A PIEZOELECTRIC BEAM ACTUATOR WITH A PURE TWISTING RESPONSE

Inbar (Hotzen) Grinberg, Nadav Maccabi, Adne Kassie and David Elata
Faculty of Mechanical Engineering, Technion - Israel Institute of Technology, Haifa, ISRAEL

ABSTRACT

We present for the first time ever, a piezoelectric beam actuator that can be directly driven in pure torsion. The beam actuator is designed with interdigitated electrodes (IDEs), on both its top and bottom surfaces. The IDEs are used for both poling and driving. When the IDEs are driven by a voltage with the same polarity as used for poling, they induce a combination of shear and expansion strains, close to the top and bottom surfaces. The expansion strains at the top and bottom surfaces are similar, and hence they produce no net bending. However, the shear strains at the top and bottom surfaces are in opposite directions, and they produce a pure twist. If the IDEs on the top and bottom surfaces are driven by the same voltage but in opposite polarity, then a pure bending response is produced. We experimentally demonstrate that the actuator can be driven in either pure torsion or in pure bending, with negligible cross-coupling.

INTRODUCTION

Piezoelectric lead zirconate titanate (PZT), unimorph actuators are one of the most prevalent piezoelectric actuators, and different models for their response have been proposed [1-4]. A piezoelectric unimorph actuator is made from a thin layer of piezoelectric material, deposited on top of an elastic substrate. The piezoelectric layer is placed between two electrodes (top and bottom), used for both poling and for actuation. When the electrodes are subjected to a voltage difference, an electrostatic field is generated in the PZT layer, which results in bending.

However, the deposited piezoelectric layers are usually limited to several microns [5, 6]. The deposition process is often challenging and the PZT properties strongly depend on fabrication parameters [7], often resulting in non-uniformity in material properties. PZT unimorphs are sensitive to temperature due to temperature expansion coefficient mismatch, and may be distorted due to residual stresses induced during the deposition process.

Bulk-unimorph PZT actuators are less sensitive to these issues, and offer an alternative to unimorphs [8]. Bulk PZT layers with good uniformity are commercially available, and can be machined using a cheap and simple sand-blasting process. Interdigitated electrodes may be deposited directly on the bulk PZT, making connectivity very simple. The bulk PZT layer serves both as an active piezoelectric layer, and as an elastic substrate, reducing sensitivity to temperature and residual stresses. Moreover, the deflection of bulk-unimorph actuators is proportional to the parameter d_{33}, which is twice as large as the d_{31} parameter that dominates the unimorph response.

In both the unimorph and the bulk-unimorph actuators, the response is a bending deformation. Bending is used in many micromirror applications, where it is converted in to a tilting response of a micromirror [9-12]. Conversion structures consume space and complicate the design, but they are necessary because there is no method for inducing direct twisting of piezoelectric beams.

Previously we demonstrated that selective stiffening elements can enhance or even determine the direction of an actuator response. Specifically, we presented a thermoelastic actuator in which such elements convert bending to torsion, and dominate the response [13, 14].

In a previous work, we adapted the notion of directional elements to piezoelectric actuators. We showed that a beam actuator with IDEs that are oriented at 45° relative to the beam axes, responds in a coupled bending and torsion deformations [15]. In this work, we extend this concept and produce actuators that respond in an uncoupled, pure twisting mode.

DEVICE DESIGN

Figure 1 presents a bulk-unimorph PZT beam actuator. Previous art (Fig. 1a) presented by Devoe [8] included IDEs oriented at 90° relative to the beam axis. Our new design (Fig. 1b) includes IDEs oriented at 45° relative to the beams axis. Previously we demonstrated that IDEs at 45° induce a coupled bending and torsion response. In the present work we used IDEs at 45° on the top surface and IDEs at -45° on the bottom surface, to produce an uncoupled, pure torsion or pure bending mode of actuation.

Principle of operation

When a piezoelectric material is subjected to an electrostatic field in the same direction as the poling field, it responds in expansion in that direction - proportional to the piezoelectric coefficient d_{33}, and in contraction in the transverse directions - proportional to d_{31}. In a unimorph actuator, the expansion and contraction are constrained by the elastic substrate, resulting in internal moments and a bending deformation of the beam.

In a bulk-unimorph actuator the interdigitated electrodes (IDEs) are used for both poling and actuation. When a voltage difference is applied to the IDEs, the electrostatic field generated in the material is not uniform, and its direction changes between each pair of electrode fingers (permanent polarization in Fig. 1a). The intensity of the electrostatic field decreases gradually in the material, and becomes negligible beyond a certain depth. Effectively, the single bulk layer is divided to an active layer, and an inert layer serving as an elastic substrate.

