Journal of Electroceramics, 8, 155–161, 2002

Piezoelectric Ring-Morph Actuators for Valve Application

SHUXIANG DONG,[1] XIAO-HONG DU,[1] PHILIPPE BOUCHILLOUX[2] & KENJI UCHINO[1]
[1]*International Center for Actuators and Transducers, Materials Research Institute, The Pennsylvania State University, University Park, PA 16802, USA*
[2]*Magsoft Corporation, 1223 Peoples Avenue, Troy NY 12180, USA*

Submitted October 26, 2001; Revised May 2, 2002; Accepted July 10, 2002

Abstract. This paper presents piezoelectric ring-morph actuators designed to produce a large flexural displacement for valve actuation application. The ring-shaped piezoelectric plate in the actuator produces a radial contraction or expansion and causes the center part of the metal disc to generate a large flexural displacement. The PZT ring creates a space under the metal disc which permits it to bend with a curvature larger than that of the conventional bimorph in the axis direction of the ring-morph when the PZT ring under the metal disc contracts. A prototype with diameter of 25.4 mm and thickness of 0.55 mm could produce a total stroke (static displacement) of over 130 μm under a driving voltage of $\pm$300 V and a load of 2 N. The maximum generative force of ring-morph actuator was about 30 N.

Keywords: piezoelectric, actuator, ring-morph

1. Introduction

Piezoelectric actuators can produce relatively large force with very high efficiency and quick response speed. However, the available displacements through the piezoelectric effect are still minute. Current commercial multi-layer piezo-actuators 20 mm in length can produce a displacement of about 15–17 μm under 100–150 V (over 1 kV/mm) [1]. To obtain a larger displacement, a mechanical amplifier is needed. The conventional bimorph type actuators can produce large flexural displacements; however, their generative force is very small [1, 2]. Two-dimensional disc type bimorph actuators have higher generative force than the one-dimensional bimorph actuators. However, their displacements are not large enough, for example, for valve applications. Thus, moonies and cymbals were proposed [3–5] by combining the multilayer with flextensional metal endcaps. Ultrasonic motors and inchworm type motors [6–8], which use the accumulation of small displacements with respect to time, have large stroke and high generative force. However, generally speaking, their structures are complex and costly. This paper describes a ring-morph actuator modified from a disc type bimorph actuator, which is an alternative structure of cymbals. A significant displacement enhancement was obtained compared with the conventional disc type bimorphs. In this paper, theoretical modeling of the ring type actuator using a finite element method is introduced and experimental results for static displacement measurements and load characteristics are reported. As an application example, this paper also describes a gas valve design that uses ring-morph actuators.

2. FEM Modeling

2.1. *Model of the Actuator*

An exploded view of the ring-morph bimorph actuator is shown in Fig. 1. The piezoelectric ring is poled in the thickness direction. Upward or downward flexure of the metal disc is obtained when a positive or negative DC voltage is applied to the piezoelectric ring. The deformation of the PZT ring can be decomposed into two components: (1) a contraction/expansion of the ring's cross-section, which is caused by the

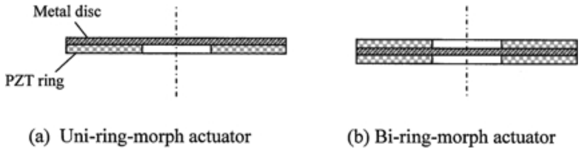

Fig. 1. Structure of the ring-shaped bimorph actuator (a) Uni-ring-morph ring actuator. (b) Bi-ring-morph actuator.

radial coupling of the piezoelectric material, and (2) a constriction/dilatation of the ring itself, which is caused by the circumferential coupling of the piezoelectric material. Due to the crystal symmetry of the piezoelectric material used, both transverse coupling effects share the same coefficient value (d_{31}). However, the circumference of the ring is much larger than its radial length, thus the constriction/dilatation effect has a greater effect on the final deformation of the actuator.

These two effects either add to each other or cancel each other, depending on the dimensions of the PZT ring. For this reason, there exists an optimum of the actuator's geometry.

