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Development of high performance stress-biased actuators through the incorporation of mechanical pre-loads

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Abstract

Stress-biased actuators, commonly referred to as thin unimorph driver (THUNDER®) and reduced and internally biased oxide wafer (RAINBOW), were first invented in 1994, and have been the subject of intense investigation since that time. Despite the exceptional performance of these devices, actuators with even greater performance are needed to pursue new applications. In this study, mechanical pre-loads, in the form of elongated springs, were added to standard stress-biased devices to alter domain switching behavior, and thus increase electromechanical response. The incorporation of the mechanical pre-load also results in an increase in stored mechanical and elastic energy within the device, which likely also contributes to the improved response of the modified devices compared to the standard devices. The displacement performance of the new actuators is two times that of the standard devices. The pre-load forces may also be employed to shift displacement resonance peaks to give additional improvements in response. Results are reported for the increased resistance of the modified devices to deformation under applied mass, the effects of pre-load force on actuator displacement response, and the capabilities of the new devices to move large (>3 kg) masses over millimeter distances at low applied power. Indirect evidence is presented that suggests that at least part of the improved response of the new devices is due to greater 90° domain switching.

Keywords: Spring; Stress-biased actuator; Pre-load; Domain

1. Introduction

Reduced and internally biased oxide wafer (RAINBOW) and thin unimorph driver (THUNDER®[1]) actuators form a unique family of stress-biased piezoelectric devices that display displacement and load-bearing responses that are substantially greater than traditional electromechanical devices [1–8]. As a result, the devices are of interest in applications where high strain is required and device space is restricted, or where power requirements must also be minimized. Such applications include micropumps, small robotic systems [9], positioners for space-based interferometers [10], needle positioners for textile machinery, and propulsion systems for swimming vehicles [11,12]. The performance characteristics of RAINBOW actuators have been summarized by Haertling [1], and a comparison of the performance characteristics of the two stress-biased devices has been given by Wise [4]. The reported performance window for RAINBOW devices reaches 1 MPa stress and 500% strain. Typical THUNDER® devices constructed with piezoelectric lead zirconate titanate layers that are 0.2 mm in thickness can demonstrate a range of motion of a few millimeters.[2]

RAINBOW devices are formed by the partial reduction of lead-based ferroelectric compositions, most typically, those based on lead zirconate titanate (PZT), to form a composite piezoelectric–cermet structure. THUNDER® devices areformed by a different process, but again, the devices are composite (piezoelectric–metal) in nature. Both devices are fabricated at elevated temperature, and as a result of the thermal expansion mismatch between the two principal layers, a domed device with a superimposed stress profile

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[1] THUNDER is a registered trademark of Face International Corporation, Norfolk, VA. For further information, the reader may find the following website helpful: http://www.faceco.com.

[2] Face International Corporation reports at their website (http://www.faceco.com) that an “8R” actuator (piezoelectric layer ∼4 cm× ∼1 cm × 0.02 cm) under simply supported conditions without load has a displacement response of 1.98 mm for an operating voltage of 480 V_{pp} (no applied bias). See also [7,8] for further information.

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is formed after cooling. RAINBOW and THUNDER® devices thus resemble unimorph actuators, with the most significant differences being the domed nature of the stress-biased devices and the superimposed stress profile. For devices fabricated with layer ratios of about 2:1 (piezoelectric:metal or cermet), the surface region of the piezoelectric is believed to be under significant tensile stress, while the lower portion of the piezoelectric is under compressive stress [13–15]. Devices fabricated with layers of this thickness ratio have also been shown to generate the highest displacement response [1,4,15].

Because of their enhanced performance and potential utilization in a variety of applications, study of the underlying mechanisms that contribute to the response of stress-biased devices has received significant attention. Suggested contributing factors include simple mechanical effects, as might be expected based on the resemblance of the devices to unimorphs [16,17], enhanced extrinsic contributions to piezoelectric response due to stress and field effects on domain configuration and switching [18–20], and potentially, mass-loading effects [21,22]. While quantifying the relative contributions of these various mechanisms to the observed response of the devices has proven difficult, the importance of altered domain configuration and enhanced domain switching seems indisputable. Prior work by several investigators, primarily using X-ray diffraction, has focused on characterization of domain effects in these devices [13–15,20]. To summarize these studies, samples with different reduced layer thicknesses were fabricated to alter device stress state, and consequently, domain configuration and switching. It was determined that, compared to poled polycrystalline ceramics of the same composition, RAINBOW (and by inference, due to their similar nature, THUNDER®) actuators display a higher a-domain population in the surface region of the devices. Interestingly, despite the presence of comparatively large lateral tensile stresses in this region, under an applied electric field, greater 90° domain switching occurred. That is, more domains that originally had their polarization vectors oriented parallel to the surface of the actuator were switched to a configuration parallel to the applied electric field. Because of the crystalline anisotropy of these materials, which is ~1–2%, 90° switching of even a small fraction of the domain population results in a significant enhancement in strain response [20].

