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Anh Kim Tran <sup>a</sup> & Kwang Joon Yoon <sup>b</sup>

<sup>a</sup> Artificial Muscle Research Center, Department of Aerospace Information Engineering, Konkuk University, C-387, College of Engineering, 01 Hwayang-dong, Kwangjin-gu, Seoul 143-701, Republic of Korea

<sup>b</sup> Artificial Muscle Research Center, Department of Aerospace Information Engineering, Konkuk University, C-387, College of Engineering, 01 Hwayang-dong, Kwangjin-gu, Seoul 143-701, Republic of Korea; Email: [kjyoon@konkuk.ac.kr](mailto:kjyoon@konkuk.ac.kr)

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# Design and Performance Evaluation of Mini-Lightweight Piezo-Composite Actuators

Anh Kim Tran and Kwang Joon Yoon\*

Artificial Muscle Research Center, Department of Aerospace Information Engineering,  
Konkuk University, C-387, College of Engineering, 01 Hwayang-dong, Kwangjin-gu,  
Seoul 143-701, Republic of Korea

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## Abstract

In this paper, through an evaluation process conducted on several designs of mini-LIPCA (Lightweight Piezo-Composite curved Actuator), an optimal design of a mini-LIPCA has been proposed. Comparing with the LIPCA-C2, the design of the mini-LIPCA comes with reduced overall size and a thinner active layer. Since a variation in the number and lay-up of fiber composite layers may strongly affect the performance of the device, one is able to configure several designs of mini-LIPCA. The evaluation process is then followed in order to determine a configuration which characterizes the possibly optimal performance. That is, a design of a mini-LIPCA is said to be optimal if it is capable of producing a maximum out-of-plane displacement. The size of the LIPCA to be investigated was selected to be 10 mm × 20 mm in which the thickness of PZT plate is about 0.1 mm. The thickness of glass/epoxy and carbon/epoxy are about 0.09 mm and 0.1 mm, respectively. The evaluation process has been conducted thoroughly, i.e., analytical estimation, numerical approximation and the experimental measurement are all involved. Firstly, the design equation was used to calculate essential parameters of proposed lay-up configurations. Secondly, ANSYS, a commercial FEA package, was utilized to estimate displacement outputs of the actuators upon being excited. Finally, experimental measurements were able to verify the predicted results.

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## Keywords

Unimorph, PZT, LIPCA, miniature

## 1. Introduction

These days, piezoceramic materials have drawn intensive interest from those researchers who desire to develop high-performance actuators. Among many actuators which employ piezoceramic materials, unimorph actuators have been known as being able to generate large out-of-plane displacements and sustain a considerably sizable load. Currently in the market, THUNDER [1, 2] and LIPCA [3] feature

\* To whom correspondence should be addressed. E-mail: kjyoon@konkuk.ac.kr

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the two most advanced unimorph actuators which can produce larger displacements than any other actuator of the same size and similar driving mechanism. Those actuators are both manufactured by sandwiching and bonding an active piezoelectric ceramic layer with several other layers of different materials in a certain sequence. For the LIPCA, the stacked layers are then vacuum bagged and cured at an elevated temperature (177°C) in an automatically controlled oven. The main difference between THUNDER and LIPCA is that, for the LIPCA, the heavy metal stainless layer of the THUNDER is replaced by fiber-reinforced plastic layers, thereby achieving a considerable reduction in weight.

The improved design of the LIPCA makes it easier for fabrication as well as improving the performance. Because of that, the best configuration of the actuator, the LIPCA-C2, was realized only after a thorough evaluation process [4]. In reality, there are problems in the applications in which LIPCAs are employed: not all applications are appropriate for the LIPCA-C2, which features comparably bulky size and high power consumption. Therefore, it is crucial to have LIPCAs in different sizes and impedances. It turns out that a need for performance improvement becomes critical when there is a dimensional change from the original configuration of the LIPCA. For instance, a reduction in thickness of the piezoceramic layer, from 0.25 mm down to 0.1 mm, will strongly affect the calculation of bending stiffness of the device and will produce considerable changes in the moment arm length and out-of-plane displacement of the device when it is excited. The fact is, by keeping the original lay-up structure with the modified thickness of piezoceramic layer, the LIPCA may fail to keep its advanced performance. Probably, there exists another configuration of the lay-up structure that provides the optimal displacement for the device. Therefore, one may need to re-configure the design of the LIPCA in order to obtain an optimum performance for a set of given parameters.

