Lead-free Piezoelectric-Metal-Cavity (PMC) Actuators

Kwok-Ho Lam, Dun-Min Lin, Kin-Wing Kwok, and Helen Lai-Wa Chan

***Abstract*—A piezoelectric piezoelectric-metal-cavity (PMC) actuator was reported previously that can exhibit a large flexural displacement. In this paper, a lead-free piezoelectric ceramic was used as a driving element of the PMC actuator. $Bi_{0.5}(Na_{0.725}K_{0.175}Li_{0.1})_{0.5}TiO_3$ (abbreviated as BNKLT) is a soft-type piezoelectric ceramic with good piezoelectric properties at room temperature. Both the electrical and mechanical properties of the BNKLT PMC actuator were measured. With good piezoelectric coefficients and low density, the BNKLT ceramic has the potential to be used as the driving element of the lead-free actuator.**

I. Introduction

The most widely used piezoelectric ceramics are lead-based ceramics, especially $Pb(Zr,Ti)O_3$ (PZT), because of their superior piezoelectric properties [1]. Recently, with concern about the environmental pollution of waste disposal of PbO, it has become desirable to use lead-free materials for environmental protection. Lead-free piezoelectric ceramics have widely attracted considerable interest as replacements for the lead-based material systems [2]–[4]. $Bi_{0.5}Na_{0.5}TiO_3$ (BNT) is considered to be one of good candidates of lead-free piezoelectric ceramics because of its large remanent polarization [5]. However, due to their high coercive field, pure BNT ceramics are difficult to pole to possess much lower piezoelectric properties compared with PZT ceramics [5], [6]. To improve the properties of BNT ceramics, new $[Bi_{0.5}(Na_{1-x-y}K_xLi_y)_{0.5}]TiO_3$ lead-free piezoelectric ceramics (BNKLT - x/y) were proposed [7]. The partial substitution of Na^+ by K^+ and Li^+ effectively decreases the coercive field of the ceramics. Simultaneously, the strong ferroelectricity is still maintained with good piezoelectric properties [8].

A piezoelectric piezoelectric-metal-cavity (PMC) actuator (Fig. 1) is introduced as a high displacement actuator with relatively low fabrication cost, which is a flexural or bending type actuator. The piezoelectric unimorphs act as a driving element of the actuator. When the electric field was driven along the polarization direction of the unimorph, it would be bent depending on the lateral strain (d_{31}^*E) generated in the piezoelectric layer [9]. The steel ring sandwiched between the unimorphs acts as a simple support medium, enlarging the bending curvature of the unimorphs. It was found that the piezoelectric performance of the PMC actuator (effective $d_{33} \sim 40,000$ pC/N) can be highly enhanced compared with the cymbals (effective $d_{33} \sim 20,000$ pC/N) with similar dimensions [10].

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II. Materials Used

The piezoelectric lead-free PMC actuator was fabricated using BNKLT unimorphs that consist of ceramic thin discs and metal plates. The BNKLT powders were fabricated by a conventional ceramic technique. All the industrial-grade metal oxides or carbonates—Bi_2O_3 (99%), Na_2CO_3 (99%), Li_2CO_3 (97%), K_2CO_3 (99.8%), and TiO_2 (99.5%)—were mixed by ball milling and calcined at 850°C for 2 h. Slurry based on BNKLT material was prepared for roll-casting, and then it was cast into green sheets with the thickness of about 0.2 mm. These green sheets were subsequently cut into discs of 15 mm diameter. The stack of the green discs was sintered at 1100°C for 2 h in an air atmosphere. The co-fired silver was used as an electrode. The thin ceramic discs were poled under dc electric field of 4 kV/mm for 20 min in silicone oil at 100°C. After poling, the samples were short-circuit annealed at room temperature for 8 h to remove surface charges. The unimorphs were fabricated using the BNKLT ceramics attached on the brass discs of 20 mm diameter and 0.2 mm thickness using an epoxy. To compare the performance of the lead-free unimorphs, lead-based unimorphs with identical dimensions fabricated using PZT-5A ceramics were also prepared.

