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A Piezoelectric-Metal-Cavity (PMC) actuator

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Abstract A novel piezoelectric-metal-cavity (PMC) actuator has been designed to exhibit a large flexural displacement. This PMC actuator consists of a metal ring sandwiched between two identical piezoelectric unimorphs. The radial contraction of the piezoelectric ceramic is converted into flextensional motion of the unimorph, causing a large flexural displacement in the centre part of the actuator. The metal cavity acts a function of circumferential coupling of the piezoelectric unimorphs. It was found that the effective piezoelectric charge coefficient of the PMC actuator can approach 40,000 pC/N. With its high piezoelectric and electromechanical coupling coefficients, the PMC actuator gives a static displacement 16 μm can be produced under a d.c. driving voltage of ±77 V.

Keywords Piezoelectric · Actuator · Unimorph

1 Introduction

Piezoelectric actuators have been widely used in various fields because of their good displacement accuracy and high response speed [1]. However, there is still a drawback based on the small deformation of the piezoelectric materials. In the past, lots of efforts were devoted to increase the displacement of the actuators. Multilayer [2] and composite actuator structures [3] have been studied to produce high displacement. Especially the composite actuators, various types of structures have been proposed to have high displacement with high generative force such as bimorphs [4], moonies [5] and cymbals [6] and inchworm type motors [7]. However, some of their structures are complex and costly.

In this paper, a novel piezoelectric-metal-cavity (PMC) actuator is introduced as a high displacement actuator with relatively low fabrication cost, which is a flexural or bending type actuator. A theoretical modelling using a finite element method has been used to study the vibration of the actuator under its fundamental frequency. The experimental results for electrical and mechanical properties of the actuator are reported. It was found that the piezoelectric performance can be highly enhanced compared to the cymbals with similar dimensions.

2 Model design of the actuator

A schematic diagram of the PMC actuator is shown in Fig. 1. The piezoelectric unimorphs of 12 mm diameter with 0.37 mm thickness act as a driving element of the actuator. The steel ring of 0.5 mm thickness has the function of enlarging the displacement by a circumferential coupling of the unimorphs. When the electric field was driven along the polarization direction of the unimorph, it would be bent depended on the lateral strain ($d_{31}*E$) generated in the piezoelectric layer [8]. The steel ring sandwiched between the unimorphs acts as a simply support medium, enlarging the bending curvature of the

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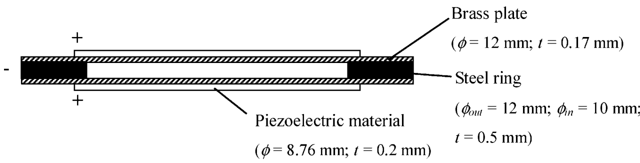

Fig. 1 Schematic diagram of the PMC actuator

unimorphs. The magnitude of deflection which is defined as the centre displacement of the actuator is proportional to the inner diameter of the steel ring, ϕ_{in} [9].

Finite element model (FEM) was created with the commercial program ANSYS. Since the actuator is circular in shape, the model was 2D axisymmetrical and only one half of the actuator is shown in Fig. 2. PZT-5A was the piezoelectric material and the metal was considered to be homogeneous and isotropic in the simulation. The major parameters used in the simulation are shown in Table 1. The simulation (Fig. 2) shows the static deformation of the PMC actuator under its fundamental mode (f_r~15.48 kHz). A flexural motion of the actuator was produced when an electric field was applied across the unimorphs.

3 Experimental

The unimorphs were fabricated using the PZT-5A ceramics (8.76 mm diameter and 0.20 mm thickness) attached on the brass discs of 12.00 mm diameter and 0.17 mm thickness. The co-fired silver was used as an electrode of the unimorphs. The d_{33} and d_{31} of the unimorphs are 374 and −171 pC/N, respectively. An insulating epoxy (Emerson and Cuming) 45 LV epoxy resin and 15 LV hardener with a weight ratio of 3:1 was used as a bonding material for attaching the unimorphs with the steel rings. After bonding, the flanges of PMC actuators were clamped and the epoxy was cured in air for 4 h at 60°C.

The performance of the actuator was evaluated by electrical and mechanical measurements. To evaluate the electrical performance of the actuator, the effective piezoelectric d_{33} coefficient and the effective coupling k_{eff} coefficient were determined. In the present work, effective d_{33} of the PMC actuator was measured using the direct

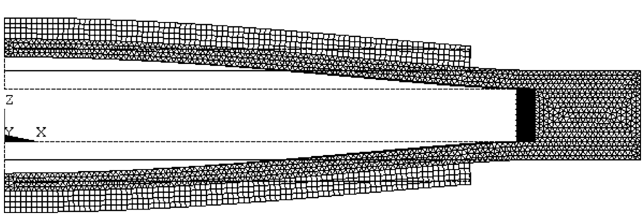

Fig. 2 The unimorph deflection during the first vibration mode of the PMC actuator (*dash line*: undeformed shape; *solid line*: deformed shape)

Table 1 List of parameters of the materials used in the simulation.