In this paper, in order to design a miniaturized LIPCA for minute applications, several designs of mini-LIPCA have been proposed and evaluated. In fact, there have been several applications employing miniature LIPCAs [5, 6] but still, none of the papers have been dedicated to a thorough investigation of their performances. Through this paper, proposed designs of mini-LIPCA are evaluated based upon analytical formulation of the original LIPCA. That is, all figures most likely to be related to the performance of the device have been calculated and rated. A nominal size for this class of LIPCA has been selected as 10 mm × 20 mm, whereas thicknesses of glass–epoxy and carbon–epoxy prepregs are considered unchanged from the original design (0.09 mm and 0.1 mm, respectively). Also, a thinner piezoceramic thickness is adopted: 0.1 mm. Number and sequences of prepregs in a design may differ from one another. This variation was considered as an effort to manually determine an optimal configuration of the actuators.

Both numerical prediction using a commercial FEM package and experimental measurement are then used to verify the predicted results.

## 2. Design of a High-Performance Mini-LIPCA

As was described in Ref. [3], an analytical equation of the LIPCA is expressed as follows:

$$\Delta\kappa = \frac{a}{D} E_a d_{31} \Delta V = c_{ua} E_a d_{31} \Delta V, \quad (1)$$

where  $\Delta\kappa$  is the curvature change from the flat configuration of the laminate;  $a$ ,  $D$  are the moment arm length and bending stiffness of the laminate;  $E_a$ ,  $d_{31}$ ,  $\Delta V$  are elastic modulus, piezoelectric charge coefficient of the active layer and exciting voltage, respectively.  $c_{ua} = a/D$  is defined as the coefficient of a unimorph actuator. The schematic illustration for the curvature change of a unimorph laminate is shown in the Fig. 1. One can easily establish a relation between performance in term of actuation displacement ( $\Delta h$ ) and curvature change ( $\Delta\kappa$ ) [3] as shown in equation (2):

$$\Delta h = \rho \left[ 1 - \cos\left(\frac{l}{2\rho}\right) \right] = \frac{1}{\Delta\kappa} \left[ 1 - \cos\left(\frac{l \cdot \Delta\kappa}{2}\right) \right], \quad (2)$$

where  $\rho = 1/\Delta\kappa$  is the radius of the curvature and  $l$  is the length of the actuator as shown in Fig. 2.

It is reasonable that properties of concerned material used for the calculation should be presented beforehand, in Tables 1 and 2.

Equation (1) is then used for the evaluation of several designs of mini-LIPCA which are denoted as s0 to s4. Each of them constitutes a different lay-up, which is shown successively in the Figs 3–7. As shown in the Fig. 1 as well as equation (1), the moment arm length  $a$  is considered a parameter that strongly impacts on the performance of the actuator. For that reason, it is easy to see that each consecutive design features a larger arm moment as illustrated in Table 3. As usual, glass–epoxy, carbon–epoxy and CTS PZT are to be used in those miniature designs. The PZT plate had a size of  $20 \times 10 \times 0.1 \text{ mm}^3$  and the fabricated LIPCAs were provided with 5 mm extension on each end. Therefore, each actuator eventually gains a total length of 30 mm ( $l = 30$ ).