The model considered (Fig. 2) is constituted of a piezoelectric ring attached to a metal disc. Finite element models were created with the ATILA software code to determine optimum relationships between the dimensions of the piezoelectric ring and the metal disc. Given the circular shape of the elements and boundary conditions, the ATILA models were 2D axisymmetrical (Fig. 3). Therefore, only one-half of the actuator's cross-section is represented in the mesh. Mechanical properties of steel or brass were used for the metal disc, which was considered to be homogenous and isotropic. The piezoelectric material was PZT-5H where the remnant polarization was oriented in the thickness direction. Mechanical boundary conditions consisted of a simple support point at the outer edge of the PZT ring. An electric voltage was applied across the PZT ring and used to produce the flexure of the actuator. Figure 4

Fig. 3. Mesh of the actuator.

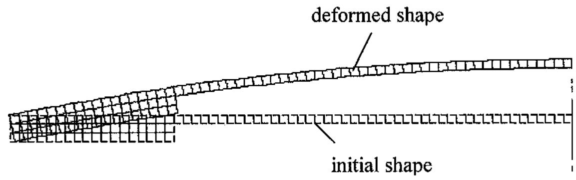

Fig. 4. Static deformation obtained with ATILA.

shows the flexure of the ring-morph actuator when a DC electric voltage was applied.

2.2. *Optimization of the Structure Parameters*

Parametric analyses were performed on the dimension d to study the influence of the ratio d/D on the displacement of the center of the metal plate (d and D are inner diameter and outer diameter of the piezoelectric ring, respectively). Results showed that there exists a d/D value that maximizes the displacement of the metal plate's center, as shown in Fig. 5.

From Fig. 5, we see that the FEM analysis confirmed important results that we were expecting: (1) ring type actuators with a d/D that is less than 0.8 and larger than 0.1 have higher displacement than the conventional disc type actuators (when d/D is close to zero, the ring actuator becomes a disc-type actuator), and (2) there exists a d/D value, about 0.7, that maximizes the out-of-plane displacement of the metal disc and gives about 20% higher displacement (for soft-type PZT) than from a disc alone. The experimental results confirmed the FEM's prediction. In fact, the experimental results showed that ring type actuators

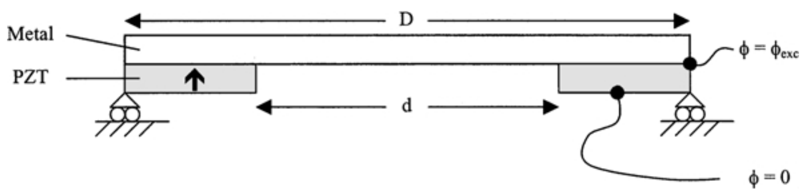

Fig. 2. Geometry of the studied actuator and boundary condition.

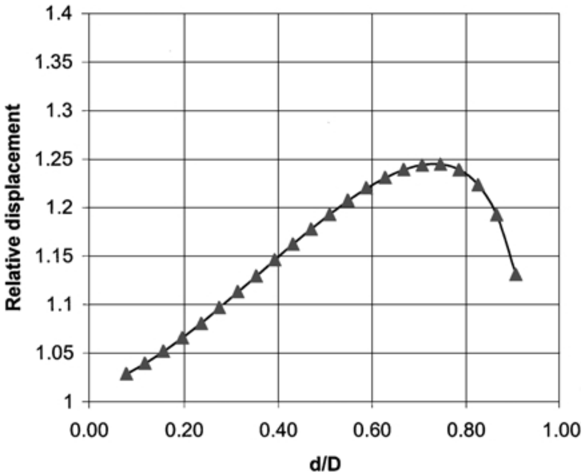

Fig. 5. Normalized displacement (ratio of displacement to its maximum value) at the center of the actuator as a function of d/D.

had a 30–50% higher displacement than conventional disc type actuators (see Section 3.3. *static displacements* in this paper).