Despite the enhanced performance characteristics of these devices, actuators with still greater response are desired. For example, in space-based interferometer applications, actuators that could produce equivalent motion to those currently under study, but which would operate at reduced power consumption levels, would be very beneficial [10]. Alternatively, actuators that demonstrate further enhancements in displacement response compared to currently available devices may open the door to other new applications and higher performance electromechanical systems. For example, investigators at Vanderbilt University have been working toward the development of small robotic systems (walkers and fliers) based on THUNDER® devices [9]. The performance of these systems could be significantly improved through the incorporation of actuators that possess enhanced electromechanical response.

In this paper, we summarize recent work on modifications to commercially available stress-biased actuators that results in devices with greater electromechanical response [23]. The concept that we have explored is based on alterations to the stress-biased devices that promote further extrinsic (domain switching) contributions to piezoelectric response, and which contribute additional mechanical and elastic energy to these structures, which likely also aid electromechanical response. The devices developed incorporate mechanical pre-loads in the form of either elongated springs or stretched elastomers, which serve to further increase the dome height of the devices, and thus alter the domain configuration and switching response. Results are presented for the displacement and load-bearing capabilities of the spring-modified devices, and indirect evidence is given for an increase in domain switching.

2. Experimental

2.1. Devices and pre-load force

The stress-biased actuators selected for investigation were THUNDER® 8R devices, available commercially from FACE International Corporation (Norfolk, VA). In their standard configuration, the devices are comprised of a piezoelectric PZT 5A layer that is approximately 200 μm thick, 3.81 cm long and 1.27 cm wide. This layer is bonded to a ~150 μm thick stainless steel layer through a curable polyimide. At the same time, a 25 μm thick top aluminum layer is attached to the top of the piezoelectric layer using the same curable adhesive to fabricate a composite electromechanical actuator consisting of five layers that are bonded together at temperatures between 250 and 350 °C. As a result of thermal expansion mismatch during cooling, a domed device with a superimposed stress profile is formed. The device is typically re-poled after fabrication because of the temperatures employed. Details of the fabrication process have been reviewed by Mossi et al. [24]. While device to device properties are reasonably uniform, the manufacturing process may still result in actuators with small variations in dome height, most likely because of slight variations in the thicknesses of the layers. In this study, actuators with initial dome heights between approximately 3.30 and 3.35 mm were selected.

We have evaluated various methods to incorporate mechanical pre-loads to the actuators, including the use of stretched elastomers and elongated springs. In this paper, we review only the results for the spring-modified devices. The springs were mounted in a configuration whereby they exerted a tensioning force on the ends of a rectangular actuator, pulling them closer together. The springs were

