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Ngoc-Trung Nguyen [a], Bum-Soo Yoon [a], Hyun Ryu [a] & Kwang-Joon Yoon [a]

[a] Artificial Muscle Research Center, Department of Aerospace Information Engineering, Konkuk University, Seoul, 143-701, South Korea

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Actuation characterization of the lightweight unimorph piezo-composite actuator for different loading cases

Ngoc-Trung Nguyen, Bum-Soo Yoon, Hyun Ryu and Kwang-Joon Yoon*

Artificial Muscle Research Center, Department of Aerospace Information Engineering, Konkuk University, Seoul 143-701, South Korea

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In this study, we focused on the actuation behavior of the lightweight piezo-composite unimorph actuator (LIPCA). Common loading configurations found in real applications of LIPCA have been studied including the center loading and tip loading cases. The domain switching effect that has strong influence on the performance of LIPCA was recorded. While a longitudinally compressed stress state within the PZT (lead zirconate titanate, Pb[Zr*(x)*Ti(1–*x*)]O_3) layer in LIPCA is preferable to avoid failure during operation, experimental results showed that, for the transverse loading cases, the actuator should be arranged in a manner such that the stress state within the PZT is in as much tension as possible to encourage the non-180° domain switching. With investigated loading cases in this paper, suitable arrangements could help improve the actuation performance. The improvement can be up to almost 33% in simply-supported with center loading and 140% in clamped tip loading case.

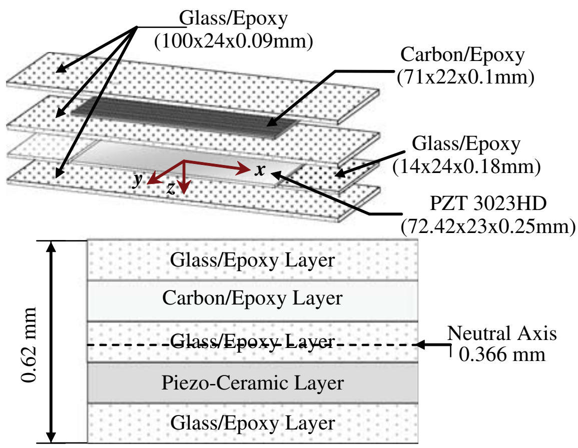
Keywords: unimorph actuator; piezoceramic; domain switching; LIPCA; compressive stress

1. Introduction

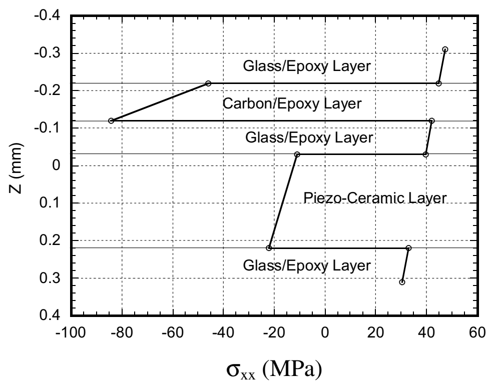
Unimorph actuator is a specific stress-biased, enhanced-displacement, bending type actuator which consists of a piezoelectric ceramic substrate bonded to one or more layers of different materials. The unimorph actuator is always subjected to a longitudinal stress in working conditions. Especially, the PZT layer should be designed in compressed state at the service temperature to avoid failure during operation. The longitudinal stress can be the internal residual stress induced in each layer due to the mismatch in the thermal expansion coefficients (CTE) of constituent materials during the curing/cooling-down process or it could be the applied mechanical load from the in-service conditions.

Stress sensitivity of piezoelectric ceramics has been studied for a long time.[1,2] It was found that the piezoelectricity is sensitive to the applied static stress not only in perpendicular but also in parallel to the polar axis. Upon the application of a small compressive preload, larger polarization and strain outputs were observed.[3] The influence of uniaxial compressive stress on the response of soft PZT indicated a significant enhancement of the piezo-effects performance with a small prestress loading.[4] The piezoelectric coefficients in a soft PZT increased initially when the stress in poled direction was increased and it reached a maximum value after which it reduced rapidly with increasing stress.[5] These results are useful for

*Corresponding author. Email: kjyoon@konkuk.ac.kr



(a) Geometry and position of neutral axis of LIPCA



(b) Residual stress of LIPCA laminate section

Figure 1. Geometry, position of neutral axis and residual stress of LIPCA.[10]