3. Experimental Measurements

3.1. Fabrication of the Ring-Morph Actuator

The actuator samples were fabricated by bonding (using epoxy resin) either one or two piezoelectric ceramic rings having an outer diameter of 25.4 mm, 12–17 mm inner diameter and 0.4 mm thickness, to a thin metal disc (brass or steel) 25.4 mm in diameter and 0.15–0.5 mm in thickness. The ceramic rings were prepared from commercialized soft PZT-5H disc or hard PZT 8 discs (APC Ltd.). A photo of 25.4 mm diameter ring-morph actuators is shown in Fig. 6.

3.2. The Properties of the PZT Ceramic Materials

Two types of PZT ceramic materials, soft type (PZT-5H) and hard type (PZT-8), were used for the ring-shaped actuators experimentally. Their properties are summarized in Table 1. Generally, soft type piezoelectric ceramic materials have higher piezoelectric constants, such as d_{31} and d_{33}. However, they also have large energy loss with low mechanical quality factors under strong electric field.

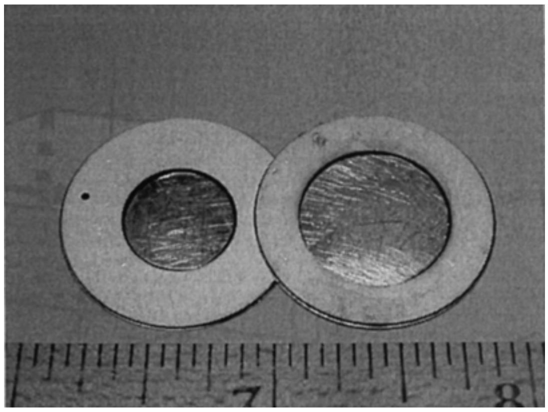

Fig. 6. Photo of 25.4 mm diameter ring-morph actuators.

3.3. Static Displacement

The static displacement curves of the ring-morph actuators for a mechanical boundary condition consisting of a simple support at the outer edge of the PZT ring were measured as a function of applied voltage at room temperature using a displacement sensor (Militron, type 1202). The sensor applied a pre-pressing force of 2.0 N to the center part of the ring-morph actuators during the displacement measurement. DC voltage was applied to the actuators in the range from −200 V to +200 V or −300 V to +300 V. After several cycles, the stabilized data were recorded.

Figure 7 shows displacement-voltage loops of the soft PZT and hard PZT type uni-ring-morph actuators under a load of 2 N and under ±200 V. A maximum positive displacement of 54 μm at 200 Volts and a maximum negative displacement of −44 μm

Table 1. Properties of the PZT ceramic materials (from APC Ltd.).

	Piezoelectric coefficient (10^{-12} C/N)		Coupling coefficient		Mechanical quality factor	Young's modulus, Y_{11}^{E} (10^{10} N/m^2)
	$-d_{31}$	d_{33}	k_{31}	k_{33}		
Soft type (PZT-5H)	270	580	0.38	0.74	75	6.1
Hard type (PZT-8)	109	275	0.33	0.68	1400	7.6

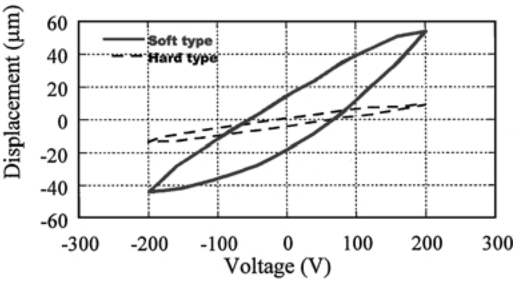

Fig. 7. Static voltage-displacement loops of the soft PZT type and hard PZT type piezoelectric uni-ring-morph actuators under 2.0 N load and ±200 V.