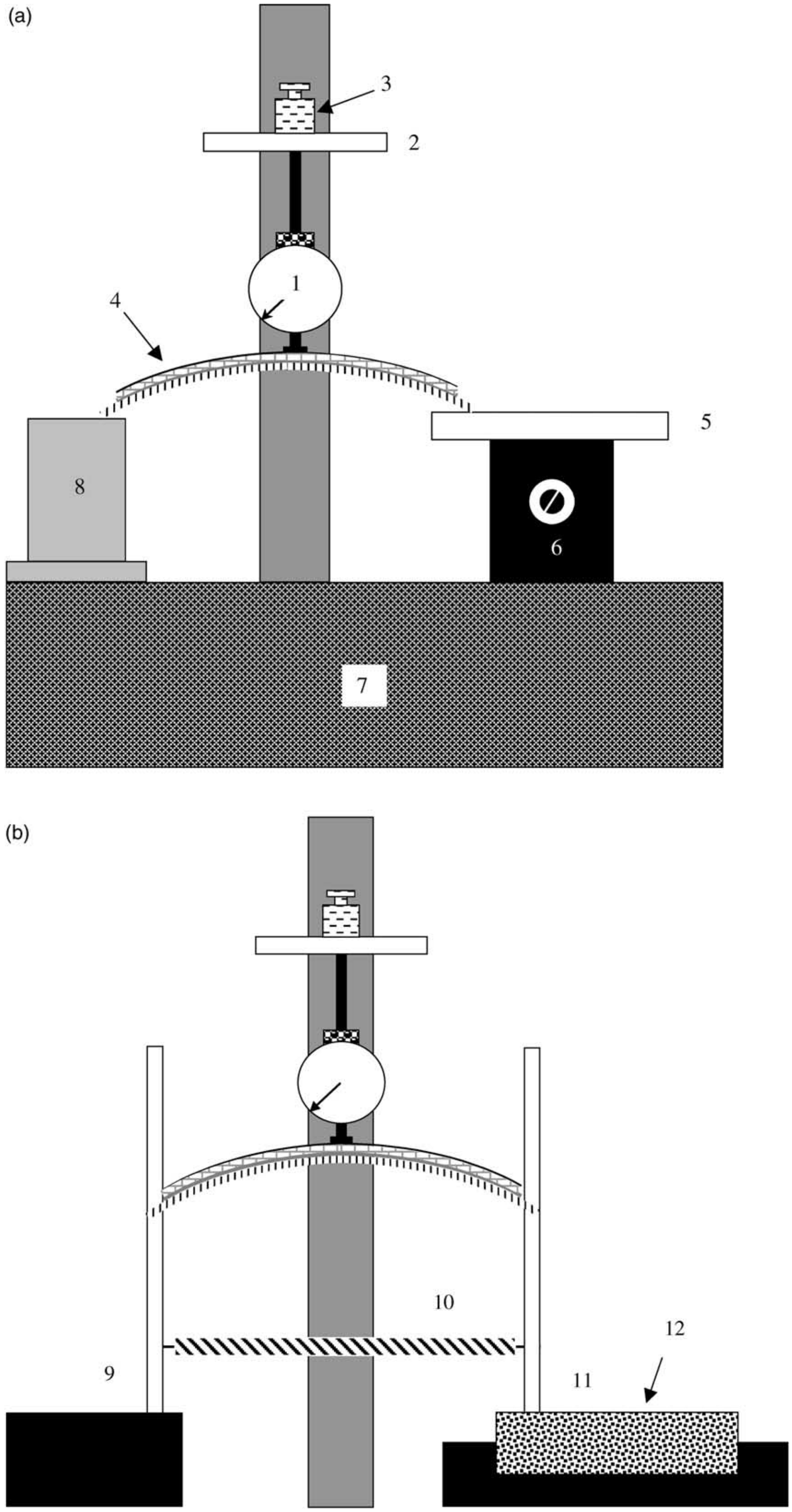

Fig. 1. (a) Schematic of the apparatus used to test the load-bearing characteristics of standard stress-biased actuators. Components are: (1) dial micrometer, (2) plastic plate, (3) known mass (0–350 g), (4) standard THUNDER® 8R actuator, (5) brass plate, (6) adjustable height stage, (7) granite block, and (8) aluminum block. (b) Schematic of the apparatus used to test the load-bearing characteristics of the pre-load-modified stress-biased actuators. Components are: (9) fixed pole, (10) spring, (11) movable pole, and (12) ball-bearing sled; other components as in (a).

purchased from Lee Spring (Brooklyn, NY), and based on calibration experiments, we estimate that the tensioning force is between 1 and 5 N, depending upon the spring. Following the incorporation of the spring, a new equilibrium dome height, greater than that resulting from the fabrication process alone, was obtained. The initial dome heights of the two types of devices were characterized using methods similar to those discussed below for measurement of deformation.

2.2. Characterization of deformation under applied load

Since these actuators are typically used to carry out work, e.g. to move a mass, one parameter we have employed to characterize the performance of the standard and modified devices is deformation (flattening; dome height reduction) under applied mass. Three samples of each type were tested and the results presented are for the average of these measurements. The commercially available THUNDER® 8R actuators were studied using the apparatus shown in Fig. 1a, while the pre-load-modified devices were evaluated with the apparatus shown in Fig. 1b. For the standard actuators, before measurement, the brass and aluminum stages were carefully adjusted to the same height. An actuator was then placed so that one end was supported by each of the stages. The end of the actuator on the brass stage was clamped using a piece of tape and the other end of the device is free, or may be viewed as being slightly clamped by frictional forces. Known masses, of up to 350 g, were added to the plastic plate and the deformation (decrease in dome height) was then measured using the dial micrometer, until a maximum deflection of ~2 mm was achieved. The masses were then removed from the sample and the final dome height was measured.

The resistance to deformation of the spring-modified devices was characterized using the apparatus of Fig. 1b. Here, the actuator is attached between two poles, one of which is fixed and the other which is attached to a frictionless-bearing sled. While the apparatus looks different from that of Fig. 1a, one end of the actuator is rigidly clamped, while the other is free to move. The clamping conditions are thus nearly identical to the apparatus of Fig. 1a.[3] While the spring may be mounted directly onto the actuator, here the spring is simply attached between the two poles. Dome height variations for the spring-modified devices under various mass loads were studied until a total deformation of ~2 mm was obtained prior to the removal of the masses. For the spring-biased actuators, upon removal of the mass, the initial dome height was restored.

