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Characterization and Modeling of Local Electromechanical Response in Stress-Biased Piezoelectric Actuators

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Abstract—**Numerous investigators have explored the factors that contribute to the high electromechanical performance of stress-biased actuators with particular attention being given to the importance of the extrinsic (domain wall translation) response mechanism. Based on the variation in lateral stress through the thickness of the piezoelectric layer within these devices, it has been suggested that the piezoelectric coefficient varies as a function of position within the layer, though no direct evidence has been previously presented. In this study, the results of Moiré interferometry investigations of local strains within these devices are reviewed. The technique permits effective depth-profiling of local deformations at reasonably high (0.25 μm) resolution. A least squares regression analysis approach was used in conjunction with classical laminate theory and free edge effects to fit this experimental data to depth-dependent piezoelectric response. As expected, higher d-coefficients were predicted for the upper free surface of the device compared to the interface with the stainless steel substrate. The predicted values were in general agreement with expectation and are further considered from the perspective of recent reports in the literature regarding multi-axial loading effects on the electromechanical properties of lead zirconate titanate-based piezoelectric ceramics.**

Keywords-actuator; piezoelectric; Moiré interferrometry

I. INTRODUCTION

Stress-biased actuators, such as Rainbow (Reduced And INternally Biased Oxide Wafer and Thunder™ (THin UNimorph Driver and sEnsoR) have been developed to meet the requirements of larger displacements and higher force generation than are achievable with conventional piezoelectric ceramics or other flextensional devices of similar dimension. The devices are prepared by cooling from elevated (300 – 1000°C) temperature during processing creating a unique domed configuration due to thermal expansion mismatch between the principal material layers. In association with the domed configuration that is formed during the fabrication process, stress-biased actuators have a complicated internal stress distribution through the thickness of the device. The non-uniformity of the internal stress in these devices leads to the assumption of a non-uniform piezoelectric d_{31} coefficient through the thickness of the PZT due to differences in domain wall translation response [1]. To date, there has been no experimental data that confirms the suggested variation. Therefore, in this study, Moiré interferometry was employed to measure the local deformation of Thunder™ actuators under various applied electric fields. Samples with different stress profiles (across the piezoelectric layer) were obtained by using actuators with various piezoelectric/substrate thickness ratios. The acquired data provided the fundamental information needed to determine the piezoelectric d_{31} coefficients as a function of position below the surface by means of mathematical fitting (least squares method) in which the deformation response was modeled by classical laminate theory [2]. The influence of edge effects on local deformation was also accounted for in the analysis [2].

II. EXPERIMENTAL PROCEDURE

A. *Moiré Interferometry*

Moiré interferometry was carried out on the polished cross-sections of Thunder™ devices with a specimen grating frequency of 1200 lines/mm. Utilizing a four-beam optical system, a reference, or virtual grating frequency of 2400 lines/mm was created with an argon ion laser (λ=514 nm). When an electric field was applied to the actuator in the thickness direction, the device deformed together with the attached grating. Moiré fringe patterns occurred as a result of the optical interaction of the specimen grating and the reference grating. The patterns that correlated to lateral strain (direction parallel to the actuator surface) were collected at 0, 5, 10 and 15 kV/cm by a video camera and transferred to a connected personal computer. Commercial image processing software

(Scion Image®) was used to process the fringe patterns for strain analysis. By measuring the distance between neighboring fringes in the immediate neighborhood of the point of interest, local strain can be extracted using standard formulas [2].

B. Classical Laminate Theory and Edge Effect Modeling

Device behavior during fabrication and electromechanical response of the actuators under applied electric field were predicted through classical laminate theory (CLT) using a computer code that was developed to run on Maple™. Material constants, including Young's moduli, Poisson's ratio and coefficients of thermal expansion, along with the thickness of lamina, were used to model dome height, stress profile and local deformation throughout the thickness of the device under various applied electric fields. Linear material response was assumed as a first step toward developing an effective model that could be used to aid understanding of device behavior [2]. Devices with a variety of configurations were modeled for comparison with experimental data obtained on analogous devices. The reader is referred to general mechanics texts or Reference 2 for further information on the specific approaches utilized. Initial simulations were carried out using a standard CLT approach and reported values of d_{31}. To improve the agreement between the simulation and experimental results of local deformation, subsequent modeling accounted for shear stress effects on deformation (i.e., boundary layer or edge effects). Still further improvement in the agreement between the model and experimental results was achieved by allowing the d_{31} coefficient to be depth-dependent, as discussed below.