The density, ρ, of the samples was measured using a method based on the Archimedes principle. Piezoelectric properties of both the ceramics and actuators were measured by means of the resonator method on the basis of the IEEE standard using an impedance analyzer (Agilent 4294A, Agilent Technologies, Santa Clara, CA) [11]. The piezoelectric coefficient, d_{33}, of the ceramics was measured by a d_{33} meter (ZJ-3B), which was supplied by the Beijing Institute of Acoustics, Academia Sinica. The properties of the BNKLT and PZT ceramics are compared in Table I. The density of the BNKLT ceramics is lower than that of PZT ceramics. Although the lead-free ceramics have lower piezoelectric coefficient compared with the PZT, their electromechanical coupling k coefficients are quite high, which are comparable to the PZT.

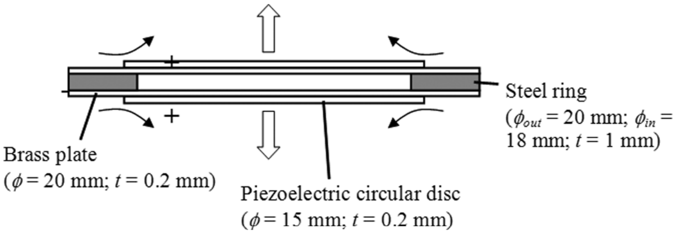

Fig. 1. Schematic diagram of a piezoelectric PMC actuator. The solid arrows show the directions of displacements when the PMC actuator is driven by an electric field parallel to the poling direction of the piezoelectric disc.

TABLE I
PROPERTIES OF VARIOUS DRIVING ELEMENTS OF THE PMC ACTUATOR.

	BNKLT	PZT-5A
ρ (kg/m^3)	5880	7700
d_{33} (pC/N)	160	400
d_{31} (pC/N)	−72	−175
k_t	0.46	0.48
k_p	0.37	0.34
ε_{33}^T	750	1800
$\varepsilon''(\varepsilon_{33}^T \tan\delta)$	22.5	27.0
Q_M	60	80
Maximum Operating Temperature (°C)	100	150

III. ACTUATORS

After fabricating the unimorphs, an insulating epoxy (Emerson and Cuming, Shanghai, PRC) 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. The flanges of PMC actuators were clamped and the epoxy was cured in air for 4 h at 60°C after bonding. The photograph of the PMC actuator is shown in Fig. 2.

The performance of the actuator was evaluated by electrical and mechanical measurements. The electrical characteristics are related to the resonance mode of the actuator including the evaluation of the effective coupling coefficient and the fastest response time. The mechanical characteristic is related to the displacement of the actuator.

After bonding the unimorphs on the steel ring, the first resonance frequency of the PMC actuator is associated with the flextensional mode of the unimorphs. It depends on the geometry of the actuator, including the dimensions of the driving element and the metal cavity; for example, a larger cavity would give a lower resonance frequency of the actuator [12]. The first resonance frequency of the actuator can be measured by an impedance analyzer. Besides, the first resonance mode of the PMC actuator can also be simulated by the finite element method (FEM) using the commercial FEM program ANSYS (ANSYS Inc., Shanghai, PRC). Fig. 3 shows how the PMC actuator deforms under its fundamental mode in the simulation. Because the actuator is circular in shape, the model was 2-D axisymmetrical so that only a section of the actuator is shown. It is shown that a flexural motion of the actuator was produced when an electric field was applied across the unimorphs.

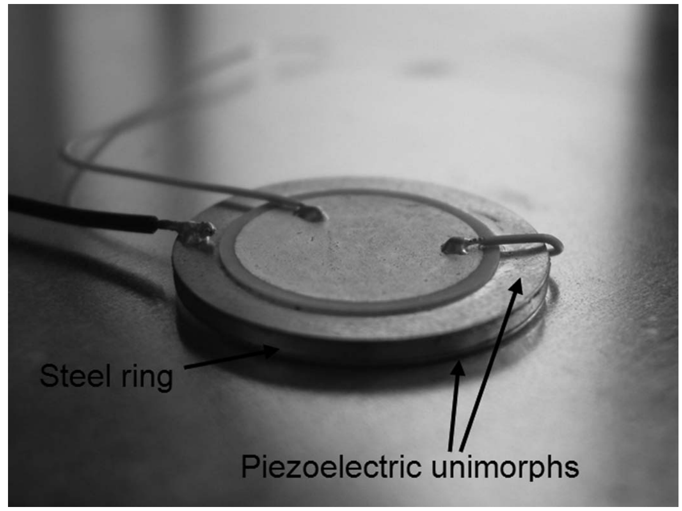

Fig. 2. Photograph of a piezoelectric PMC actuator.