2.3. Characterization of displacement response

The displacement response of stress-biased actuators is highly dependent upon the mounting conditions employed, and for certain mounting configurations, adding mass to the devices has been reported to increase their displacement response [22,25]. In the present study, we utilize essentially the same experimental apparatus as that shown in Fig. 1b, where one end of the actuator is rigidly clamped and the other is attached to the sled. Both free and loaded (100 g mass applied to the center of the actuator) displacement response was determined. The dial micrometer of Fig. 1b was replaced by a PhilTec Inc. (Annapolis, MD) RC63-BORX fiber optic probe whose output was sent to an oscilloscope (Tetronix Model T922R).

The drive signal applied to the actuators was obtained by using the sine wave output of an Agilent Technologies 33120A function generation amplified by a Trek 50/750 power supply operated at a gain of 100:1. The magnitude of the drive signal was 200 V_{pp} (peak-to-peak voltage) without bias. The response as a function of frequency was studied over the range from 1 to 50 Hz and electrical contact to the actuator was achieved through the use of alligator clips.

3. Results and discussion

3.1. Initial dome height and deformation under applied load

The introduction of the mechanical pre-loads results in an increase in the dome height of standard THUNDER® 8R actuators, and depending upon the magnitude of the pre-load force, can result in permanent (i.e. plastic) deformation. Using the techniques described above, the initial dome heights of the standard and spring-modified (Lee Spring #LE031D-5) pre-loaded devices were characterized; they were ~3.33 and ~4.22 mm, respectively. The increase in the initial dome height for the modified device is thus about 27%. Based on the reported spring constant for this spring, and a measured elongation of approximately 14.15 mm, we calculate that the pre-load force is ~2.7 N. Dome heights achieved for springs with different force constants and elongations are reported in [26].

The increased dome height of the spring-modified device is the result of the new balance of forces that exist within the system; i.e. the added tensioning force that is exerted by the elongated spring is equal, but opposite, to the resisting elastic force of the actuator. Thus, in the mounting configuration of Fig. 1b, or similar configurations in which the spring is mounted directly on the actuator to provide a tensioning force, the range of pre-load forces achievable may be limited by the mechanical properties of the actuator. Other spring pre-load strategies that allow for a greater decoupling of the mechanical properties of the actuator from those of the

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[3] Because of the mass of the sled (estimated at 90 g), the apparatus of Fig. 1b also results in a slight clamping force at the "free" end of the actuator. Under applied voltage, i.e. for the displacement response studies, the sled adds a small inertial mass to the system.

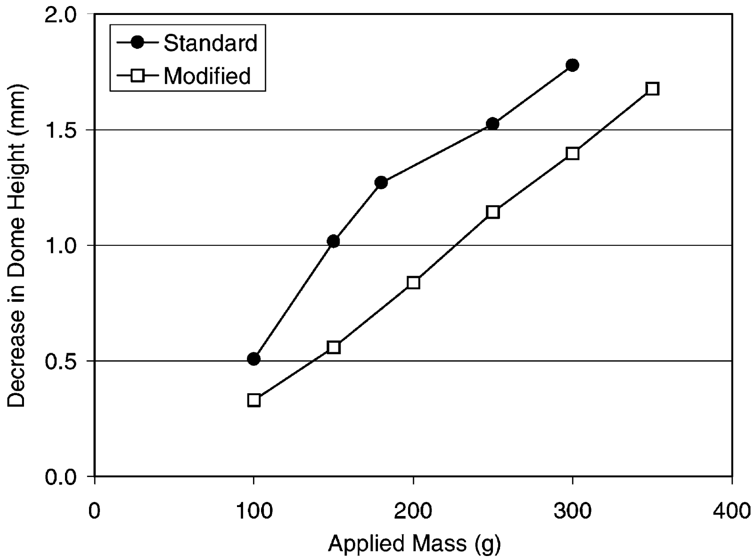

Fig. 2. Decrease in dome height of the actuators under applied mass. For the modified device, the pre-load force was 2.7 N.

spring, and which result in a greater range of achievable pre-loads, have also been investigated [23,26].

The load-bearing capabilities of the standard and modified devices are illustrated in Fig. 2. As anticipated, the spring-modified actuators display less deformation (flattening) under applied load. For the standard actuator, a 100 g mass load results in a 15% reduction in dome height while a 300 g mass causes a 54% reduction. In contrast, these same mass loads cause, respectively, 7 and 33% dome height reductions for the spring-modified device. For equivalent applied masses, in general, the spring-modified actuators deform 30–40% less than the standard actuators.