Table 1. Basic properties of actuator materials.[10]

Properties		Piezoelectric ceramic 3203HD	Carbon/Epoxy	Glass/Epoxy
Modulus	E_1 (GPa)	62.0	231.2	21.7
	E_2 (GPa)	62.0	7.2	21.7
	G_{12} (GPa)	23.66	4.3	3.99
	v_{12}	0.31	0.29	0.13
CTE	α_1 ($\times 10^{-6}$/°K)	3.5	−1.58	14.2
	α_2 ($\times 10^{-6}$/°K)	3.5	32.2	14.2
Piezoelectric strain coefficient d_{31}, d_{33} ($\times 10^{-12}$ m/V)		−320, 650	–	–
Curie point (°C)		225	–	–
Density	ρ (g/cm^3)	7.8	1.51	1.91
Thickness	t (mm)	0.25	0.1	0.09
Manufacturer & model		CTS Piezoelectric products (www.ctscorp.com)	SK chemicals, Korea	
			UPN-116B	GEP-108

stack-type actuators, where the load applies the compressive stress in the direction of actuation via d_{33} mode. The effect of longitudinal stress is more important for unimorph actuators (d_{31} mode), where the actuation displacement could be enhanced by introducing stress perpendicular to the poling direction.

Unlike in other studies on the behavior of piezoceramic materials under mechanical–electrical loading, where the bulk ceramics were used, the PZT in a unimorph actuator is a thin wafer. Thus, the distribution, configuration and orientation of the domain in PZT wafer can be more sensitive to the applied stress and/or electric field. Furthermore, a compression/tension test on this specimen is not trivial. Although there are not many studies on the effect of this transverse stress to the overall actuation of the pre-stressed actuators, it is believed that the domain switching response and/or the change in the domain configuration of PZT due to the applied stress leads to an enhancement in performance. Li et al. [6] reported the effect of transverse tensile stress at high electric fields on enhanced value of d_{31} coefficient in a thin soft PZT sample. In another study, Schwartz and Moon used the X-ray method to characterize domain configuration and switching effects in RAINBOW actuators [7] and figured out the effects of stress on extrinsic electromechanical response by altering the initial domain configuration. Preliminary experimental and numerical tests on the response of LIghtweight Piezo-Composite unimorph Actuator (LIPCA) with center loading case were also performed by the authors of this article.[8–11] The preferable loading configuration LIPCA was applied in robot actuating systems, e.g. insect-mimicking flapper,[12,13] and control surfaces of micro-air vehicle.[14]

This paper focuses on the experimental work to investigate the performance of unimorph piezoelectric actuator under different common loading cases. The study concentrates on a specific type of unimorph actuator, the LIPCA. The results will then be explained. It is useful for certain applications by improving the operational actuation of the device.

2. Experimental setup

2.1. Fabrication of LIPCA

LIPCAs are manufactured by placing a glass/epoxy fabric prepreg as the bottom layer on a flat base plate and placing a PZT 3203HD ceramic wafer on the glass/epoxy prepreg.[10]

