag{3}$$

where:

D_e is the equivalent flexural stiffness [8]; U is the voltage applied on PZT; h is the total thickness of the actuator; D_{pzt}, E_{pzt}, h_{pzt} are the flexural stiffness, Young's modulus and thickness of the PZT layer, respectively.

D_{si}, E_{si} and h_{si} are the flexural stiffness, Young's modulus and thickness of the silicon passive layer, respectively.

Eqs. (1)–(3) also apply to the ring actuator with the opposite sign of M_0. When a voltage is applied to the disc part or ring part of PZT, in-plane stress accompanied with the deflection is produced. Since the strain distribution across the thickness direction is assumed to be linear [23,24], the radial and circumferential strain-deflection relationship follows [25]:

$$\begin{pmatrix} \varepsilon_r \\ \varepsilon_\theta \end{pmatrix} = \begin{pmatrix} k_r z \\ k_\theta z \end{pmatrix} \tag{4}$$

where k_r and k_θ are the radial and circumferential curvatures, respectively:

$$\begin{pmatrix} k_r \\ k_\theta \end{pmatrix} = \begin{pmatrix} -d^2w/dr^2 \\ -\left(1/r\right) dw/dr \end{pmatrix} \tag{5}$$

z is the height relative to the neutral surface that does not have radial strain or circumferential strain. The position of the neutral surface can be calculated by [8]:

$$h_n = \frac{1}{2}\frac{E_{si}h_{si}^2/(1 - \upsilon_{si}^2) + E_{pzt}(h_{pzt}^2 + 2h_{si}h_{pzt})/(1 - \upsilon_{pzt}^2)}{E_{si}h_{si}/(1 - \upsilon_{si}^2) + E_{pzt}h_{pzt}/(1 - \upsilon_{pzt}^2)} \tag{6}$$

where υ_{si} and υ_{pzt} are the Poisson's ratio of the silicon layer and the PZT layer, respectively.

According to the constitutive equations for a transversely isotropic linear elastic piezoelectric actuator, the radial stress and circumferential stress are:

$$\begin{pmatrix} \sigma_r \\ \sigma_\theta \end{pmatrix} = \frac{E_{pzt}}{1 - \upsilon_{pzt}^2}\begin{pmatrix} \varepsilon_r + \upsilon_{pzt}\varepsilon_\theta \\ \varepsilon_\theta + \upsilon_{pzt}\varepsilon_r \end{pmatrix}. \tag{7}$$

Substituting Eqs. (2), (4) and (5) into Eq. (7), the radial stress in the ring part of PZT can be calculated when a bias voltage is applied to the disc electrode:

$$\sigma_r(r, z) = -\frac{M_0 E_{pzt} b^2}{2D_e a^2(1 - \upsilon_{pzt}^2)}[(1 + \upsilon_{pzt}) + b^2 r^{-2}(1 - \upsilon_{pzt})]z. \tag{8}$$

Similarly, when a bias voltage is applied to the ring electrode, the radial stress in the disc part of PZT can be calculated by substituting Eqs. (1), (4) and (5) into Eq. (7):

$$\sigma_r(r, z) = \frac{M_0 E_{pzt}}{2D_e a^2(1 - \upsilon_{pzt})}(a^2 - b^2)z. \tag{9}$$

From Eq. (9), we can see that the radial stress in the disc part of PZT is independent to r.