Parameters	Materials of the actuator		
	PZT	Brass	Steel
Density, ρ (kgm^{-3})	7,600	8,530	7,700
Young's Modulus, Y (Nm^{-2})	76×10^9	110×10^9	190×10^9
Poisson's ratio, σ	0.31	0.33	0.28

piezoelectric effect. A precision materials analyzer (Radiant Technologies, Inc) was used to determine the piezoelectric charge generated by the actuator in response to an applied static force normal to its surface. A pre-stress of 3 N was applied during the measurement. Figure 3 shows the relationship between the output charge and the force applied on the actuator. The effective piezoelectric d_{33} coefficient of the actuator can be obtained by determining the slope of the curve. Compared to the cymbal actuator with similar dimension (d_{33}~20,000 pC/N), the PMC actuator has much higher effective d_{33} coefficient (~ 40,000 pC/N) because two thin PZT layers were used as the driving element of the PMC actuator [10].

To determine the value of k_{eff}, the resonance characteristics of the PMC actuator were measured by an HP4294A impedance analyzer. Figure 4 shows the fundamental mode (f_r~15.68 kHz) of the PMC actuator which is the first resonance mode in the impedance / phase spectrum. The resonance mode is pure without any spurious mode where its resonant frequency agrees well with the modelling. The value of k_{eff} was determined using the following equation [11]:

$$k_{eff} = \sqrt{1 - \left(\frac{f_r}{f_a}\right)^2} \tag{1}$$

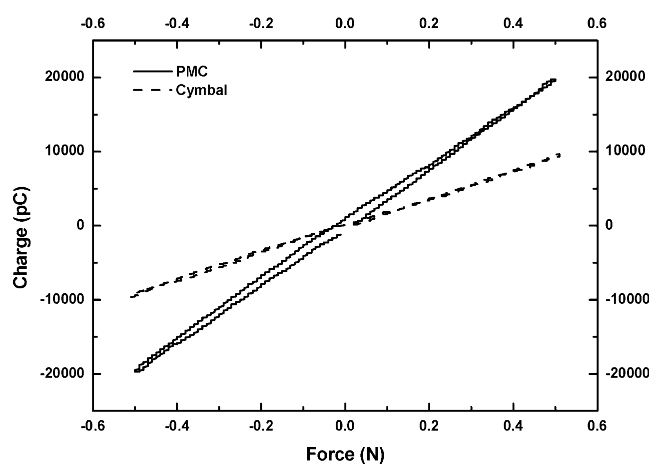

Fig. 3 The relationship between the output charge and the applied force of the PMC and cymbal actuators

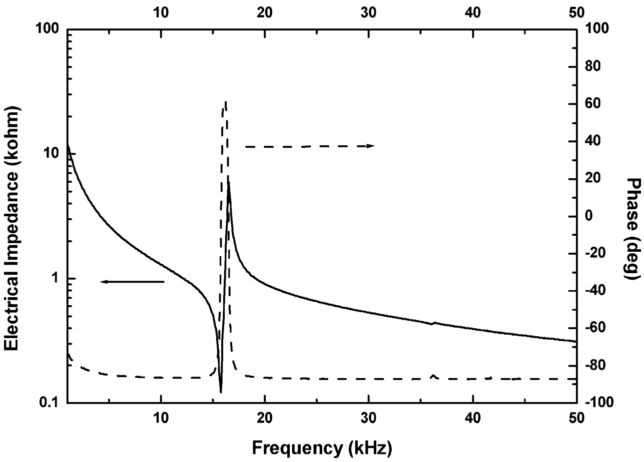

Fig. 4 The fundamental mode of the PMC actuator

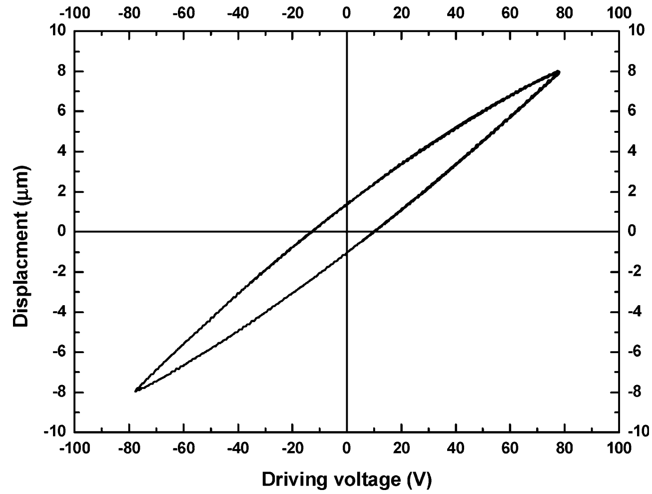

Fig. 5 Static displacement-voltage loop of the PMC actuator under ±77 V

where f_a is the anti-resonant frequency of the fundamental mode. The value of k_{eff} of the PMC actuator is around 0.37 which is comparable to that of the cymbal actuators.

The mechanical characteristic was related to the displacement of the actuator. The d.c. axial displacement was measured by a photonic sensor (MTI-2000) consists of a non-contact type fibre-optic probe. During the measurement, the actuator was simply supported at the flange of the unimorph and driven by a triangular electric signal of 0.1 Hz. In Fig. 5, the displacement loop shows that the d.c. displacement of the PMC actuator reached 16 μm under the driving voltage of ±77 V.

4 Conclusion

The study of the PMC actuator has been developed. A flexural motion of the actuator was observed using the FEM analysis. The experiments showed that the effective d_{33} coefficient of the PMC actuator can be greatly enhanced compared with that of the cymbal actuators with the comparative dimensions. The PMC actuator with high effective electromechanical coupling coefficient could produce a total displacement of 16 μm under ±77 V. With its outstanding piezoelectric performance, PMC actuator has great potential on sensors and actuators applications in the automotive industry.

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