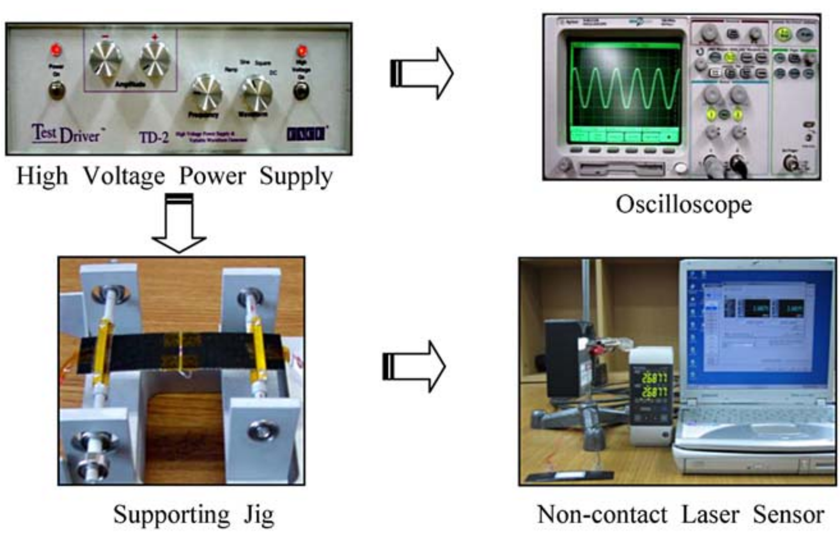
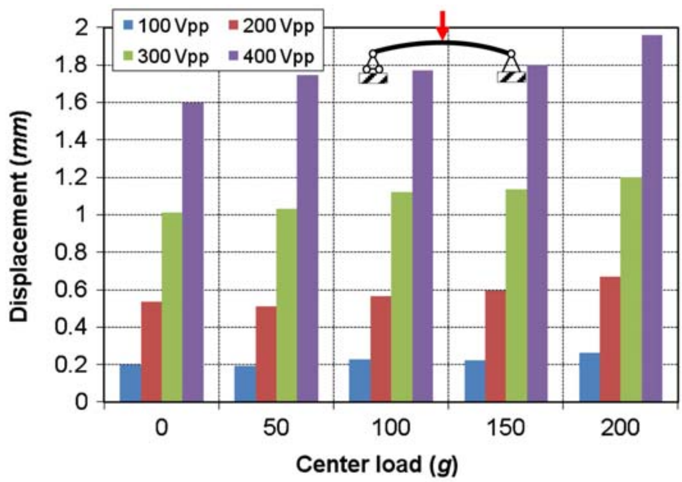


Figure 2. Experimental setup for actuator loading behavior test.

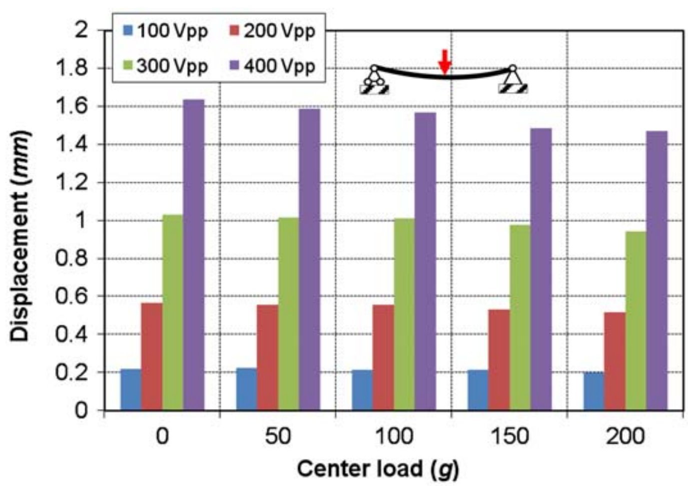
A carbon/epoxy unidirectional prepreg and glass/epoxy fabric prepreg are stacked over the ceramic wafer in accordance with the lay-up design. The stacked layers are then vacuum bagged and cured at an elevated temperature (177 °C) following an autoclave bagging process. The induced stress in each layer is calculated by the ANSYS finite element package. Mismatch in the CTE of constituent materials also leads to the curved shape of the manufactured actuators. The lay-up structure, geometry and residual stress of LIPCA are shown in Figure 1. Material and physical properties of each layer are given in Table 1.

2.2. Apparatus and experimental setup

To characterize the behavior of the unimorph piezoelectric actuators under load, a testing system was constructed as shown in Figure 2. The system consisted of an actuator supporting