Now, if an electrostatic field in the same direction as poling is applied, the active part of the bulk PZT responds in expansion in that direction, while contracting in the transverse directions. These strains are constrained by the inert part of the bulk PZT, so internal bending moments are generated resulting in a bending deformation (Fig. 1a).

978-1-5090-5078-9/17/$31.00 ©2017 IEEE

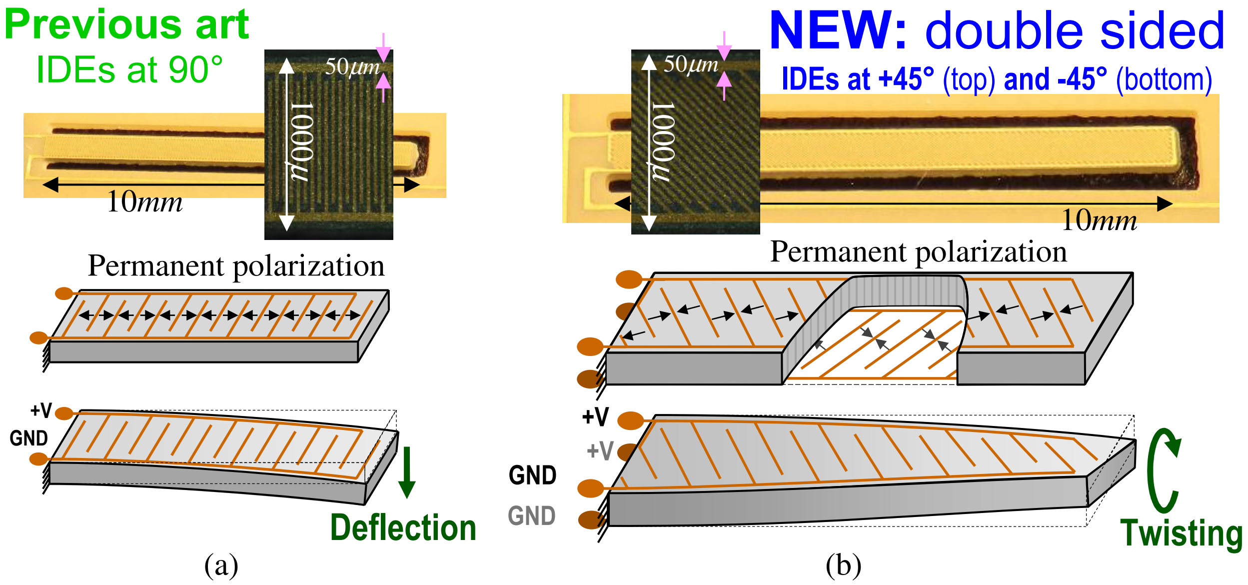

Figure 1: Bulk-unimorph PZT cantilever beams. (a) Previous work by DeVoe [8] with IDEs oriented at 90°. (b) New design with double sided electrodes oriented at ±45°. A microphoto of the fabricated devices is shown at the top. The middle schematic view of the beams shows the driving electrodes, and the bottom illustration is of the driven states.

New design - IDEs at 45°

When the bulk-unimorph beam actuator is poled and driven using IDEs rotated at 45° relative to the beam axis, the expansion and contraction strains are also rotated. These strains can be considered as a superposition of a small isotropic expansion, and a large shear strain acting in the beam cross-section. Both strains are limited to the vicinity of the surface, and they are constrained by the inert part so internal moments are created. The isotropic expansion in the vicinity of the surface may give rise to bending moments, and the shear strain in the vicinity of the surface may give rise to twisting moments.

Double sided actuation

When IDEs on one surface only are actuated, the result is coupled bending and torsion deflections. To eliminate this coupling, in the new design we deposited another set of IDEs at -45° on the bottom surface of the beam (Fig. 1b middle). When both top and bottom electrodes are actuated using voltages in the same direction as poling, the bending moments are mutually balanced (i.e. canceled out), while torsion moments are compounded, resulting in pure twisting of the beam. If however, while the top IDEs are actuated using voltages in the same direction as poling, but the bottom IDEs are actuated using voltages in an opposite polarity, a pure bending is induced.

EXPERIMENT RESULTS

The out-of-plane displacements were measured using a laser vibrometer. In quasi-static experiments, the actuators were subjected to slow 10*Hz* harmonic voltage signals (far from resonance). To avoid large fields opposite the poling direction, which may result in de-poling, an additional constant dc voltage was applied.