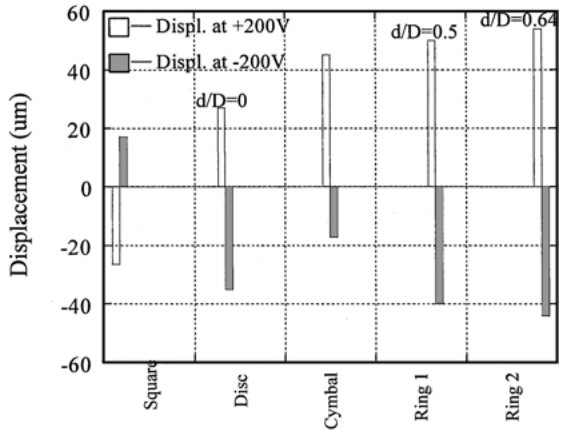

Fig. 8. Comparison of different actuators under 2.0 N load and ±200 V.

at −200 Volts with a hysteresis of 32.6% were obtained for the soft sample. Total travel range under ±200 V was 98 μm. This travel range is larger than the other types of piezoelectric actuators with a similar size. By using a hard type PZT ceramic ring, we could obtain a smaller hysteresis. However, its total travel range under 2.0 N load and under ±200 V was only 23 μm. For higher driving voltage, ±300 V, its total travel range could be increased to 41 μm, which was still small.

For comparison with proposed ring-morph actuators, we also assembled some cymbal type actuators, disc type actuators and ring-morph actuators with the same stainless steel discs (25.4 mm in diameter and 0.15 mm in thickness), the same soft type piezoelectric material (25.4 mm outer diameter, 0.4 mm in thickness and poled along its thickness), and the same assembly techniques. The static displacements for a disc-shaped unimorph, square-shaped unimorph,[1] cymbal type actuator, and two ring-morph actuators were measured under 2.0 N load and under ±200 V, as shown in Fig. 8. The square bimorph actuator (spring steel plate size: $25.4 \times 12.7 \times 0.15$ mm^3, PZT plate is 0.2 mm in thickness and thickness poling) was also measured at ±100 V in order to compare displacement. Table 2 gives structure parameters of these actuators.

From the measurements in Fig. 8, we can see that the two ring-morph actuators exhibit higher displacement both in the positive and negative directions than the others. The total range (displacement) for the ring-morph actuator with $d/D = 0.5$ is 90 μm, and the total range (displacement) for the ring-morph actuator with $d/D = 0.64$ is 98 μm, which is about 50% higher than the one from the disc type actuator ($d/D = 0$, and total displacement, 63 μm). The results coincide with FEM theoretical prediction as shown in Fig. 5: the displacements of ring-morph actuators increase with the d/D (ratio of inner diameter to outer diameter of a piezoelectric ring) until the d/D reaches 0.7.

Table 2. Structure parameters of the actuators.

	Beam type unimorph	Disc type unimorph	Cymbal type actuator	Ring type 1 unimorph	Ring type 2 unimorph
PZT materials (soft type)	PZT-5	APC851	APC851	APC851	APC851
Dimensions of PZT components	$15 \times 12 \times 0.2$	$\phi = 25.4$ $t = 0.4$ $d/D = 0$	$\phi 25.4 \times 0.4$	$\phi = 25.4$ $t = 0.4$ $d/D = 0.5$	$\phi = 25.4$ $t = 0.4$ $d/D = 6.4$
Metal materials	Spring steel	Stainless steel	Stainless steel	Stainless steel	Stainless steel
Dimensions of metal plates	$25.4 \times 12.7 \times 0.15$	$\phi = 25.4$ $t = 0.15$	$\phi = 25.4$ $t = 0.15$	$\phi = 25.4$ $t = 0.15$	$\phi = 25.4$ $t = 0.15$

ϕ: Diameter.
t: Thickness. All units in mm.

In our experiment, the disc type actuator had a smaller positive (upper) displacement than negative displacement. However, when using the PZT ring instead of the PZT disc, the positive displacement became larger than its negative one. The reason for this difference is from the PZT ring structure. The PZT ring leaves a space at the center of the metal disc and permits it bending larger in the positive (upper) direction when the PZT ring under the metal disc contracts. A cymbal actuator also had large positive displacement; however, its negative displacement is very small. The unimorph beam showed a lower total displacement (center position of the plate), only 44 μm, under 2.0 N load and $\pm$100 V. In addition, the beam type unimorph actuator had low load capability.