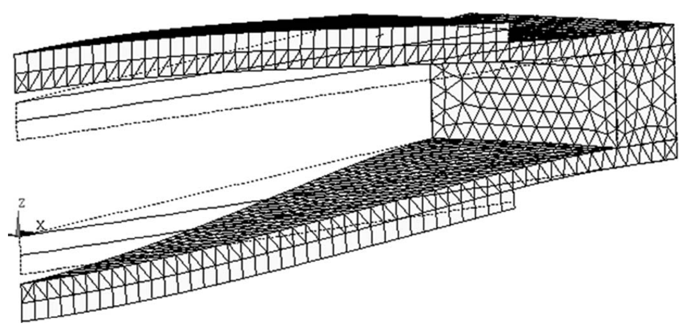

Fig. 3. The first vibration mode of a PMC actuator in a FEM analysis (dashed line: undeformed shape; solid line: deformed shape).

IV. EXPERIMENTAL

To compare the first resonance frequency simulated in the FEM model, the actuator was evaluated experimentally. Fig. 4 shows the fundamental mode of the BNKLT PMC actuator, which is the first resonance mode ($f_r \sim 6.0$ kHz) in the impedance/phase spectra. The measured fundamental resonance frequency of the PMC actuator is close to that estimated by FEM simulation as shown in Table II. It is found that the fundamental resonance frequency of the BNKLT PMC actuator is higher compared with that of the PZT actuator. It can be explained using the thin plate theory because the resonance frequency is inversely proportional to its density [13].

To evaluate the electrical performance of the PMC actuator, the effective coupling coefficient, k_{eff}, and the fastest response time, $t_{(\text{FRT})}$, were evaluated. The effective coupling coefficient describes the conversion of energy from

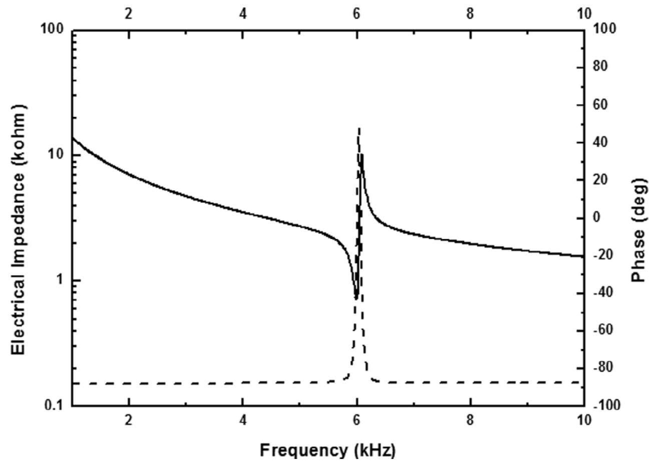

Fig. 4. The fundamental mode of a lead-free BNKLT PMC actuator.

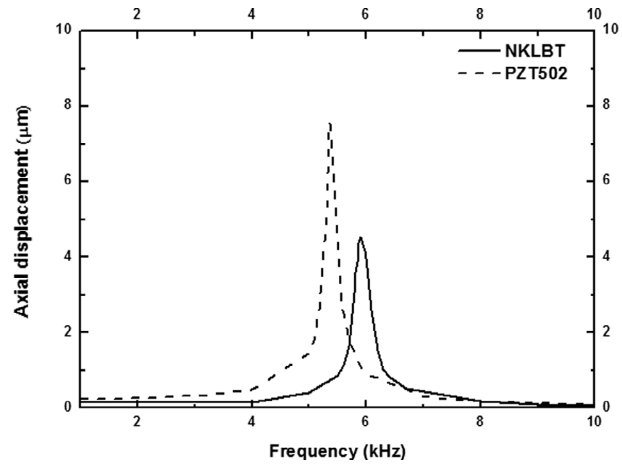

Fig. 5. The displacement of PMC actuators with BNKLT and PZT driving elements as a function of driving frequency.

TABLE II
Comparison of the Fundamental Resonance Frequency of PMC Actuators Fabricated Using Different Driving Elements in Which Two Determine Methods are Compared.