Single side actuation

To demonstrate the coupled bending and torsion response of the beam actuator with IDEs at 45°, we applied voltage only to the IDEs on the top surface of the beam. The measured out-of-plane deflections, at different points along the centerline of the beam are presented in Fig. 2, for both beams with IDEs at 90° and with IDEs at 45°. The displacements along the beams centerline represent the bending deformation. While both beams exhibit bending, the beam with IDEs at 90° has larger displacements.

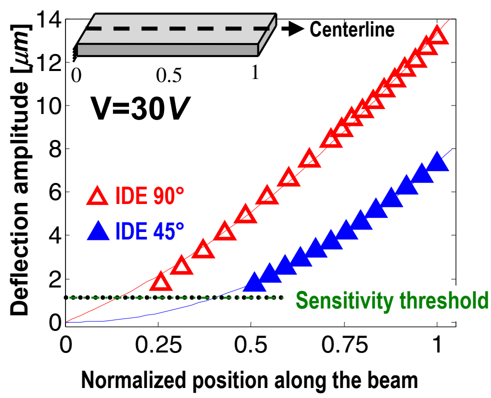

Figure 2: Deflection measured along the centerline, for the beams with IDEs at 90° and IDEs at 45°, for a constant actuation voltage.

The twist angles of both beams (with IDEs at 90° and 45°) along the beams are presented in Fig.3. It is clear that the beam with IDEs at 90° does not twist, while the beam with IDEs at 45° has a monotonically increasing twist angle - as expected for a beam subjected to an internal torsion moment.

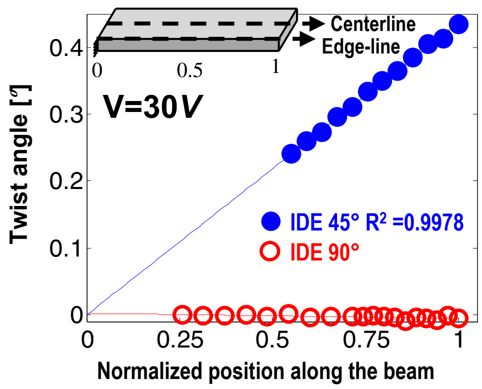

Figure 3: Twist angles for the beams with IDEs at 90° and IDEs at 45°. The beam with IDEs at 90° does not twist, while the beam with IDEs at 45° has a linearly increasing twist angle.

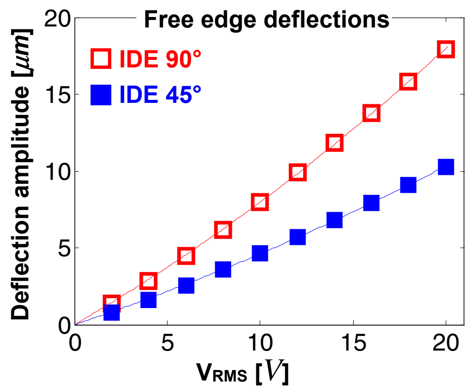

Figure 4: Deflection measured at the center of the free edge of both beams, as a function of increased voltage amplitude. Both beams show a linear relation between edge deflection and voltage amplitude with R^2=0.99.

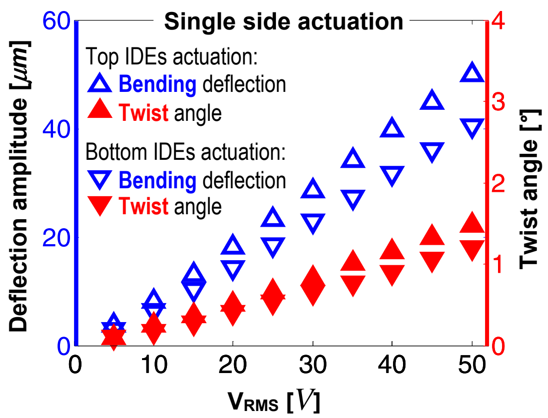

Figure 5: Peak-to-peak deflections and twist angles of the free edge of the beam with IDEs at 45°, when only top or bottom electrodes are used for actuation. The bending and twisting angles in single-side actuation are clearly coupled.

The deflections at the center of the free edge of both beams, as a function of increasing voltage amplitude, are presented in Fig. 4. Both beams exhibit a linear increasing edge deflection.