Figure 9 shows a displacement comparison for the soft type piezoelectric disc and uni-ring-morph, and a hard type piezoelectric uni-ring-morph under 2.0 N load and $\pm$300 V. Again, the soft type piezoelectric ring-morph actuator showed larger stroke than the disc type actuator. The total stroke for the soft type piezoelectric ring-morph actuator was nearly 140 μm, compared with the soft type piezoelectric disc type actuator ($\sim$100 μm). The former was about 30–40% higher than the latter. However, the ring-morph actuator made from the hard piezoelectric ceramic material had very small stroke. Though d_{31} under a small electric field of the soft PZT ceramic ring was about 2 times that of the d_{31} of the hard PZT ring, the total displacement under a large electric field of the soft ring actuator was 3 times the displacement of the hard ring actuator. It was rational that the PZT ring should have contraction/expansion

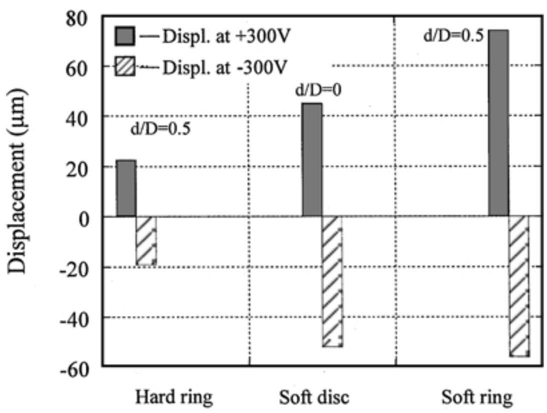

Fig. 9. A displacement comparison of soft type piezoelectric disc type unimorph, hard and soft type piezoelectric ring type unimorph under 2 N load and $\pm$300 V.

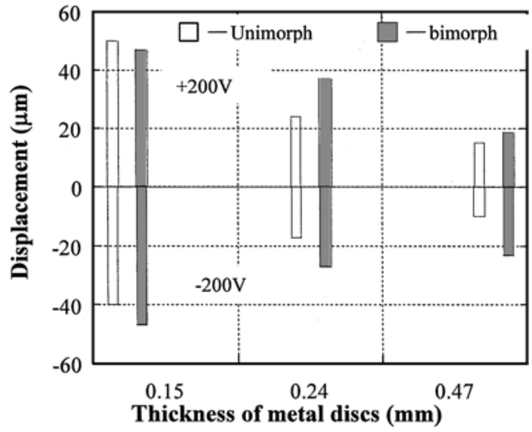

Fig. 10. Displacement comparisons for soft type piezoelectric uni-ring-morph/bi-ring-morph with different thickness of metal discs, 0.15 mm, 0.24 mm and 0.47 mm, respectively, under 2 N load and $\pm$200 V.

displacements enough large for obtaining large bending displacement at the center part of the metal disc.

The stiffness of the metal disc has a significant effect on the displacement of the ring type actuators. With increasing the metal disc thickness, the bending stiffness of the metal disc also increases correspondingly. Thus, it becomes more difficult for the PZT ring to drive the disc into bending. As a result, the output displacement of the ring type actuator decreases correspondingly with the thickness of the metal disc (Fig. 10). However, the bimorph structure (two PZT rings together with a metal disc) enhanced its displacement for the thicker metal disc. Figure 10 shows that for the metal disc with small stiffness (0.15 mm in thickness), both unimorph and bimorph ring type actuators had almost the same displacement, about 90 μm. When the thickness of the metal disc increased to 0.24 and 0.47 mm, the displacement for the ring type unimorph actuator decreased to 41 μm and 25 μm, respectively. However, with the bimorph structure, its displacement could be sustained around 64 μm, and 41 μm, about 56% and 64% higher than the unimorph, respectively.