To understand the importance of the mechanical pre-load generated by the spring on the resistance of the actuator to deformation, it is informative to consider the magnitudes of the forces involved. For applied masses that cause a 1.0 mm deformation, a load of 230 g must be applied to the spring-modified actuator. Because of the domed nature of the device, at the same time the dome height is decreased, the device undergoes a lateral elongation. From a simple Hook's law perspective ($F = k\,\Delta x$, where F is the generated force, k the spring constant and Δx is the extension), because of the lateral extension that occurs under applied load, the force generated by the spring should increase with applied mass. This should contribute to an increased resistance to deformation. For the spring-modified actuator, the 230 g load causes a lateral elongation of approximately 0.65 mm, which when added to the Δx in Hook's law, results in an additional tensioning force ($490\ \mathrm{N/m} \times 0.65 \times 10^{-3}\ \mathrm{m}$) of 0.3 N. This seems reasonable considering that we estimate the tensioning force generated by the spring in the static, unloaded actuator to be 2.7 N. Because the applied mass load is 2.25 N, and the change in the spring-generated force is only about 10% of this value, this suggests that the additional load-bearing capacity of the spring-modified devices arises from the more domed nature of these devices. This conclusion is in agreement with a basic statics analysis of the effect of the radius of an arch on load-bearing capability: structures with smaller radius arches demonstrate greater load-bearing characteristics [27].

The development of a more deformation-resistant device has additional advantages with regard to electromechanical performance. While RAINBOW and THUNDER® devices are fabricated to develop an internal stress profile that contributes to enhanced domain switching, the addition of mass loads results in a deformation that both reduces the dome height, and decreases the magnitude of the internal stress. This causes an alteration in domain population (fewer a-domains) and a decrease in 90° domain switching [20]. As a result, the deformed device demonstrates a diminished extrinsic piezoelectric response, and a reduced performance enhancement compared to standard unimorph actuators. Hence, the inclusion of the pre-load force not only results in devices that are more resistant to deformation, but by improving shape retention under applied mass, the modified devices are better able to maintain the desirable performance enhancements associated with standard stress-biased devices operated under unloaded conditions.

3.2. Displacement performance

The free displacement response of the standard and modified devices is shown in Fig. 3. The standard actuator demonstrates a displacement response that is essentially frequency-independent and whose magnitude is ~0.36 mm. This value is lower than the quoted response of these devices (see Footnote 2), although the reported performance characteristics are based on the maximum positive and negative drive voltages that may be applied.

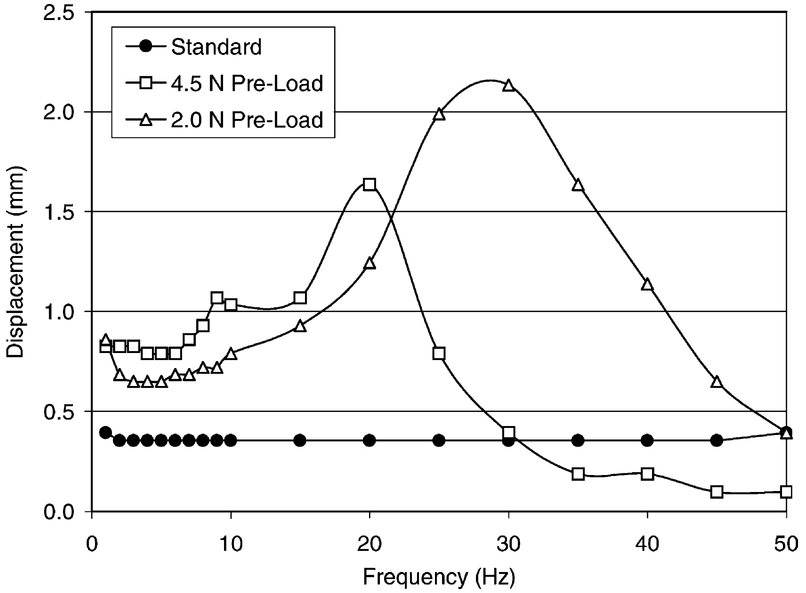

Fig. 3. Free displacement response as a function of drive frequency for a drive voltage of 200 V_{pp} with no applied bias. A standard actuator and actuators pre-loaded with 2.0 and 4.5 N of force are shown.

The spring-modified actuators were quite different in their response characteristics and displayed a resonance frequency at which the displacement was maximized. The resonance frequency, and the maximum displacement at resonance, were dependent on the magnitude of the pre-load force [26]. For the 2.0 N pre-load, the displacement response at resonance was approximately six times that of the standard device. At other frequencies, the improvement in performance is more modest, but is still significant. We believe that the increased displacement response is due to three effects: (1) enhanced domain switching under the presence of the pre-load; (2) the added mechanical force that is present in the system in the form of the extended spring; and (3) an increase in the amount of stored elastic energy due to the increased dome height. The reasons for the observation of the displacement resonance are still under investigation, although it should be pointed out that the commercial (standard) devices also demonstrate a displacement resonance; it simply occurs outside of the range of investigated drive frequencies. The decrease in the response of the 4.5 N pre-load device compared to the standard actuator is also not fully understood at this time, but may be associated with the natural resonance characteristics of the spring-based system.