During experiments we found that there is a difference in deflection amplitudes, when only the top IDEs are used for driving, or when only the bottom IDEs are used. Since our aim is to obtain a pure torsion actuation or a pure bending actuation, deflections generated by the top and bottom IDEs must be the same. We characterized the response of the beam with IDEs at ±45°, as function of voltage, when only one set of IDEs was used (Fig. 5). The left ordinate indicates peak-to-peak displacements and the right ordinate indicates twist angle. When only the top IDEs were used the measured displacements and angles are marked by '△' and '▲', respectively, and when only the bottom IDEs were used the measured displacements and angles are marked by '▽' and '▼', respectively

Double sided actuation

In order to obtain a pure torsion actuation or a pure bending actuation, the results presented in Fig. 5 were used for calibration.

First, we calibrated the ac signal applied to the top IDEs, such that bending was balanced-out. Figure 6 present the edge bending deflection (left ordinate) and twist angle (right ordinate) as a function of increasing voltage. It is evident that the bending deflections are negligible, and a pure torsion mode is achieved. The twist angle of the free edge reaches a maximal value of 4.6°, which is about 4 times larger than the twist angle achieved when only the top IDEs were used.

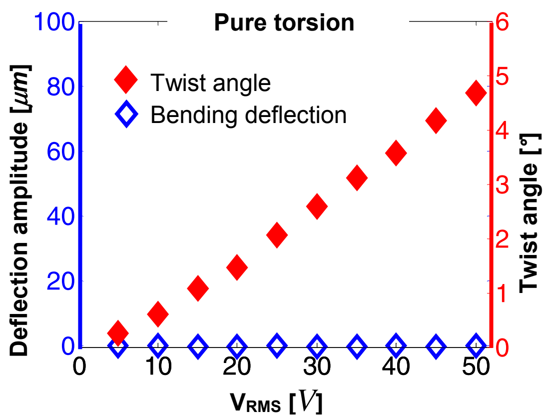

Figure 6: Bending deflections and twist angles measured at the free edge, when both top and bottom electrodes are actuated using voltage signals in the same polarity as poling. Bending is negligible and a pure torsion mode is obtained.

Then, we applied 180° out-of-phase signals to the top and bottom IDEs, and used a calibrated ac signal to the top IDEs such that twisting was balanced-out.

Figure 7 presents the edge bending deflection (left ordinate) and twist angle (right ordinate) as a function of increasing voltage. The bending deflections are about double as large as those achieved with one-sided IDE actuation (Fig. 5), while the twist angles are marginal.

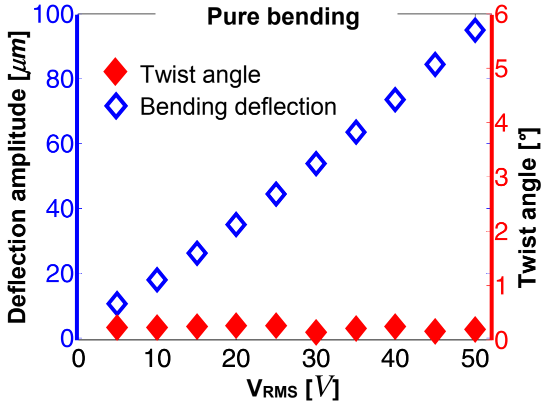

Figure 7: Bending deflections and twist angles, measured at the free edge, when both top and bottom electrodes are subjected to voltage signals that are 180° out-of-phase. Torsion deformation is negligible and a pure bending mode is obtained.

Frequency response

To characterize the dynamic response of the beam, and extract the resonance frequencies of the first bending and the first twisting modes, we drove only the top IDEs with an ac signal of $3.5V_{RMS}$.

The frequency response of the beam actuator with IDEs at 45° is presented in Fig. 8. The first bending mode resonance frequency is 492Hz, with sharpness (a.k.a. quality factor) of 15 in atmospheric pressure. At this frequency twisting was measured to be negligible.

The first torsion mode frequency is 10.3 KHz, with sharpness of 25, and at this frequency bending was measured to be negligible.

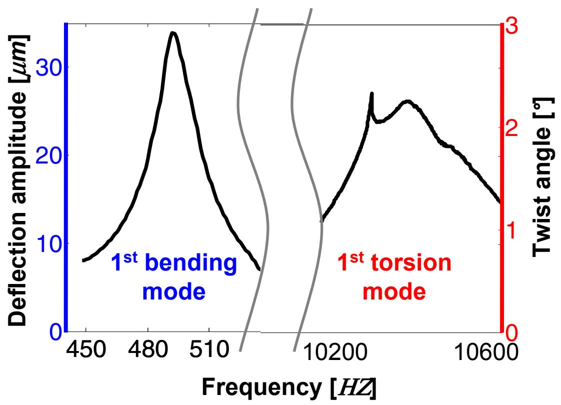

Figure 8: Frequency response of the beam actuator, measured for an actuating voltage of $3.5V_{RMS}$. The first bending mode resonance frequency is 492 Hz, and the first twisting resonance frequency is 10.3 KHz.