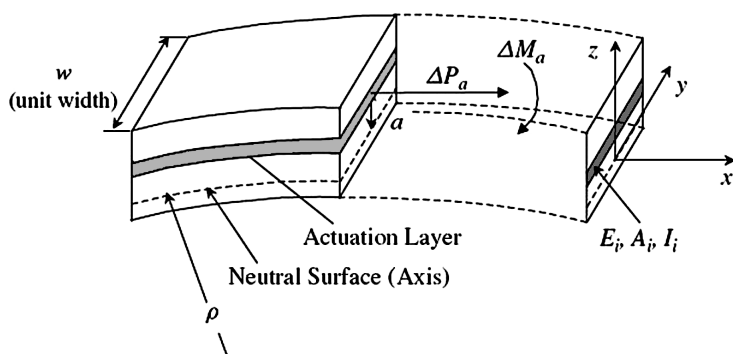


Figure 1. A laminated beam with a piezoceramic active layer [3].

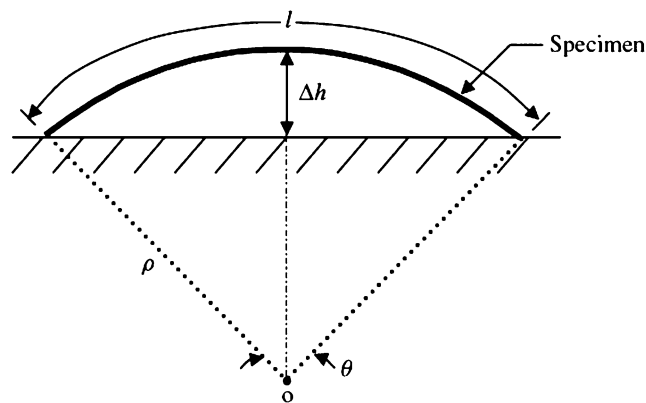


Figure 2. Schematic for curvature calculation of a curved laminate [3].

Table 1.  
Selected properties of piezoelectric ceramic (CTS 3203HD)

Properties			Value	Properties			Value
Elastic modulus (GPa)	$E_1, E_2$	62	Charge coefficient ( $10^{-12} \text{ mV}^{-1}$ )	$d_{31}$			−320
	$E_3$	49		$d_{33}$			650
Elastic constant ( $10^{-12} \text{ m}^2/\text{N}$ )	$S_{11}^E$	16.6	Dielectric constant	$d_{15}$			1000
	$S_{33}^E$	21		$K_3^T$			3800
	$S_{55}^E$	52.4		$K_1^T$			3200
	$S_{12}^E$	−4.2	Coefficient of thermal expansion ( $10^{-6} \text{ K}^{-1}$ )	$\alpha_1, \alpha_2$			3.5
	$S_{13}^E$	−8.2		$E_c$			8
Length (mm)	$l$	20	Width (mm)	$W$			10
Thickness (mm)	$t$	0.1	Density ( $\text{g}/\text{cm}^3$ )	$\rho$			7.8

Table 2.  
Properties of concerned fiber composites

Properties		Carbon/epoxy	Glass/epoxy
Modulus (GPa)	$E_1$	231.2	21.7
	$E_2$	7.2	21.7
	$G_{12}$	4.3	3.99
Poisson's ratio	$\nu_{12}$	0.29	0.13
Coefficient of thermal expansion ( $10^{-6} \text{ K}^{-1}$ )	$\alpha_1$	−1.58	14.2
	$\alpha_2$	32.2	14.2
Length (mm)	$l$	20	30
Thickness (mm)	$t$	0.1	0.09

