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A piezoelectric tube with a double-layer configuration

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Abstract

A piezoelectric ceramic tube with a double-layer configuration was proposed in this paper. This actuator, made of a hard piezoelectric ceramic, was successfully prepared using an advanced technique, known as electrophoretic deposition (EPD). The fabrication process was introduced and the prepared piezoelectric tube showed a uniform structure. The bending displacement of the tube at clamped-free boundary condition was then theoretically derived and experimentally confirmed at various driving conditions. The predicted values showed good consistency with the experimental values.

Keywords: C. Piezoelectric properties; D. PZT; E. Actuators; EPD; Double layer

1. Introduction

The piezoelectric field-induced strain normally is less than 0.1% [1–3]. As a result, to achieve a relatively large displacement, the piezoelectric actuators are usually operated at several hundreds to several thousands of volts. This results in the difficulties as high power supplies are needed. But both driving and control circuits normally consist of components designed for voltages of typically 60 V or less [3].

However, by using the multilayer approach, i.e. when the piezoelectric elements are made very thin and stacked together, the voltage needed can be tens of volts to obtain a large displacement. Thus, the construction of multilayer actuator, in which the piezoelectrically active layers interleaved with metallic electrodes, has been investigated intensively [4,5]. However, most of the multilayer actuators have a flat type structure. In this paper, a curved and layered structured actuator was introduced, which is a piezoelectric tube as shown in Fig. 1. The tube has double layers, with the inner and outer layer separated by an imbedded intermediate electrode. The poling direction can be either anti-parallel or parallel in the two layers. For processing simplicity, in this paper the parallel poling direction are applied as shown in the Fig. 1.

2. Fabrication

The ceramic applied to fabricate the tube is a hard PZT material with compositions of $0.95Pb(Zr_{0.52}Ti_{0.48})O_3 \cdot 0.03BiFeO_3–0.02Ba(Cu_{0.5}W_{0.5})O_3 + 0.5$ wt.% MnO_2 [6]. The raw oxide powders of PbO, ZrO_2, TiO_2, Bi_2O_3, Fe_2O_3, BaO, CuO, WO_2 and MnO_2 (Aldrich Chemical Company, Inc., USA) were first mixed with the designed stoichiometrical composition and then ball-milled for 24 h. The mixed powders were then calcined at 750 °C for 2 h. Finally, the calcined powders were ground using a planetary ball-milling machine at a speed of 150 rpm in ethanol for 8 h.

Suspensions were prepared by adding prepared powders in ethanol and then subjected to ultrasonic agitation for 6 min. The powder concentration in the suspension was 50 g/l and the suspension pH value was controlled to be 4.6 at room temperature. The suspension was stirred for 3–6 h to make sure the complete dissolution and dispersion of the powders in the medium. The electrophoretic cell includes a cathodic rod substrate placing in the center of a stainless-steel counter-electrode. The deposition was performed at a constant voltage of 100 V for 3–8 min depending on the desired thickness of the tube. The deposits were dried thoroughly, painted with uniform platinum paste and then the second layer deposition was performed. After drying for 12 h, the deposits were sintered in a programmable furnace at 1100 °C for 1 h.

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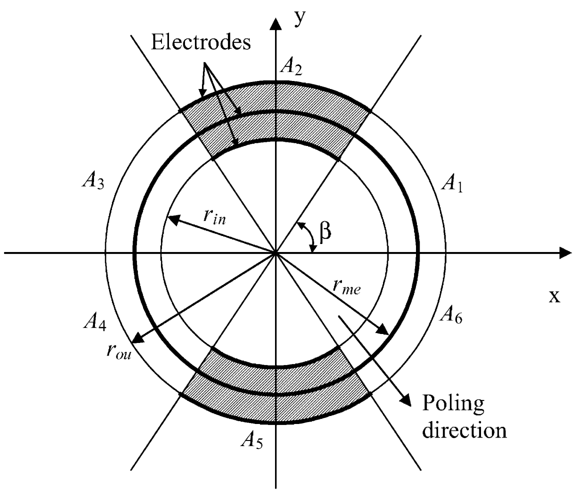

Fig. 1. Configuration of the double-layer tube.