C. Linear Least Squares method

A linear least squares method was employed to model the experimentally determined local deformations by assuming the d_{31} coefficient varied as an n^{th} order polynomial in the distance, z, from the neutral plane. The sum of the squared deviations between the predicted and experimentally determined strains was minimized with respect to the corresponding n+1 polynomial coefficients via the least squares approach. The n+1 unknown polynomial coefficients were then obtained by solving the resulting n+1 linear equations. The linear least squares analysis was repeated assuming d_{31} to vary as a 1^{st} through 9^{th} order polynomial in z. Since only 10 data points through the thickness of the PZT layer were obtained, the maximum possible polynomial order was nine [2].

III. RESULTS AND DISCUSSION

A. Fringe Patterns

The fringe patterns for the 6 mil and 20 mil-substrate devices under positive field (device flattening) are shown in Fig. 1, (a) and (b), respectively. As electric field magnitude increased, the space between fringes (∂x) decreased and the fringes rotated clockwise, which corresponds to flattening of the devices. The 6 mil-substrate devices exhibited a greater change in the fringe patterns than the 20 mil-substrate devices, due to a greater deformation response. The fringe patterns for

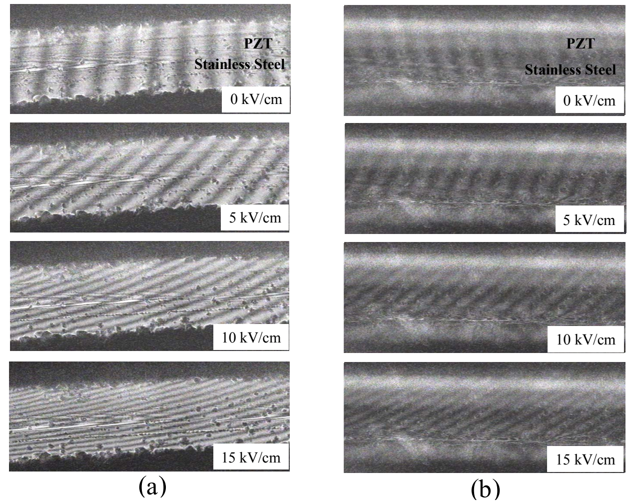

Figure 1. Fringe patterns of Thunder™ device under various applied electric fields. (a) 6 mil-substrate (b) 20 mil-substrate

both devices exhibited non-linear, gradual changes of the fringe slope across the device thickness, which indicated non-linear differences in response from the top to the bottom of the device. Greater non-linearity in strain was observed in the surface region of the PZT layer, while, as would be expected, deformation of the stainless steel substrate layer across the thickness of the layer was linear.

B. Local Deformations under Applied Electric Fields

Local strains across the thickness of Thunder™ devices were evaluated at different applied electric fields and are shown in Fig. 2 and 3 for the 6 mil and 20 mil substrate devices, respectively. The negative (compressive) and positive (tensile) strains indicate contraction and expansion, respectively, across the thickness of the device. Close to the surface of the PZT, compressive strain was measured due to dimensional contraction in the plane of the surface by reorientation of a- to c-domains (i.e., reorientation of domains with polarization vectors parallel to the surface to an orientation perpendicular to the surface) and through intrinsic effects. With increasing applied fields, higher strains were

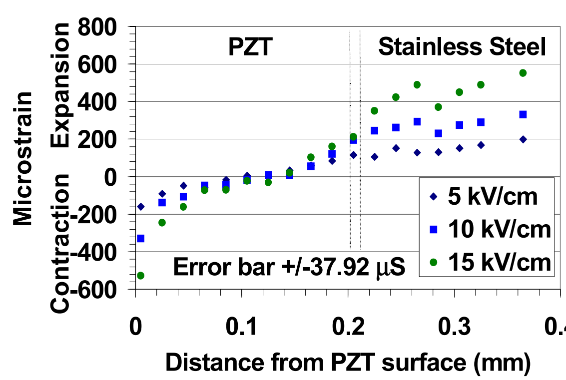

Figure 2. Local deformation of the 6 mil-substrate Thunder™ actuator under positive fields.

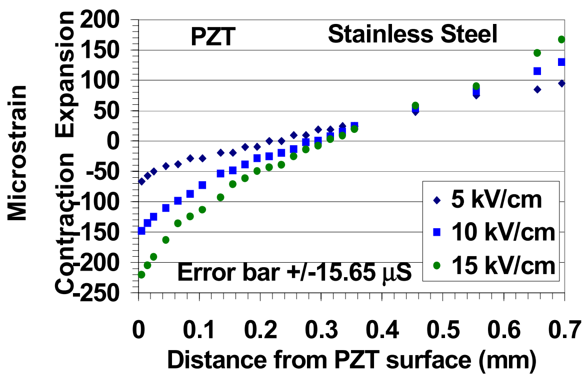

Figure 3. Local deformation response of the 20 mil-substrate Thunder™ actuator under positive fields.

observed due to more domain reorientation and a higher intrinsic response contribution. Compressive strain close to the PZT surface of the 6 mil-substrate device increased from approximately 160 µS at 5 kV/cm to 330 µS at 10 kV/cm and 530 µS at 15 kV/cm. For the 20 mil-substrate device, compressive strain increased from approximately 70 µS at 5 kV/cm to 145 µS at 10 kV/cm and 285 µS at 15 kV/cm.