The displacement response of the actuators under applied mass is illustrated in Fig. 4. As for the free displacement

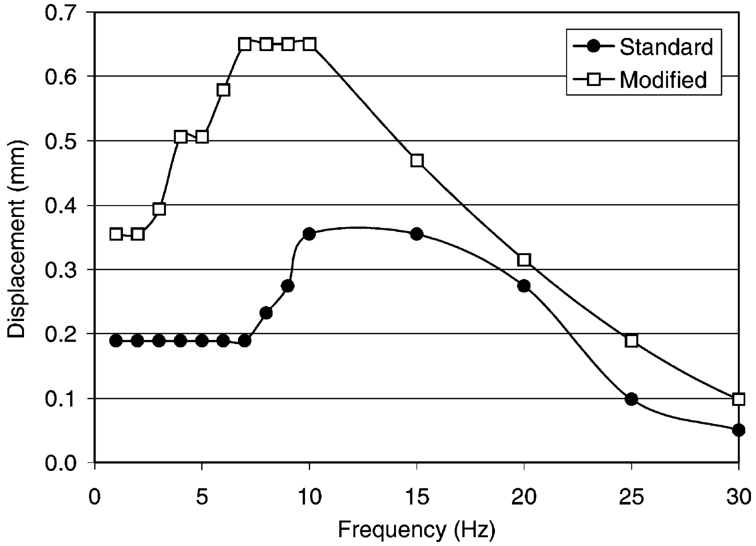

Fig. 4. Actuator displacement response as a function of drive frequency under an applied load of 100 g added to the apex of the actuator. Drive voltage: 200 V_{pp} with no bias; the pre-load force was 3.4 N.

response, the incorporation of the spring pre-load results in improved electromechanical response. Depending upon frequency, the enhancement is a large as a factor of two and it is most significant at lower frequencies. The altered actuator shape, which from a mechanics perspective supports greater loads [27], together with increased domain switching, the added mechanical energy of the stretched spring, and the increased elastic energy of the more highly deformed actuator probably contribute to the greater displacement performance of the modified device under load. While a detailed assessment of the stored elastic energy is beyond the scope of the paper, based on simple force balance considerations, we would expect the elastic force to be of the same magnitude as the pre-load force, which is of the order of 2–4.5 N. We therefore expect the spring to play a significant role in the response of the modified devices, because in addition to altering the domain configuration and switching behavior of the piezoelectric, it represents an additional energy (or force) that is added to the actuator system that may contribute to electromechanical response when the actuator is asked to perform work.

It is also evident in Fig. 4 that the displacement resonance shifts to lower frequency upon the inclusion of the spring pre-load. While this might be expected due to the added mass of the spring within the system, this behavior could also be an indication of greater 90° domain switching. Piezoelectric materials that undergo more extensive domain switching are more compliant because domain switching is a ferroelastic, as well as a ferroelectric, phenomenon. The more compliant nature of the ceramic for the spring-modified devices would be expected to result in a shift of the resonance peak to lower frequency, as observed. In support of this argument, Wang et al. have reported that with increasing electric fields, which would cause increased domain switching, a decrease in the resonance frequency of RAINBOW devices occurs [28]. The authors attributed this behavior to ferroelastic softening.

In reporting the displacement response of actuators such as THUNDER® and RAINBOW devices, most investigations report only the overall displacement, i.e. the sum of motion in the doming and flattening directions. These responses are typically asymmetric, even for standard stress-biased actuators. Thus, by reporting only total displacement, some information regarding the contributions of the various mechanisms to the performance of the actuator is lost. Fig. 5 shows the bi-directional response of the standard and spring-modified actuators. The standard actuator shows a greater displacement response in the flattening direction by approximately a factor of two to four times, depending on frequency; a similar trend is observed for the spring-modified device. We believe that these results provide yet another confirmation of the importance of 90° domain switching to the performance of stress-biased actuators.

To analyze the response of the spring-modified devices shown in Fig. 5, we first need to consider the electromechanical response of standard stress-biased actuators. When the performance of these actuators is discussed, more attention is always focused on the surface region of the actuator. This is because the tensile stresses in this region induce greater 90° domain switching, which results in higher effective piezoelectric coefficients for this region compared to the lower region of the piezoelectric, due to the greater extrinsic response. The lower region, which is under compressive stress, is believed to possess a domain configuration that is even more highly oriented (poled) than standard poled polycrystalline bodies [14]. As such, the electromechanical