3.4. Load Characteristics

With a displacement sensor (Militron, type 1202) and a simple setup for applying force, the load-displacement characteristics of the ring-morph actuators could be obtained (Fig. 11). The mechanical boundary condition of

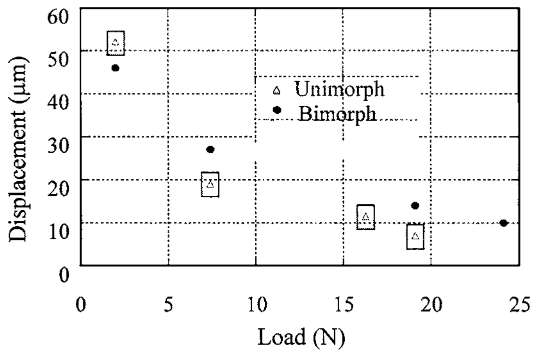

Fig. 11. Load-displacement characteristics of the soft type piezoelectric uni/bi-ring-morph under 200 VDC.

the actuator was a simple support at the outer circumference of the PZT ring (that means the actuator was simply placed on a thin metal ring that has the same outer diameter as the ring-morph actuator). A square metal beam, *m*, its one end was placed on the center part of ring-morph actuator with a point contact, and its other end was a simple support. Then, with a pressing force, *f*, the displacement sensor was pressed against the end of the beam that was placed on the center of the actuator. The load, $f + 1/2\ (W + m)$, was applied at the center point of the actuator when a weight *W* was hung on the middle of the beam. The d/D of PZT rings (soft type) of the actuators was 0.5, and the diameter and the thickness of the metal discs were 25.4 mm and 0.15 mm, respectively. The voltage applied to the two actuators was +200 V. Experimental results showed that the maximum generative force of the uni-ring-morph at its center point was about 20 N. Apparently, the bi-ring-morph actuator (two PZT rings) has larger load ability than the uni-ring-morph actuator (one PZT ring). Experimental results showed that the maximum generative force of the bimorph at its center point was near 30 N.

4. Application for Valve Actuation

A control valve using two piezoelectric ring-morph actuators is shown in Fig. 12. The two ring type 1 unimorph actuators (their structure parameters are shown in Table 2) are layered together to obtain a double displacement stroke, and its voltage-displacement loop under 2 N load and ±200 V is shown in Fig. 13. The maximum displacement under 2 N load and 300 V is over 100 μm in both the upward and downward directions. The center part at the bottom of one actuator is fixed at the valve case, and the upper center part of another actuator drives a shaft that is connected to a ball for ball position control. The ball is pressed against the nozzle of the valve with a pre-pressing spring, and it constructs a normal-closed valve.

When a voltage is applied to the two ring-morph actuators (see Fig. 12), the two layered actuators will produce a displacement toward the upper direction and drive the ball in the ‘up’ direction and the valve becomes open. By controlling the voltage amplitude applied to two ring-morphs, the ball position can be adjusted, and the gas flow quantity passed the nozzle can be controlled precisely.

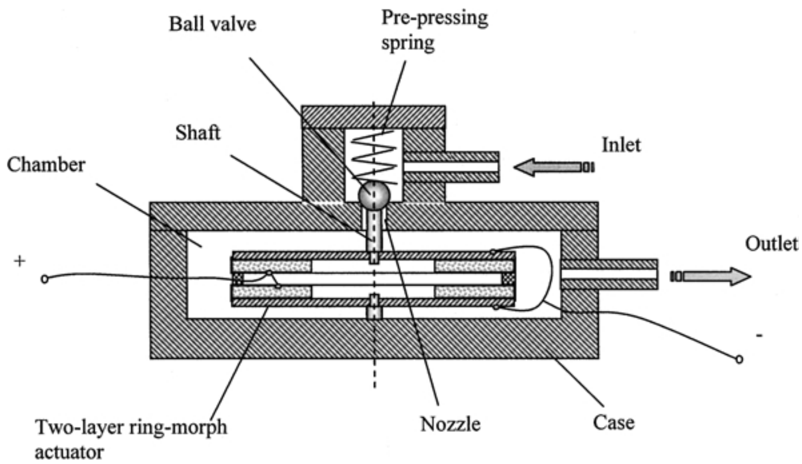

Fig. 12. Normal-closed valve using piezoelectric layered two ring-morph actuators.