SUMMARY

We presented a novel bulk-unimorph PZT beam actuator that can be directly driven in a pure quasi-static twisting mode. By changing the voltage scheme, the very same actuator can be driven in a pure bending mode.

In the pure twisting mode, the free edge twist angle was 4.6°, which is four times larger than the twist angle obtained in the single sided actuation (1.3°). By actuating the beam using both top and bottom IDEs we doubled the internal twisting moment, but the angle has increased four-fold because we eliminated bending. In a one-sided actuation, the unavoidable bending deformation increases the torsional stiffness of the beam, and hence twisting is constrained. In double-sided actuation, when bending is eliminated, the beam remains straight and torsional stiffening remains minimal.

REFERENCES

[1] D. L. DeVoe and A. P. Pisano, "Modeling and optimal design of piezoelectric cantilever microactuators," *IEEE-JMEMS*, vol. 6, pp. 266-270, 1997.
[2] M. Krommer, "On the correction of the Bernoulli-Euler beam theory for smart piezoelectric beams," *Smart Materials & Structures*, vol. 10, pp. 668-680, 2001.
[3] M. S. Weinberg, "Working equations for piezoelectric actuators and sensors," *IEEE-JMEMS*, vol. 8, pp. 529-533, 1999.
[4] E. Elka, D. Elata, and H. Abramovich, "The electromechanical response of multilayered piezoelectric structures," *IEEE-JMEMS*, vol. 13, pp. 332-341, 2004.
[5] S. T. a. K. Mateti, "Piezoelectric MEMS sensors: state-of-the-art and perspectives," *Measurement Science and Technology*, vol. 20, pp. 092001, 2009.
[6] P. Muralt, "Recent Progress in Materials Issues for Piezoelectric MEMS," *Journal of the American Ceramic Society*, vol. 91, pp. 1385-1396, 2008.
[7] S. Trolier-McKinstry and P. Muralt, "Thin Film Piezoelectrics for MEMS," *Journal of Electroceramics*, vol. 12, pp. 7-17, 2004.
[8] P. Hareesh, I. Misri, S. Yang, and D. L. DeVoe, "Transverse Interdigitated Electrode Actuation of Homogeneous Bulk PZT," *IEEE-JMEMS*, vol. 21, pp. 1513-1518, 2012.
[9] W. Liao, W. Liu, Y. Tang, B. Wang, and H. Xie, "Tip-tilt-piston piezoelectric micromirror with folded PZT unimorph actuators," presented at IEEE-NEMS 2013, 2013.
[10] Q. L. Zhao, M. S. Cao, J. Yuan, R. L. Lu, G. P. He, and D. W. Wang, "Fabrication and characterization of a piezoelectric micromirror using for optical data tracking of high-density storage," *Microsystem Technologies*, vol. 20, pp. 1317-1322, 2014.
[11] S. Gu-Stoppel, H. J. Quenzer, and W. Benecke, "Design, fabrication and characterization of piezoelectrically actuated gimbal-mounted 2D micromirrors," presented at Transducers 2015, 2015.
[12] M. Tani, M. Akamatsu, Y. Yasuda, and H. Toshiyoshi, "A two-axis piezoelectric tilting micromirror with a newly developed PZT-meandering actuator," presented at MEMS 2007., 2007.
[13] I. H. Grinberg, O. Ternyak, S. Shmulevich, and D. Elata, "Selective Stiffening for Producing a Mass-Fabrication Compatible Motion Conversion Mechanism," *Journal of Microelectromechanical Systems*, vol. 24, pp. 2101-2108, 2015.
[14] I. Grinberg, S. Shmulevich, and D. Elata, "Reversing the action of thermoelastic bimorphs using selective directional stiffeners," presented at The 18th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS'15), Anchorage, USA, 2015.
[15] I. Grinberg, N. Maccabi, A. Kassie, S. Shmulevich, and D. Elata, "Direct torsion actuation of bulk PZT beams using directional interdigitated electrodes," presented at Eurosensors 2016, Budapest, Hungary, 2016.

CONTACT

I. Grinberg, inbar28@gmail.com
D. Elata, elata@technion.ac.