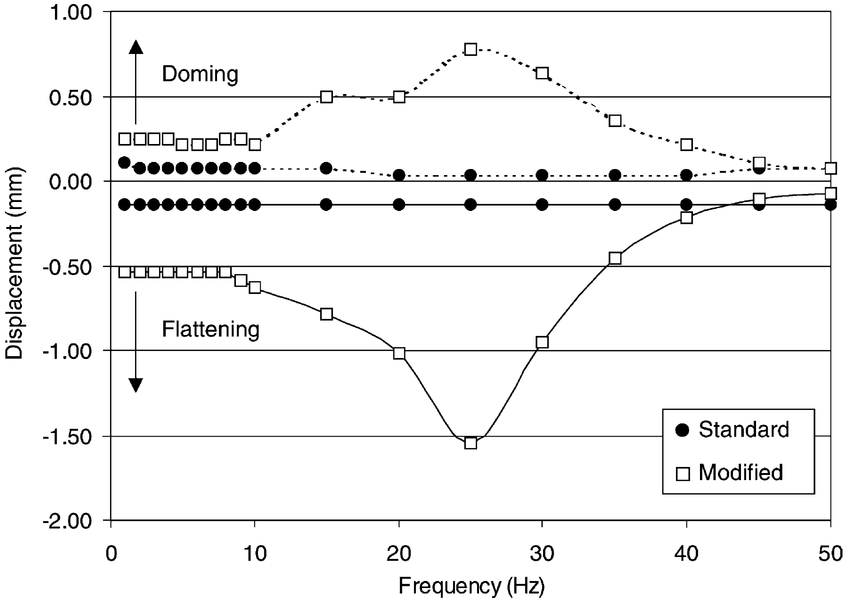

Fig. 5. Bi-directional displacement response of a standard THUNDER® 8R actuator and the spring pre-load-modified actuator. The pre-load force was 2.7 N and the drive voltage was 200 V_{pp} with no bias. Zero on the displacement response axis represents the position of the dome height under no applied voltage.

response of this region has a suppressed extrinsic contribution and demonstrates lower effective piezoelectric coefficients compared with typical bulk materials. Although both intrinsic and extrinsic response mechanisms contribute to the observed deformations under applied electric field, because of these stress and domain configuration considerations, the upper region of the piezoelectric layer should dominate the electromechanical response of the device.

It is also informative to consider the effects of bias on the direction and magnitude of the deformation response. When the applied electric field is in the same direction as the original poling direction, the actuator deforms by flattening. Both the intrinsic d_{31} response and 90° domain switching, i.e. the extrinsic response, result in flattening of the device. When the applied electric field is opposite to the poling direction, the device domes. Here, the intrinsic response mechanism causes a lateral expansion, which results in an increase in the dome height of the device. Any 90° domain switching that occurs (in the surface region) would be expected to result in flattening of the device, and would thus oppose the intrinsic response. Because the intrinsic and extrinsic mechanisms lead to deformations that tend to oppose, rather than compliment each, we would expect the doming response to be of lower magnitude than the flattening response. This trend may be observed in Fig. 5.

With this understanding of the asymmetric displacement response of standard stress-biased devices, we can now give attention to the observed asymmetries in the response of the spring-modified actuator. If the fraction of domains switching is increased by the inclusion of the spring pre-load, we would expect that the flattening response would be increased to a greater extent than the doming response. This effect can be clearly seen in the figure at low drive frequencies, prior to the onset of resonance; the flattening displacement is increased by a factor of approximately five times, while the doming response is increased by only a factor of approximately three times. We believe that this observation provides indirect evidence that domain switching is, in fact, increased in the spring-modified devices. However, without in situ studies of domain configuration and switching during application of the electric field to the modified devices, at this time, we can only speculate that enhanced domain switching is taking place.

Another reason why this conclusion is speculative is that other factors may contribute to the increased flattening response of the spring-modified actuator. One potential factor is the greater stored elastic energy that exists within the structure due to its increased dome height. Because the actuator is deformed to a greater extent than after fabrication, it possesses greater stored elastic energy. This energy should be partially released when the actuator is electrically driven into a flatter configuration. Therefore, in addition to enhanced domain switching, the reduction in stored elastic energy may also contribute to the enhancement in the flattening response of the modified devices. A thorough assessment of the magnitude of this effect remains to be carried out, but unfortunately, the ferroelastic nature of the piezoelectric complicates this analysis.

With regard to the increase in doming response that is observed for the modified actuators, we can draw the following conclusions. The intrinsic response should be relatively unaffected by the addition of the spring, and the greater domain switching anticipated might actually reduce doming, since it opposes the intrinsic piezoelectrically generated lateral elongation. It seems reasonable, therefore, to suggest that the observed improvement in doming response is due primarily to the tensioning force of the spring, which is partially relaxed as the device attains a more highly domed shape.