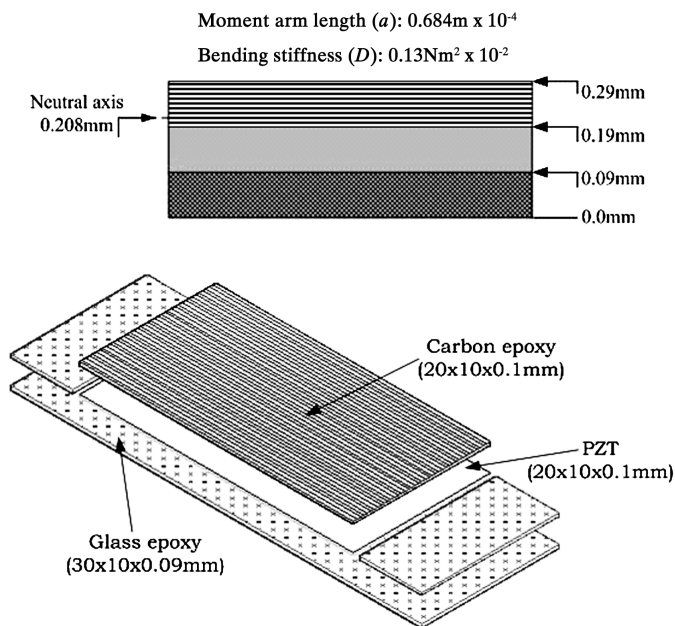


Figure 3. Lay-up of s0 design.

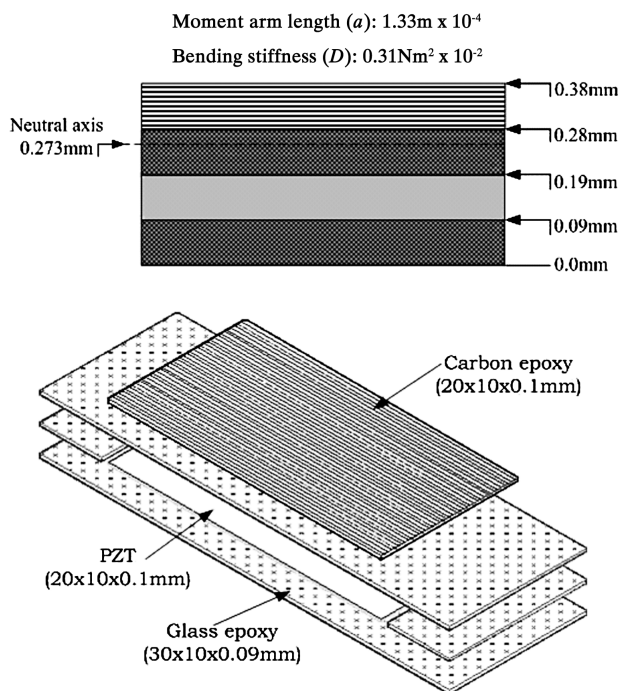
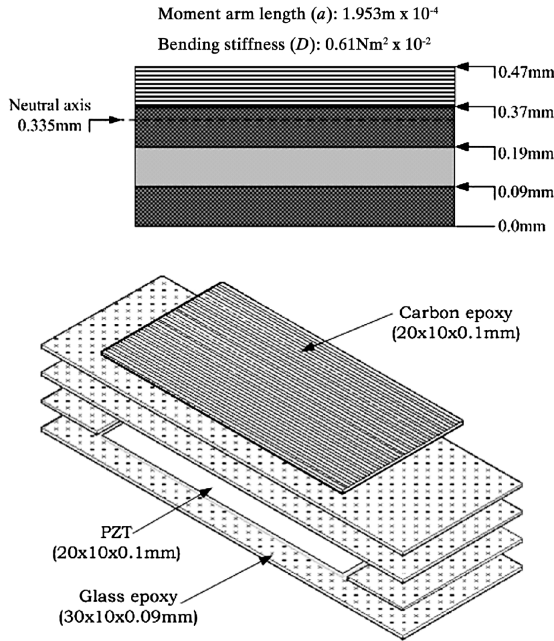
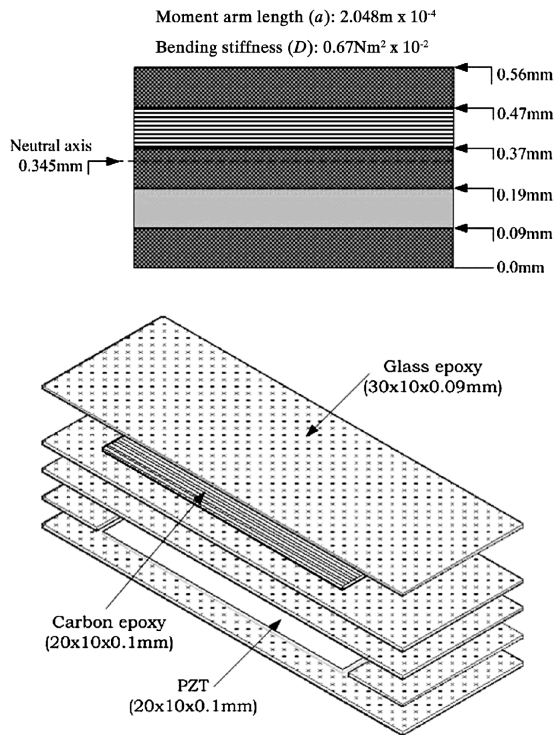