(a) Curved-up

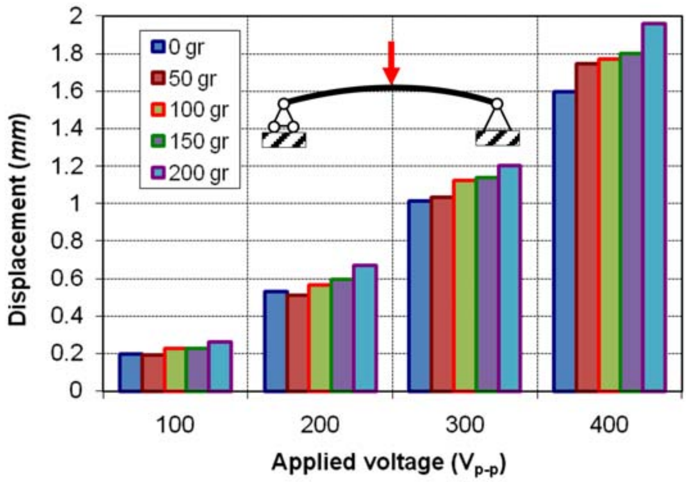


(b) Curved-down

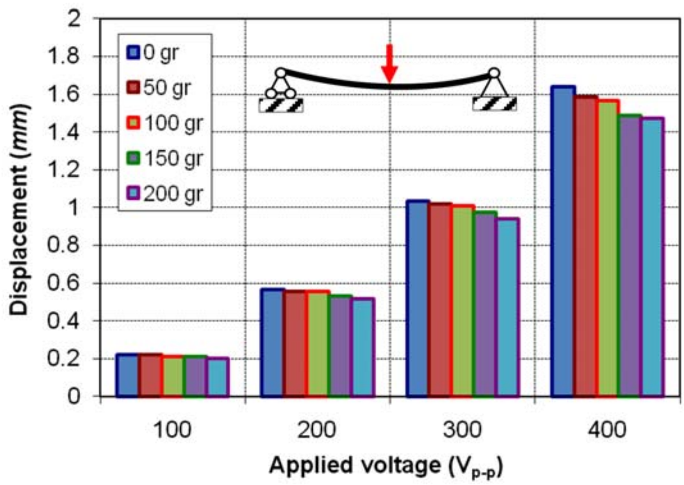
Figure 3. Behavior of simply-supported LIPCA with a center loading.

jig, a high voltage signal function generator (TD-2 Power supply, Face International Corporation), a non-contact laser displacement measuring system (Keyence LK-081, RJ-800), and an HP 54622A oscilloscope.

Two loading configurations of LIPCA were investigated: simply supported with center load and clamped with tip load. In the first case, LIPCA is simply supported at both ends. The weight is suspended by a small rope at the mid-line of the actuator. The second case is the setup with actuator clamped at one end and free-hanging a weight on the other end. The actuator was excited by the power supply with ±50, ±100, ±150, ±200 V at an operating frequency of 1.0 Hz for varying loads. The displacements of the actuator are captured at the mid-point for the first case and at the free end for the second case for each applied electric



(a) Curved-up



(b) Curved-down

Figure 4. Comparison between the actuation displacement of load-free and simply-supported LIPCA with center loading.

field using a non-contact laser displacement measuring system. Each loading case was investigated with 3–5 specimens. The representative results are shown in the next sections.

3. Results and discussion

3.1. Simply-supported configuration with center load

The experimental results of LIPCA for the simply supported configurations with center load are shown in Figure 3. An interesting trend in the loading behavior was found with the curved-up configuration: the actuation displacement of LIPCA becomes larger with increasing load. This means the actuation of LIPCA is enhanced with the curved-up configuration. The trend is reversed for the THUNDER actuator with the same configuration and loading.[8] By considering the location of the neutral axis in THUNDER and LIPCA, the behavior can be interpreted as a result of the stress state in the piezoelectric wafer. The neutral axis is located below the PZT layer for THUNDER, and thus with center loading the ceramic wafer is in more compression, whilst in LIPCA the situation is reversed and the ceramic wafer is in more tension. From the experimental results, we intuitively had a conclusion: by changing the mechanical stress state in the PZT layer by external loading, the actuation strain of the piezoelectric ceramic in the actuator can be increased or decreased.[8] Thus, the stress state in the piezoelectric wafer could encourage or discourage the non-180° domain switching. The reversed trend can be explained as the resultant of the higher compressive stress present in the piezoceramic of THUNDER than in that of LIPCA when the loads are applied. The argument is quite consistent with the results of previous experimental studies on piezoceramic materials in the viewpoint of enhanced extrinsic contributions to piezoelectric response due to stress and field effects on domain switching.[2,7]

The curved-down configuration shows a considerable reduction in the actuated displacement as the loading increases. As LIPCAs with the same residual stress were used, the only difference is the arrangement: curved-down configuration vs. curved-up configuration.