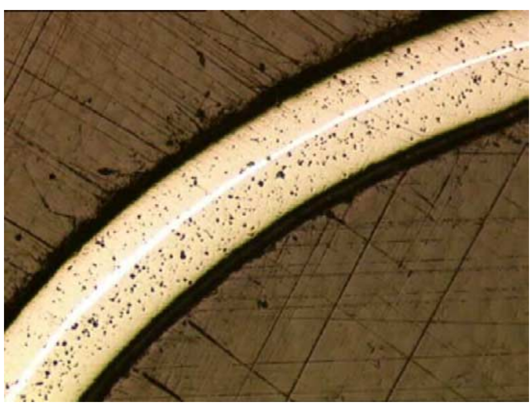

Fig. 2. Cross section of the double-layer tube.

The sintered tube was then cut into the designed length and painted with silver paste as electrode before firing at 850 °C for 20 min. Poling was next carried out in silicone oil at 100 °C by applying a DC field of 2 kV/mm along the radial thickness direction for 2 h.

After sintering, the cross section of the double-layer tube was observed using an optical microscope as shown in Fig. 2. The tube has an inner radius of 1.60 mm and an outer radius of 1.80 mm. The intermediate radius of the tube and thickness of the electrode are about 1.71 mm and 7 μm, respectively.

3. Theory

The bending displacement can be estimated using the following derived expressions. The tensile or compressive stress and strain along the longitudinal direction are denoted as T_1 and S_1 for the driving parts and T_1' and S_1' for the driven parts, respectively. The stress and strain relations are then expressed as

$$\begin{cases} T_1 = S_1/s_{11}^{\mathrm{E}} - E_3 d_{31}/s_{11}^{\mathrm{E}} \\ T_1' = S_1'/s_{11}^{\mathrm{E}} \end{cases} \tag{1}$$

where s_{11}^{E} is the constant of elastic compliance, E_3 is the electric field in thickness direction. In the first and second layer of the tube, the electric fields can be expressed as

$$E_{\mathrm{1st}} = \frac{V_1}{r\ln(r_{\mathrm{me}}/r_{\mathrm{in}})} \text{ and } E_{\mathrm{2nd}} = \frac{V_2}{r\ln(r_{\mathrm{ou}}/r_{\mathrm{me}})} \tag{2}$$

In Eq. (1), $S_1(S_1')$ can also be written as

$$S_1 = -\frac{y}{\rho_{\mathrm{r}}} \tag{3}$$

where y is the distance from neutral surface and ρ_{r} is the radius of curvature. ρ_{r} can be estimated using the following relation [7,8]

$$M = \iint_{A_1+A_3+A_4+A_6} yT_1'\,\mathrm{d}A + \iint_{A_2+A_5} yT_1\,\mathrm{d}A = 0 \tag{4}$$

Taking Eqs. (1)–(3) into (4), the radius of curvature is obtained

$$\frac{1}{\rho_{\mathrm{r}}} = -\frac{8d_{31}\cos\beta}{\pi(r_{\mathrm{ou}}^4 - r_{\mathrm{in}}^4)}\left(\frac{V_1(r_{\mathrm{me}}^2 - r_{\mathrm{in}}^2)}{\ln(r_{\mathrm{me}}/r_{\mathrm{in}})} + \frac{V_2(r_{\mathrm{ou}}^2 - r_{\mathrm{me}}^2)}{\ln(r_{\mathrm{ou}}/r_{\mathrm{me}})}\right) \tag{5}$$

Introducing the following expression

$$\zeta = \frac{L^2}{2\rho_{\mathrm{r}}} \tag{6}$$

the displacement of a double-layer tube is obtained

$$\zeta_{\mathrm{D}} = -\frac{4d_{31}L^2\cos\beta V_1(r_{\mathrm{me}}^2 - r_{\mathrm{in}}^2)}{\pi(r_{\mathrm{ou}}^4 - r_{\mathrm{in}}^4)\ln(r_{\mathrm{me}}/r_{\mathrm{in}})} - \frac{4d_{31}L^2\cos\beta V_2(r_{\mathrm{ou}}^2 - r_{\mathrm{me}}^2)}{\pi(r_{\mathrm{ou}}^4 - r_{\mathrm{in}}^4)\ln(r_{\mathrm{ou}}/r_{\mathrm{me}})} \tag{7}$$