Figure 4. Lay-up of s1 design.



**Figure 5.** Lay-up of s2 design.



**Figure 6.** Lay-up of s3 design.



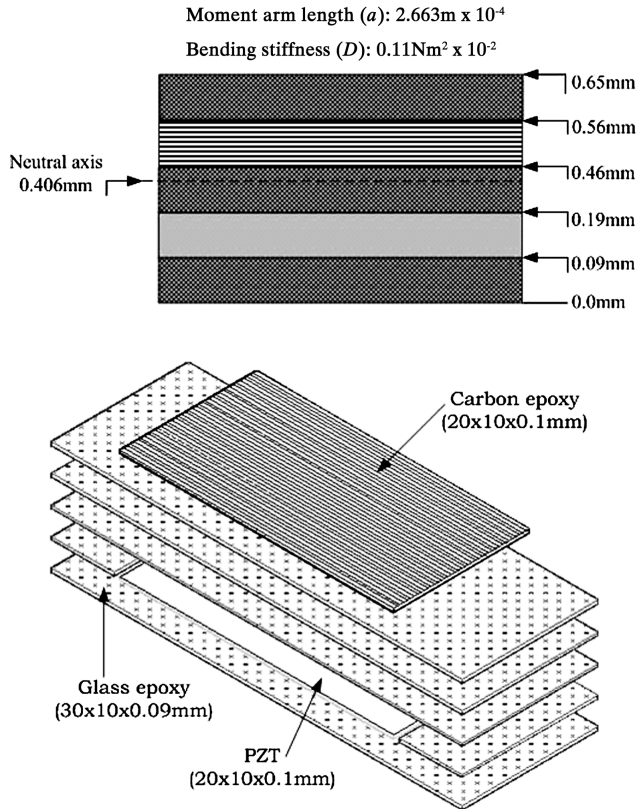


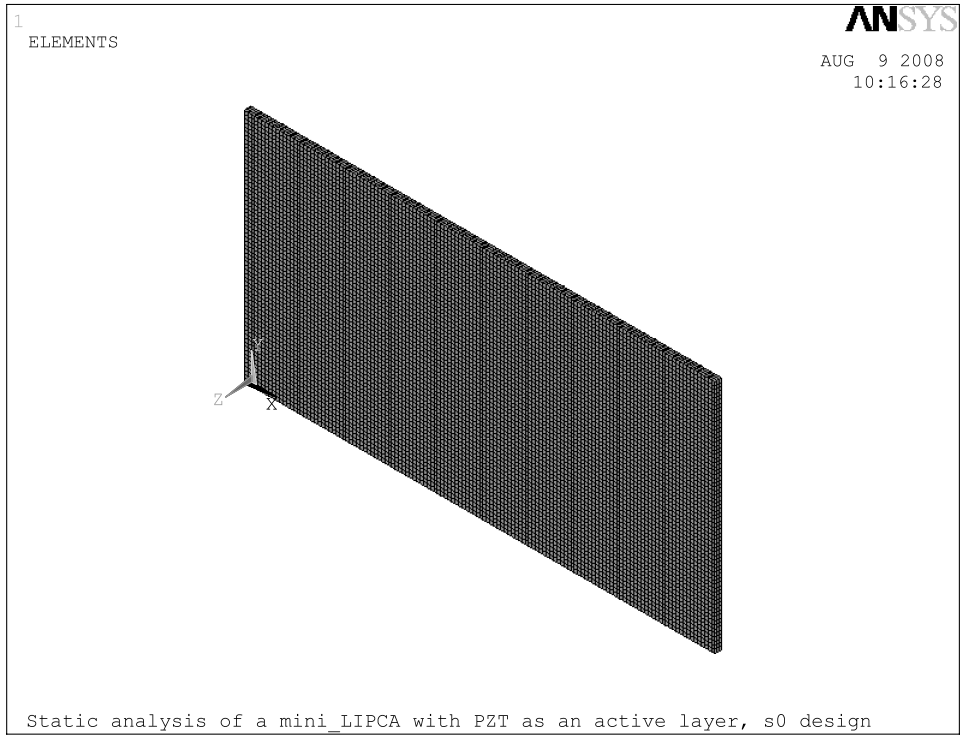
Figure 7. Lay-up of s4 design.