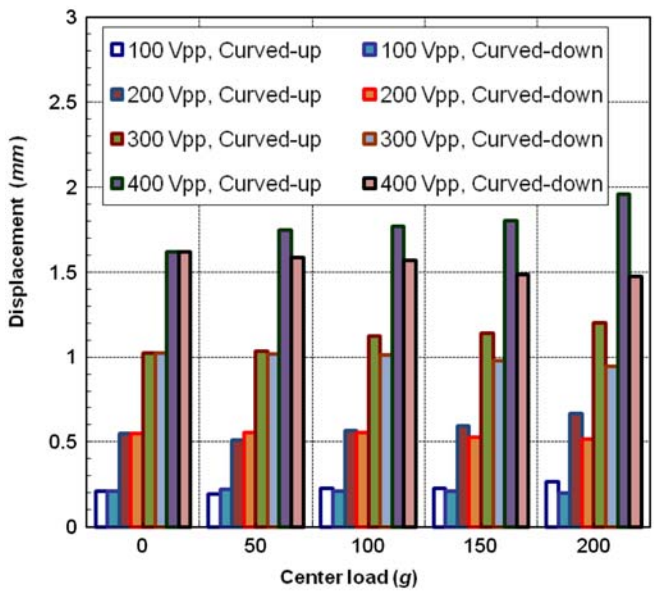
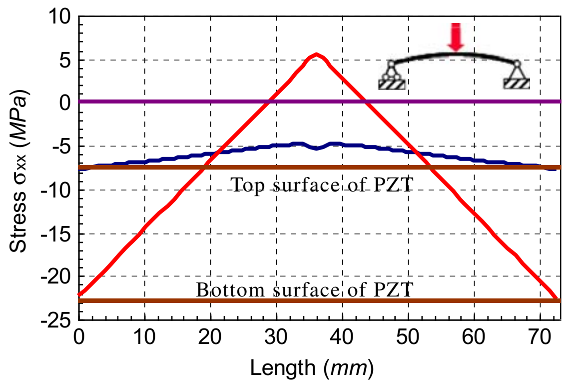


Figure 5. Actuation displacement of simply-supported LIPCA with two center loading arrangements.

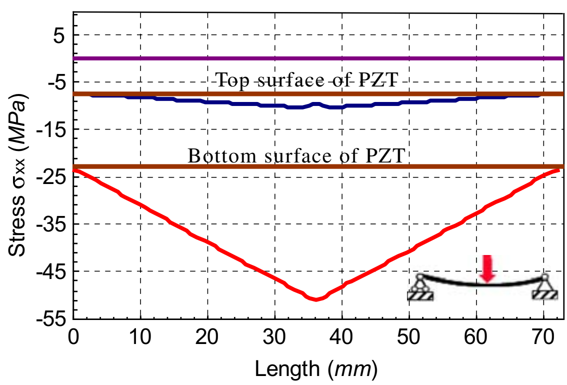
By referring to the location of the neutral axis, we can see that the PZT layer in curved-down configuration is in more compression than curved-up configuration.

The curved-up arrangement gives higher actuation displacements than load-free case; 7.8, 9.4, 11.2, and 21% increased as shown in Figure 4(a), and the curved-down arrangement gives smaller values than load-free ones; 3.8, 6.3, 7.8 and 9.1% decreased as showed in Figure 4(b) when 400$V_{p–p}$ is applied with center loads of 50, 100, 150 and 200 g, respectively. Nonlinearity is observed to be more severe with higher applied electric fields and the change of displacement fluctuates with loading values. Figure 5 shows the comparison of two data sets of curved-up and curved-down configurations with different values applied. The differences in the actuation displacements at 400$V_{p–p}$ are 31.4, 29.7, 27.5 and 33% for center loads of 50, 100, 150 and 200 g, respectively.

By finite element analysis, for the curved-up arrangement, the longitudinal compressive stress in PZT layer becomes smaller as shown in Figure 6. This stress induces mechanical depolarization and a portion of domains are aligned orthogonally to the applied load. The applied electric field in this experiment is large enough to reorient most of the domains parallel to the poling direction again. Thus, the non-180° domain switchings are repeated during the cyclic electric field loading process, which results in a larger strain output. Consequently, the piezoelectric actuation performance is enhanced.



(a) Curved-up



(b) Curved-down

Figure 6. Longitudinal stress in PZT layer with 200 g center load: (a) curved-up; (b) curved-down (red color for points on the bottom surface, blue color for points on the upper surface).