3.3. Actuator design strategies for the motion of large masses

The use of mechanical pre-loads may also lead to the design of low power consumption actuators capable of moving large (up to 5 kg) masses. These masses may be moved vertically or horizontally, depending upon actuator design and mounting configuration. For example, to move large masses vertically (i.e. in the doming/flattening direction), we suggest that it may be possible to use higher preload forces for applications in which the actuator is asked to move a larger mass. Stated otherwise, it should be possible to balance the mass that is to be placed on the actuator against the pre-load force. The basic strategy would be to allow the spring to do the work required to support the load, freeing the actuator to perform its work in moving the load. We have carried out preliminary experiments to investigate this concept and it appears feasible: irrespective of mass load, a similar range of motion was achieved for actuators asked to move a broad range of masses, provided that the magnitude of the pre-load force and force resulting from the applied mass were appropriately balanced. A word of caution here is also appropriate. The procedures employed to add the pre-load and the mass to the actuator must be carefully followed to avoid unrecoverable (and undesired) plastic deformation of the actuator.

While stress-biased actuators are most often used for positioning applications, or motion, in a direction perpendicular to the surface of the device, the actuators demonstrate a concomitant lateral displacement response that is typically about 70% of the vertical displacement. Therefore, they may also be used to move mass in a horizontal direction. To operate in this configuration, the apparatus of Fig. 1b could be modified to remove the mass that is shown, and a mass could be added to the frictionless-bearing sled. Fig. 6 shows that, at specific drive frequencies, large masses may be displaced laterally. Although results are shown only for two different masses, we have studied the effects of mass loads as high as 5 kg and observe the same general trend: higher mass shifts the displacement resonance to lower frequency. Thus, if the actuator is operated under drive conditions that result in a displacement resonance, large

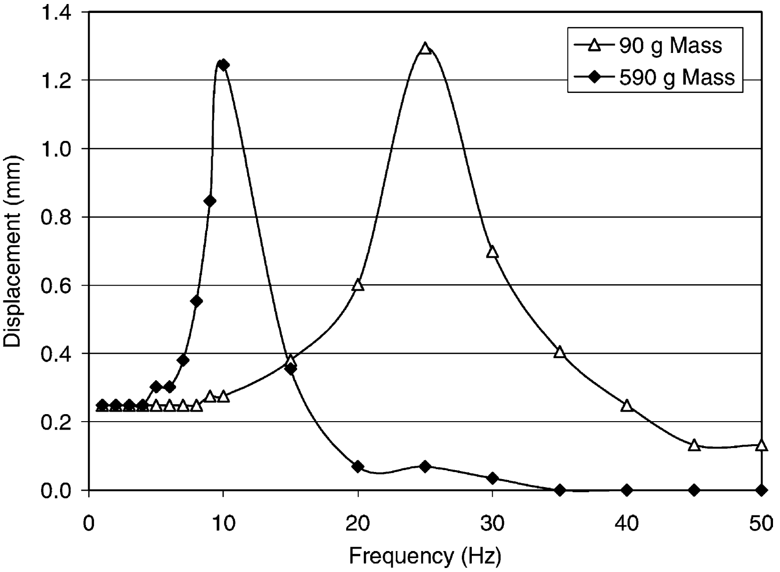

Fig. 6. Lateral displacement response of a 2.9 N pre-load-modified actuator under two load conditions. The 90 g load represents the mass of the empty sled; the 590 g load represents the response of the device when a 0.5 kg mass is placed on the sled.

loads may be moved over reasonable distances using comparatively low electrical powers. However, to fully understand the performance of these devices, the development of a more complete perspective of the various forces and effects at work is required. These include inertial effects of applied mass loads, effects of the pre-load force on domain switching, changes in stored elastic energy that result from the inclusion of the spring into the device, and any variations in electrical-to-mechanical conversion efficiency (coupling coefficient) that occur for different pre-loads or inertial forces.

4. Conclusions

The effects of a spring pre-load on the displacement response and load-bearing capacity of stress-biased actuators have been studied. The initial premise that led to these investigations was that it should be possible to promote further domain switching in stress-biased devices by further altering the dome height and stress levels within these devices. Indirect evidence suggests that this contribution to enhanced response, in fact, occurs. However, a more thorough consideration of the effects of the pre-load force suggest that the mechanical energy added to the structure, as well as an increase in the stored elastic energy of the actuator likely also contribute to the observed increase in displacement response. While further investigation of these mechanisms is required, we can still conclude that mechanical pre-loads may be used advantageously to significantly improve the performance of THUNDER® devices, which already possess stress and strain characteristics superior to direct extensional, flextensional, and unimorph devices. It seems likely that an analogous approach may be used to improve the performance of RAINBOW or standard unimorph devices. Finally, by further developing alternate incorporation strategies that more effectively decouple the elastic properties of the actuator from the spring [23], we anticipate that improvements in displacement response, beyond those that have already been achieved, will be possible.

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