Table 3.

Analytical design parameter of different designs of mini-LIPCA

Actuator name	Bending stiffness ( $10^{-2} \text{ N m}^2$ )	Moment arm length ( $10^{-4} \text{ m}$ )	$c_{ua}$ ( $10^{-2} \text{ N}^{-1} \text{ m}^{-1}$ )
s0	0.13	0.684	5.26
s1	0.31	1.33	4.29
s2	0.61	1.953	3.2
s3	0.67	2.048	3.06
s4	1.11	2.663	2.4

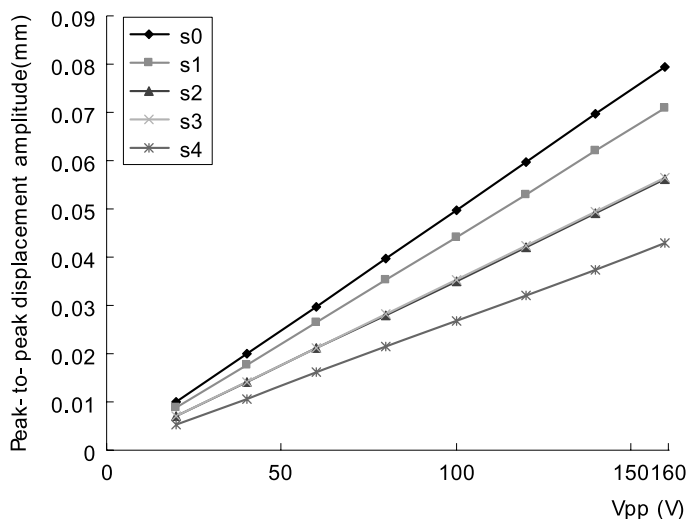
As a result, performance parameters of the actuator have been calculated and listed in Table 3. By looking at this table, it is obvious that the configuration of s0 displays the best performance, since it is associated with the largest  $c_{ua}$ . In order to verify the results, numerical approximation and experimental measurements were then conducted and these are discussed in the next two sections.



**Figure 8.** A FEM modeling of LIPCA device.

### 3. Numerical Approximation

A commercial FEM-based software, the ANSYS, has been utilized for our estimation process. For simplicity in modeling, all layers of the device are considered to have the same length as that of the PZT layer (20 mm). 3D solid elements like solid45 (for normal solid elements) and solid5 (for piezoelectric elements) in ANSYS have been used for modeling of LIPCA devices. Illustration of the modeling and its meshing can be found in Fig. 8. It turns out that performance of the actuator is somewhat poorer than that obtained from experiment. However, at least, for a certain aspect, one may find useful information from this approximation. As was reported in Ref. [3], the stacked layers have to be vacuum bagged and cured at an elevated temperature (177°C) before they are put into use at a room temperature (25°C). After curing, the LIPCA is naturally curved up due to the effect of internal residue stresses, which may have much influence on the actuation displacement of the device. Therefore, both curing and excitation should be taken into consideration when estimating the vertical displacement of the actuators. That is, besides the temperature variation ( $\Delta T = 25 - 177 = -15^\circ\text{C}$ ) applied to all solids (solid45 and solid5 elements), an excitation signal is also applied to piezoelectric solids (solid5) as a voltage boundary condition in order to approximate a total actuation displacement of the device. Estimation results for actuators are shown in Fig. 9