The magnitude of compressive strain decreased non-linearly from the surface to the lower part of the PZT layer, suggesting greater domain contributions to response at the surface region compared to the lower region. This result is in agreement with the previous work [3] that showed enhancement of extrinsic effects by tensile stress, while the effect was reduced by compressive stress. The degree of non-linearity of the curves increased with electric field as would be expected for greater extrinsic contributions to response [4,5]. The strain became tensile in the stainless steel layer due to the extensional response associated with flattening of the devices under positive electric fields. The distribution of strain in the substrate layer was relatively linear compared to the PZT layer, since only mechanical, and not ferroelectric or ferroelastic, effects were present. With lower compressive stress at the surface in the 6-mil substrate device (~ 41 MPa) compared to the 20-mil substrate (~ 200 MPa at the surface), and a higher stress gradient, the 6-mil substrate device would be expected to possess more a-domains and to exhibit greater a- to c- domain reorientation. Thus, a greater degree of non-linearity in the response, particularly near the free surface would be anticipated, in agreement with observed results. The extent of non-linearity increased with applied electric field, most likely due to increased extrinsic contributions to response.

One unique aspect of the response of the 6 mil-substrate devices was the tensile strain that developed in the lower region of the PZT layer under applied field. This expansion behavior in the lower region would not be predicted from the piezoelectric effect. However, the observed behavior could be explained by free-edge effects, which are expected since the experiment is carried out on the free cross-sectional surface of the laminate devices. In a deformed laminate cross-section, the uniform distribution of stresses has been reported to change near the laminate boundary as the interface between layers is approached [4,6,7]. Thus, the strain behavior observed in the lower region of the PZT layer, which is close to the interface, is affected by free-edge conditions. The effect is less obvious in the 20-mil substrate device due to the smaller deformation. Another possible explanation for the expansion in the lower region of the PZT layer is that the mechanical expansion of the stainless steel substrate associated with flattening of the devices overrides the contraction due to intrinsic and extrinsic piezoelectricity. Since the intrinsic effect is usually a minor contribution and less domain wall motion occurred in the lower region of these devices, due to a lower a-domain population and high compressive stress, contraction in this region could be overshadowed by mechanical expansion of the substrate.

C. *Determination of d_{31} Coefficient*

The experimental strain data were fit by a linear least squares method and % full-scale errors corresponding to the linear least squares fits of 1st to 9th order were evaluated. A significant decrease in full scale error between the 2nd and 3rd order polynomial models may be seen in Fig. 4. From the general shape of fitting curves and the significant decrease in error from the 2nd to the 3rd order models, the 3rd order model was determined to be optimum for fitting the experimental data. Thus, based on the local strain data, the local d_{31} coefficient as a function of position (z) along the thickness of stress-biased devices can be expressed with polynomial equation of 3rd order ($d_{31}(z)=a+bz+cz^2+dz^3$).

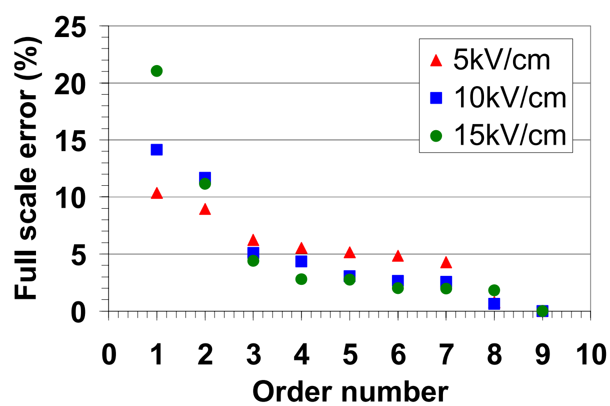

Figure 4. Full scale error as a function of polynomial order number.