	Fundamental resonance frequency, f_1 (kHz)	
	BNKLT	PZT-5A
Simulation (ANSYS)	6.9	5.3
Experimental	6.0	5.2

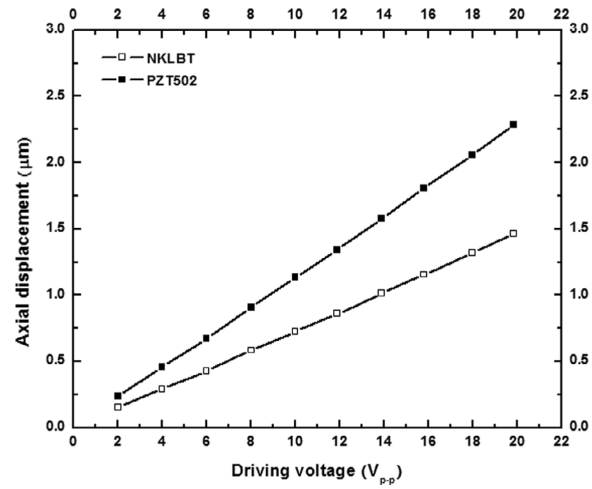

Fig. 6. The displacement of PMC actuators with BNKLT and PZT driving elements as a function of driving voltage.

electrical to mechanical form or vice versa. The fastest response time is defined as the time for the device to achieve the precise response without overshooting and ringing. Those parameters were determined by the series and parallel resonant frequencies of the fundamental mode of the actuator based on the IEEE standard on piezoelectricity [11]. As shown in Table III, compared to the PZT actuator, the BNKLT actuator has relatively low k_{eff}. On the other hand, the lead-free actuator has shorter response time because of its higher fundamental resonance frequency.

Besides the electrical performance, the mechanical characteristics of the PMC actuator were also evaluated. The displacement of the actuators was measured by a Polytec "outplane vibrometer" (Model no. OFV-3300-2, Polytech GmbH, Waldbronn, Germany). The displacement characterization was done as functions of driving frequency, driving voltage, and position of the actuator. Fig. 5 compares the axial displacement of the PMC actuators using BNKLT and PZT driving elements as a function of driving frequency. The actuators were driven by 2 $V_{\text{p-p}}$, and the measurement location was the center of the actuator. As expected, the displacement of the BNKLT actuator is lower but at higher frequency. Although the difference of d coefficient between PZT and BNKLT ceramics is big, the lead-free actuator shows a reasonable displacement. A similar phenomenon can be seen in Fig. 6, which shows the displacement as a function of driving voltage. Under a driving voltage of 20 $V_{\text{p-p}}$ at 1 kHz, the displacement of the lead-free and lead-based actuator approaches 1.5 μm and 2.3 μm, respectively. Fig. 7 shows the displacement of the BNKLT and PZT actuators as a function of position of the actuator. During the measurements, the laser scans the surface of the actuator while the actuator was driven by 2 $V_{\text{p-p}}$ at 1 kHz.

TABLE III
Comparison Between the PMC Actuators Fabricated Using Different Driving Elements.

	BNKLT	PZT-5A
k_{eff}	0.20	0.28
$t_{(\mathrm{FRT})}$ (ms)	0.17	0.19

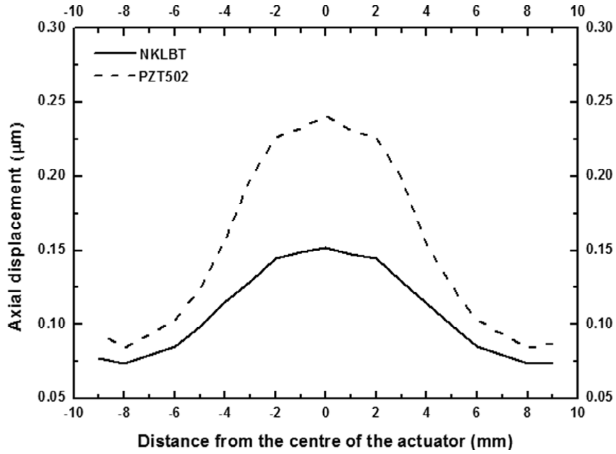

Fig. 7. The displacement of PMC actuators with BNKLT and PZT driving elements as a function of position on the surface of actuator.

V. Conclusions

The PMC actuator fabricated using the lead-free BNKLT ceramics has been studied. Both the electrical and mechanical properties of the actuator were measured. Because of its low density, the lead-free PMC actuator has higher fundamental resonance frequency compared with the lead-based one and hence has a shorter response time. Although the d coefficients of BNKLT ceramics are much lower compared with PZT ceramics, the resultant mechanical performance of the BNKLT actuator is acceptable. With good piezoelectric coefficients and low density, the BNKLT ceramics has the potential to be used as the driving element of other actuators.

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