**Figure 9.** Estimated displacements of the device centrals.

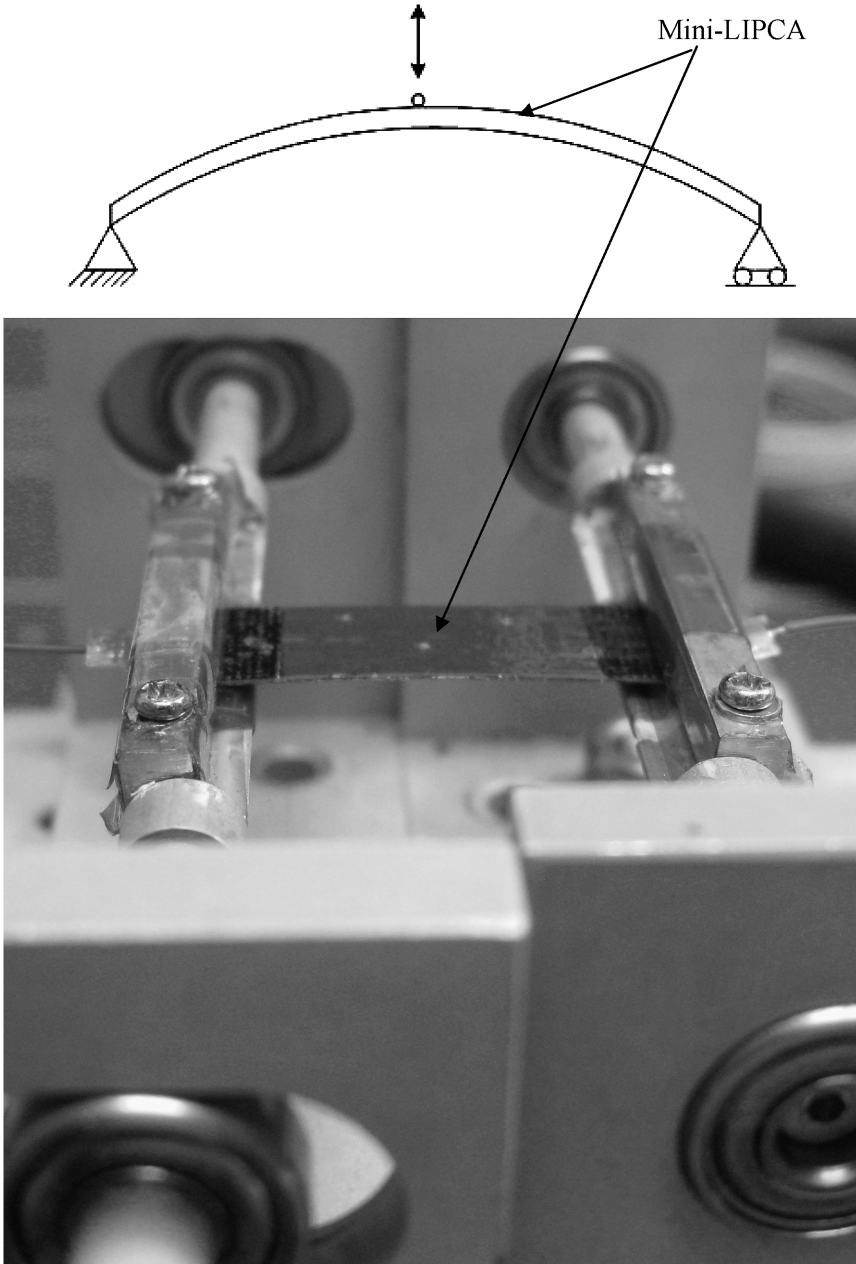
where displacement of a central point on the convex side of the device was approximated. The boundary condition follows the simply supported setting as illustrated in Fig. 10. These results definitely support our previous conclusion. That is, mini-LIPCA s0 is simply the best actuator which can produce the largest displacement among proposed designs.

