Out-of-Plane Translational PZT Bimorph Actuator with Archimedes’ Spiral Actuating Tethers

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Abstract. The design, finite element analysis (FEA), and experimental characterization of a MEMS out-of-plane (vertical) translational lead-zirconate-titanate (PZT) bimorph actuator supported on Archimedes’ spiral tethers are presented. Two types of bimorph actuators with different electrode patterns (with spiral tethers half actuated or fully actuated) are designed and fabricated. Both designs are fabricated by commercial processes and are compatible with integration into more complex MEMS systems. Finite element analysis (FEA) was used to analyze and predict the displacements of both types of actuators. The deflections of both fully-actuated and half-actuated devices were measured experimentally to validate the design. At an applied voltage of 110V, the out-of-plane deflections of the actuators with half-actuated and fully-actuated tethers were measured at about 17 µm and 29 µm respectively, in good agreement with FEA predictions of 17.1 µm and 25.8 µm. The corresponding blocking forces are predicted as 10 mN and 17 mN by FEA.

1. Introduction
Piezoelectric actuators can produce high forces and operate at high speed, but their native displacements are relatively small. Larger displacements can be engineered into piezoelectric actuators at the expense of some of their output force, for example through the use of piezoelectric bimorph benders. Thin film, microfabricated piezoelectric bending actuators are classic examples of trading force for increased displacement [1-4]. For applications in which large displacement from a small-footprint actuator is the primary requirement, thin film piezoelectric actuators can provide a superior solution. For applications in which actuator force is also important, thin film piezoelectric bending actuators are less attractive. In addition to the actuators’ small force, the lithographic processing required to fabricate their complex, multi-layer thin film and released structures increases their cost.

For actuators in which a compromise between force and displacement is paramount, more macroscale approaches can offer satisfactory performance. Examples include fully macroscale actuators with mechanisms for displacement amplification, such as drum actuators [5-6] and cymbal and moonie actuators [7-9]. However, their large sizes limit their integration into microsystems. The actuator of [10] offers a smaller, partially microfabricated alternative, with tens of mN of force and displacements of up to 11 µm. However, the actuator in [10] is manually assembled from individual parts, limiting its manufacturability. For higher force actuators, their ability to be integrated into small-scale systems can be limited by their size or by their complexity of assembly.
This article presents a piezoelectric MEMS out-of-plane (vertical) actuator that addresses the coupled challenges of high force, high displacement piezoelectric actuators via an approach that can be manufactured efficiently and integrated with other MEMS parts at the die scale to create more complex systems. The present devices are translational lead-zirconate-titanate (PZT) Archimedes’ spiral tether bimorph actuators. The actuators are fabricated by a commercial PZT manufacturing process, and their design offers large deflection and large force in a compact, mechanically and thermally robust structure that has accessible, easy to fabricate electrical connections. To characterize the unique behavior of spiral-tether actuators, two types of actuators with different electrode patterns (half-actuated tethers and fully-actuated tethers) are simulated, fabricated, and tested.

2. Design and Fabrication
The goal of the actuator design is to maximize the out-of-plane displacement and force while minimizing the lateral dimensions and maintaining the simplest possible fabrication process. Some trade-offs must be made between displacement and force; the present actuator is designed for a gas-phase microfluidic application and requires a minimum displacement of 25 µm. One seemingly straightforward approach would be to support a moveable central island on a set of straight actuating tethers, similar to [3]. Despite its simplicity, this design has drawbacks. The primary drawback lies in the challenges of achieving a compact device; the tethers must have sufficient length to enable the necessary displacement, but tether length directly translates into the lateral device dimensions for the case of straight tethers. A secondary drawback lies in the stress concentrations, which are magnified by the sharp corners of a purely straight tether architecture; stress concentrations may be moderated by rounding out the corners. Supporting a moveable central island on a set of folded flexures offers greater compactness, but providing electrical connections such that alternating regions of the actuating flexures will curve up and down to achieve large net displacements increases the fabrication complexity of the device [2, 11]. Stress concentrations also pose a challenge for folded flexures.

An alternative that can potentially achieve compactness while avoiding stress concentrations and maintaining simple wiring for straightforward fabrication is to use curved actuating tethers. Curved tethers can be tightly packed, minimizing wasted space, and their naturally rounded shape minimizes stress concentrations and the chance of failure. For these reasons, a central moveable plate supported on curved actuating tethers is chosen for the present device. In particular, an Archimedes’ spiral shape is selected for the actuating tethers because it offers three key advantages. First, the spiral-supported actuator maximizes the length of the actuating tethers in a constrained space; second, the smooth Archimedes’ spiral minimizes stress concentration; and third, the Archimedes’ spiral guarantees uniform spacing between adjacent actuating tethers. To obtain large out-of-plane displacement in both the upward and downward directions, an X-poled bimorph is selected.