If the tube has only one layer, the bending displacement becomes

$$\zeta_{\mathrm{S}} = -\frac{4d_{31}V\cos\beta L^2}{\pi(r_{\mathrm{ou}}^2 + r_{\mathrm{in}}^2)\ln(r_{\mathrm{ou}}/r_{\mathrm{in}})} \tag{8}$$

4. Results and discussion

The displacement in both axial and transverse direction of the fabricated piezoelectric tube was measured. The measurement system consists of a RT6000HVS (Radiant Technologies, Inc.), a Vibraplane (RS Kinetic Systems, Inc.), a MTI-2000 fotonic sensor (probe: MTI2032RX. MTI Instruments) and the piezoelectric tube. The tube was measured at the Clamped-Free boundary condition with one end fixed to

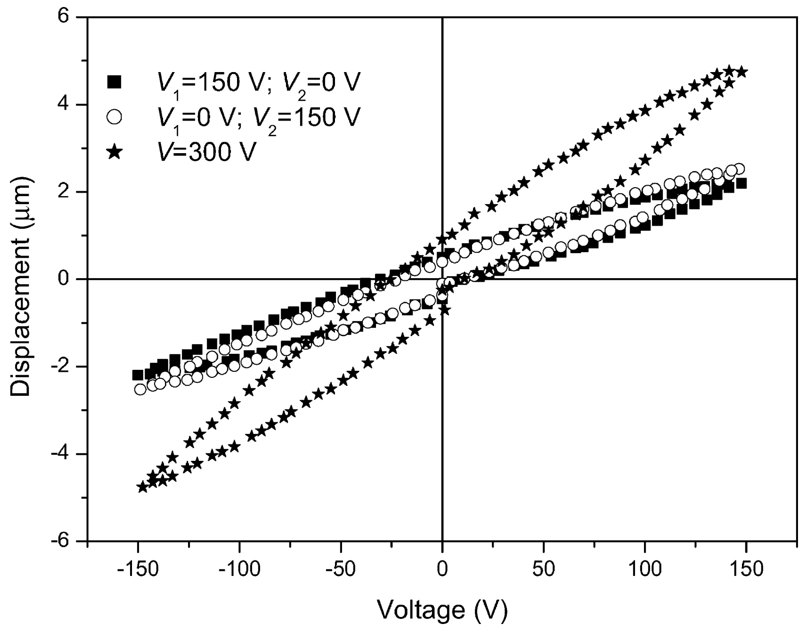

Fig. 3. Bending displacement hysteresis loop at various driving conditions.

Table 1
Calculated and measured displacement at various driving conditions

Driving condition	Calculated (μm)	Measured (μm)
$V_1 = 150\,V$; $V_2 = 0\,V$; $\beta = 0°$	2.13	2.19
$V_1 = 0\,V$; $V_2 = 150\,V$; $\beta = 0°$	2.39	2.52
$V(V_1 + V_2) = 300\,V$; $\beta = 0°$	4.48	4.76

the vibraplane. The other end produces displacement in response to the bipolar step voltage given by RT6000HVS and finally the fotonic sensor provides the displacement results.

The displacement in the axial direction was measured by applying various electric fields across the wall thickness direction, using

$$S_1 = d_{31} E_3 \tag{9}$$

the piezoelectric constant d_{31} can be calculated to be 5.77×10^{-11} m/V.

The bending displacement in transverse direction was both calculated using derived Eqs. (7) and (8) and experimentally measured. The measurement conditions and results are shown both in Fig. 3 and Table 1. Calculated and measured results were compared and found to be in good agreement, indicating that the derived Eqs. (7) and (8) provide reasonably accurate descriptions of the displacement.

5. Conclusion

A piezoelectric ceramic tube with a double-layer configuration was studied. EPD technique can successfully prepare the double-layer tubes with a uniform structure. The bending displacement of the tube was theoretically predicted and compared with that obtained from experiments. It is found that the two methods are in reasonably good agreement.

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