Fig. 5 shows the variation of d_{31} coefficient for the 6 mil-substrate device determined by the 3rd order polynomial fit. The values seem reasonable considering the PZT material used and the stress profile of the device. The surface d_{31} coefficients were calculated to be –486 pm/V, -629 pm/V and –683 pm/V at 5 kV/cm, 10 kV/cm and 15 kV/cm, respectively. These values are higher than reported for a stress-free flat plate (-271 pm/V). This result seems to be in conflict with the picture of the importance of tensile stress in these materials contributing to enhance domain reorientation because these devices are completely under compressive stress, even in the surface region of the PZT. One possible explanation for this behavior is that the associated changes in the stress state of the device when

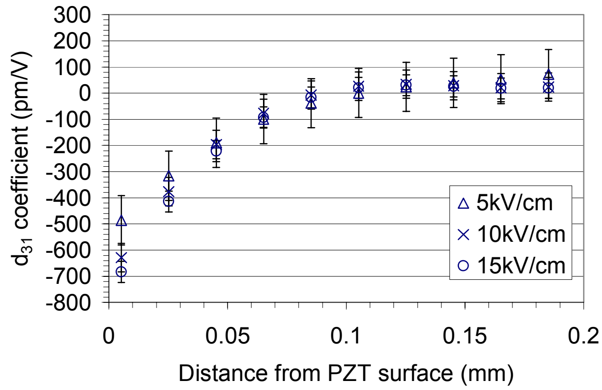

Figure 5. Distribution of piezoelectric d_{31} coefficient throughout the thickness of the 6-mil substrate device expressed by the 3rd order polynomial equations.

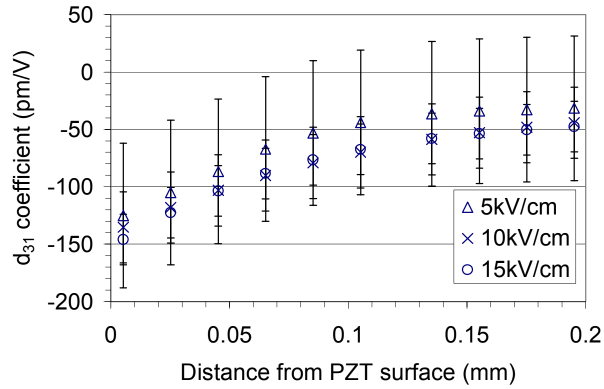

Figure 6. Distribution of piezoelectric d_{31} coefficient throughout the thickness of the 20-mil substrate device expressed by the 3rd order polynomial equations.

deformed under applied field promote domain reorientation through ferroelastic effects. When compared to a flat plate ceramic, although there are less a-domains due to the compressive stress state, higher domain reorientation takes place through a combination of ferroelectric and ferroelastic effects, leading to higher d_{31} coefficients, as predicted by the linear least squares model.

The magnitude of the d_{31} coefficient decreased from these values at the surface to approximately zero in the lower region of the PZT, confirming the greater domain reorientation of the devices in the upper region. The very low values of the coefficient in substrate interface region suggest that substrate effectively clamps domain reorientation in this region of the PZT layer, even more effectively than predicted by Li *et al.* [1].

This figure also shows that as the magnitude of the electric field was increased, the magnitude of the d_{31} coefficients increased. This would be an expected result based on the higher degree of domain reorientation that would be expected for higher electric field. This effect is most pronounced at the free surface region of the device where domain contributions to electromechanical response would be expected to be most significant. This result is thus in line with expectation.

The d_{31} coefficients for the 20 mil-substrate device were also determined by the 3rd order model and are shown in Fig. 6. The surface d_{31} coefficients are -125 pm/V at 5 kV/cm, -135 pm/V at 10 kV/cm and -146 pm/V at 15 kV/cm. The magnitudes of the d_{31} coefficients are smaller than for a stress-free flat plate value (-271 pm/V), which is reasonable for a material under significant compressive stress. Ferroelastic behavior contributes less to the response of the 20-mil substrate device compared to the 6-mil substrate device due to less deformation, and therefore, a lower change in stress state under applied field.

The d_{31} coefficients decreased non-linearly from the surface and became relatively constant in the lower region of the PZT. The magnitudes of the d_{31} coefficients at the PZT/substrate interface are -32 pm/V at 5 kV/cm, -44 pm/V at 10 kV/cm and -48 pm/V at 15 kV/cm. Higher d_{31} coefficients in the upper region of the PZT seem to confirm higher domain switching in this region under electric field compared to the lower region, which is reasonable based on stress level in this device. Interestingly, the lower region of the 20-mil substrate devices showed higher piezoelectric coefficients than the same region of the 6-mil substrate devices.

IV. CONCLUSION

Local deformations of Thunder™ actuators under applied electric fields were measured by Moiré interferometry. The results indicate greater domain contributions to response in the upper region of the piezoelectric material and confirmed the suggestion of previous work that the piezoelectric coefficients are enhanced in the surface region of the devices. By using a linear least squares method to fit the experimental data, the variation of the piezoelectric d_{31} coefficients along the thickness was determined and can be best expressed with a 3rd order polynomial equation. The results confirm the suggested variation of d_{31} coefficient along the thickness of the PZT, with higher d_{31} values at the surface region, and lower values at the lower region.

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