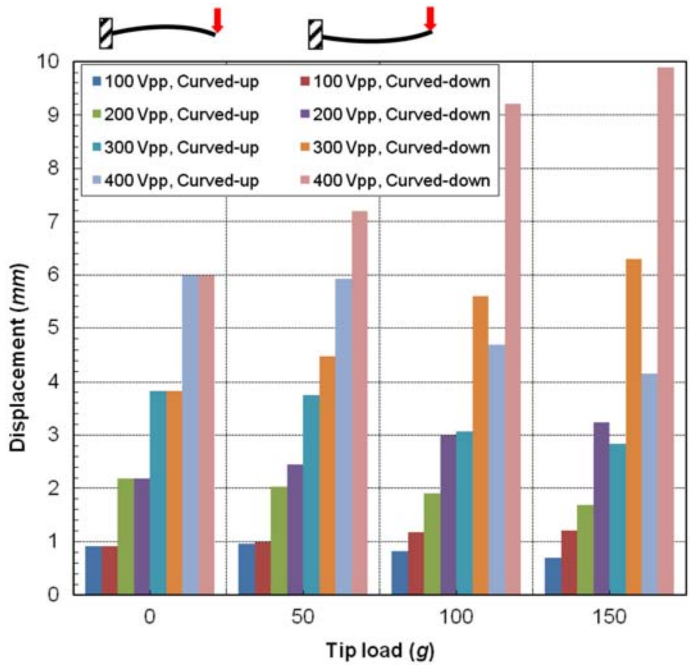


Figure 7. Actuation displacement of clamped LIPCA with two tip loading arrangements.

For the curved-down arrangement, the longitudinal compressive stress in PZT layer increases. At a certain value of stress, the mechanical depolarization predominates as most of the domains are aligned perpendicular to the applied load and are constrained by the high compressive stress. Small applied electric field could be insufficient to overcome this stress, resulting in fewer domains that can be reoriented to contribute to the polarization and the strain.

3.2. *Cantilevered configuration with tip load*

The same behavior of LIPCA can be found in the second loading case as presented in Figure 7. LIPCA is clamped at one end and the vertical load is applied at the other end by hanging weights through a thin string. The actuator is clamped in two ways: curved-up and curved-down as in the first configuration. With the same loading condition these two settings give different stress states within the piezoceramic layer, one is more compressive while the other is more tensile. Once again, with the same argument as stated earlier, by changing the magnitudes of the compressive stress in the piezoceramic could improve the performance of actuators. It is obvious that the 'upside down' setting gives much higher actuation displacement compared to the other. Comparison between two data sets gives differences of 73.4, 92, 121.7, and 138.6% for load of 150 g at 100, 200, 300 and 400$V_{p–p}$, respectively. These differences get bigger and bigger with increasing applied load and electric field as a result of the material nonlinearity in piezoceramic.

4. Concluding remarks

Experimental results show that the actuation performance of the LIPCA can be improved or degraded in the same transverse loading conditions but with different arrangement concerning the longitudinal stress in the piezoceramic layer. When compared to the load-free test, suitable loading arrangements for each of these cases could help improve the actuation performance of the actuator considerably and vice versa. The underlying mechanism behind this phenomenon could be seen as the result of the domain switching potential, dependant on the loading conditions. To obtain the best actuation performance, the actuator should be arranged in a manner such that the stress state within the PZT wafer is in as much tension as possible to alleviate the high compressive prestress due to the manufacturing process. With the above argument, we can predict that at high compressive stress levels, the predominant mechanical depolarization effect makes the material exhibit reduced piezoeffect.

The enhanced/degraded performance also reflects the nonlinear behavior in PZT material. The compression/tension in PZT layer due to the curing process and applied mechanical load could be a crucial factor in improving the actuation of LIPCA. Enhanced actuation of the PZT material is attributed to the non-180° domain switching induced by combined electromechanical loading. Thus, enhanced actuation capabilities associated with larger nonlinearities and hysteresis could be found in LIPCA with the PZT layer driven by an electric field in a longitudinal stress range. The improvement can be up to 33% in simply-supported with center loading, 140% in clamped tip loading and 110% in simply-supported with compression-tension loading case. As the next step, more tests on the sensitivity of the soft PZT wafer CTS 3203 HD under longitudinal compression should be conducted for a fully understanding of LIPCA performance.

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