#### 4. Experimental Verification

To experimentally verify the performances of mini-LIPCA, the devices were fabricated and tested with the simply supported condition. As mentioned before, the fabricated mini-LIPCA were provided with an extension length of 5 mm on each end to all layers except the PZT. As a result, the actuator gains a total length of 30 mm. This design allows the devices to be well protected against electric shock, de-lamination and life-time shortage. Besides, the extension of grips enables the device to gain an equal additional displacement to that fabricated with the length similar to that of the PZT layer. Measured displacements of a central point on the convex surface of the devices are shown in the Fig. 11. The Keyence LK-G3001V non-contact laser sensor (Fig. 12) was used for the measurement.

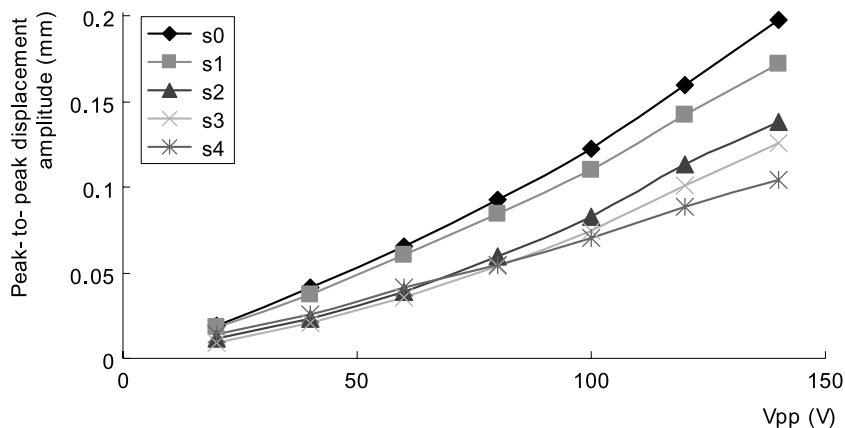
#### 5. Conclusion

A performance evaluation of a miniature LIPCA in term of actuation displacement has been discussed in this paper. It is clear that the LIPCA should be shaped in different sizes and impedances, so finding an appropriate lay-up configuration of a mini-LIPCA certainly becomes a primary concern and this is explored in this paper. The design was started with the simplest configuration (s0) and then followed with

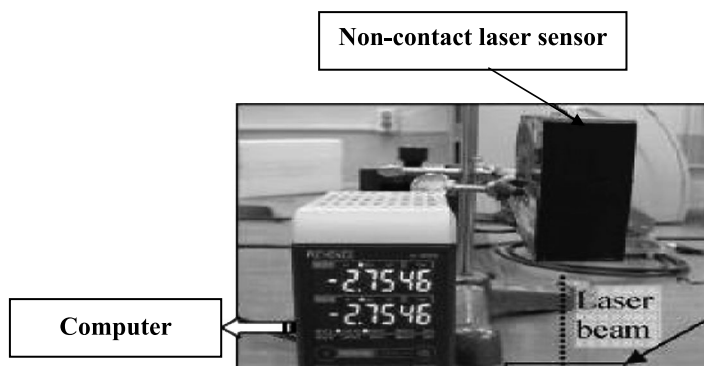


**Figure 10.** Simply supported boundary condition.

configurations denoted from s1 to s4. As explained, each following design features a larger moment arm length which suggested the possibility of bringing a higher bending moment to the device. The performance evaluation process then started with analytical analyses which produced the result that s0 is the best design among



**Figure 11.** Measured displacements of the device centrals.



**Figure 12.** The Keyence LK-G3001V non-contact laser sensor.

those proposed. An FEM approximation and experimental realization need to be followed in order to verify the predicted results.

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