When a voltage is applied across the electrodes and the actuator’s outer edge is constrained, the central island of the actuator moves up and down, depending on the voltage’s polarity. If one were to design the spiral-supported actuator based on the physics of straight bimorph bending beams, one seemingly promising method would be to actuate the outer halves of the tethers (closest to the circular supporting frame) with one polarity and the inner halves of the tethers (closest to the central island) with the opposite polarity, similar to [2]. This approach is not chosen, for two reasons. First, the physics of curved actuators are not the same as the physics of straight actuators. For curved bimorphs, torsion plays an important role in generating net displacement, and it will be seen through finite element analysis (FEA) that actuating the halves with opposite polarity is ineffective. Second, even if that configuration were beneficial, it would greatly complicate wiring. Two alternatives are considered instead. In the first, only the outer half of the spiral (nearest the supporting frame) is actuated; this approach would also generate net displacement in a straight actuator, similar to [1, 3]. In the second, the full length of the spiral tether is actuated; this approach would generate zero displacement in a straight actuator but offers net displacement here because of the effects of torsion. Two types of X-poled PZT bimorph actuators are fabricated as shown in figure 1. Each actuator comprises three actuating tethers shaped as Archimedes’ spirals, a central island, and a circular
supporting frame. The electrical and mechanical structures of both types of actuators are defined by laser cutting of nickel-coated PZT plates by a commercial vendor, Piezo Systems, Inc. Through-plate cutting is used to pattern the PZT features, and shallow cutting is used to pattern the electrode on one side of the actuator. The reverse-side electrode covers the full actuator. In figures 1a and 1c, the patterned electrode extends over only the outer half of the spiral tethers, whereas in figures 1b and 1d, the patterned electrode extends over the full length of the tethers. The material used to fabricate the actuators is PZT-5A4E, which guarantees a high Curie Point (350 °C) for compatibility with moderate temperature applications. Table 1 shows the actuator dimensions.

| Property                              | Notation | Value           |
|---------------------------------------|----------|-----------------|
| Archimedes’ spiral constant ($r = a\theta$) | $a$      | 0.768 mm       |
| Thickness of single PZT layer         | $t$      | 0.135 mm       |
| Width of single tether                | $w$      | 1.129 mm       |
| Diameter of actuator                  | $d$      | 19 mm          |
| Electrode starting angle              | $\theta_1$ | Full-actuated: 1.990 rad |
| Electrode ending angle                | $\theta_2$ | Half-actuated: 6.301 rad |

3. Finite Element Analysis
The behaviors of devices with fully-actuated and half-actuated tethers are modeled and simulated using finite element analysis (FEA) in Abaqus. Voltages are input, and the out-of-plane (vertical) translational displacement of the central island is predicted. The outer edge of the circular supporting frame is considered to be fully constrained, with zero rotation and zero deflection. Static voltages of 30 to 110 V are applied in increments of 10 V to drive each actuator. The thicknesses of the electrodes and of the adhesion layer that connects the bimorph’s layers are assumed to be negligible. The C3D20E element (a 20-node quadratic piezoelectric brick element) is used in the mesh.

Figure 2 plots the FEA displacement contour at a voltage of 110 V for actuators with fully-actuated tethers and for actuators with half-actuated tethers. The maximum predicted out-of-plane deflections of the central island are 25.8 µm and 17.1 µm for the fully-actuated and half-actuated devices, respectively. The blocking forces for half-actuated and fully-actuated devices are calculated at 10 mN and 17 mN, respectively. For comparison, the out-of-plane deflection of the central island is predicted to be just 9 µm when the outer and inner halves of the tethers are actuated with opposite polarities as described above. The much smaller deflection under actuation conditions that would be optimal for a
straight beam underscores the differences between the bending-driven physics of straight actuating beams and the combined physics of partially bending-driven and partially torsion-driven bending of curved actuating beams.

4. Experiments

The deflections of both fully-actuated and half-actuated devices are measured. Each device is mounted on three pieces of pre-cut, 50 µm thick tin-plated copper foil tape that are evenly distributed around the edges of the actuators. The pieces of tape are soldered together to provide a common voltage. The tape provides electrical contact to the reverse-side electrodes and acts as a mechanical spacer above the underlying surface, ensuring that the center of the actuator can move both up and down. The tape and the actuators are constrained by epoxy on a 3D printed platform to approximate fully constrained boundary conditions. DC voltages of 30 V to 110 V are applied in 10 V increments with a DC power supply (MASTECH® HY5005E-2) and a high voltage amplifier (WMA-005, Falco Systems). The displacements of the actuators’ central islands are obtained by measuring the heights at which a micrometer (Newport® 461 Series) achieves electrical contact with a metal tip glued on the central island. Three repeated displacement measurements are made at each voltage for each type of actuator. The average of the three measurements is recorded as the deflection for that voltage and actuator.

Figure 3 plots FEA and experimentally-measured results for deflection versus actuating voltage for both half-actuated and fully-actuated devices. The results show that for both actuators, the displacements increase monotonically with the applied voltage, as predicted by the simulations.
is close agreement between FEA and experimental results for the actuator with half-actuated tethers, whereas the device with fully-actuated tethers shows reasonable agreement but with some deviation between FEA and experimental results. The fully-actuated device consistently offers greater displacement than the half-actuated device. The device with fully-actuated tethers deflects about 0.235 μm/V, whereas the device with the half-actuated tethers deflects about 0.155 μm/V.

5. Conclusion

Archimedes’ spiral-supported piezoelectric bimorph actuators were shown to produce up to 29 μm of deflection and 17 mN blocking forces under unipolar actuation. The largest deflections and blocking forces were produced by devices in which uniform actuation was applied over the full length of the spiral tethers, in contrast to the behaviour of straight bimorph actuators. The high performance of the fully-actuated devices is attributed to the torsion generated in the spiral tethers. The experimental results are in good agreement with FEA predictions. The devices have a simple planar architecture for straightforward integration into more complex MEMS systems, and their fabrication via a commercial process provides an effective actuator solution that does not require access to fabrication facilities.

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