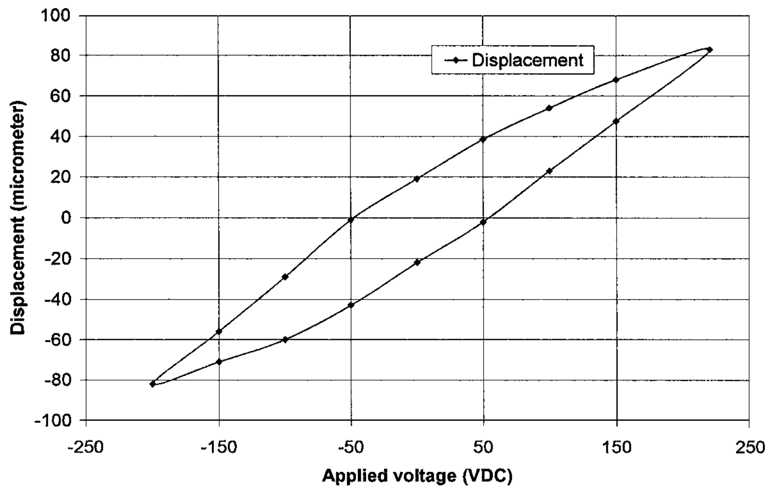

Fig. 13. Static voltage-displacement loops of the actuator laminated with two ring-morphs for valve actuation.

5. Summary

A ring-morph actuator and a valve actuated by the two-layered ring-morph actuator have been developed.

- New type ring-morph actuators showed relative large displacement and driving force. Both the finite element computation and experimental results confirmed that the ring type actuator had a 30%–50% higher displacement than the disc type actuators.
- Using ATILA modeling, the ring-morph actuator structure could be optimized. There exists an optimum d/D value for ring-morph actuators with a specific geometry and material, about 0.7, that maximizes the out-of-plane displacement of the metal disc.
- A ring-morph prototype with diameter of 25.4 mm and thickness of 0.55 mm could produce a total stroke of 130 μm under a load of 2.0 N and $\pm$300 V. The maximum generative force of the ring-morph actuator was about 30 N.
- With layered ring-morph structure, total displacement stroke of the ring-morph actuators could be enlarged further without changing its driving force.
- As a precision actuation element, a layered ring-morph actuator has been applied to a new valve.

Acknowledgment

The authors gratefully acknowledge the support from Time Engineering Co., LTD., in Japan, for the research project. Authors also would like to acknowledge to Dr. Jim Tressler in Naval Research Laboratory for his meaningful suggestions for improving this paper's quality.

Note

1. Face Int. Company, Norfolk, Virginia, USA 23508.

References

1. PI, Physik Instrumente, CAT 114.NP/E. 2/98.20, p. 803.
2. Tokin, Piezoelectric actuators, 1998 Tokin Corporation, Cat. No. TA001 9805-100-P1, p. 38.
3. A. Dogan, Q.C. Xu, K. Onitsuka, S. Yoshikawa, K. Uchino, and R.E. Newnham, *Ferroelectrics Proceedings of the 8th International Meeting on Ferroelectricity (IMF-8)*, Aug. 8–13 1993, Part 6 (of 9), Vol. 156, Nos. 1–4, pt 6, 1994.
4. R.E. Newnham, A. Dogan, Q.C. Xu, K. Onitsuka, J. Tressler, and S. Yoshikawa, *Proceedings of the IEEE 1993 Ultrasonics Symposium*, Baltimore, MD, USA, Oct. 31–Nov. 3, 1993, Part 1 (of 2), Vol. 1, p. 509.
5. Y. Sugawara, K. Onitsuka, S. Yoshikawa, Q.C. Xu, R.E. Newnham, and K.Uchino, *J. Amer. Ceram. Soc.*, **75**(4), 996 (1992).
6. K. Uchino, *Piezoelectric Actuators and Ultrasonic Motors* (Kluwer Academic Publishers, Norwell, Massachusetts, USA, 1997).
7. D. Roberts, *Proceedings of SPIE—The International Society for Optical Engineering Proceedings of the 1999 Smart Structures and Materials—Smart Structures and Integrated Systems*, March 1–4, 1999, Vol. 3668, No. II.
8. Toshiiku Sashida and Takashi Kenjo, *An Introduction to Ultrasonic Motors* (Clarendon Press, Oxford, 1993).