Piezoelectric ultrasonic bidirectional linear actuator for micropositioning fulfilling Feynman's criteria

James Friend,[a] Leslie Yeo, and Matt Hogg
Micro/Nanophysics Laboratory, Monash University, Wellington Road, Clayton, Victoria 3800, Australia

(Received 30 August 2007; accepted 20 October 2007; published online 11 January 2008)

A bidirectional linear microactuator with a stator less than 400 μm^3, fulfilling Feynman's original criteria for a motor less than 1/64th of an inch on a side [R. Feynman, Engineering and Science Magazine (Caltech) **4**, 23 (1960)], is shown to generate forces over 30 mN in either direction at speeds of up to 40 mm/s using a large 28 g polished alumina slider. Using the thickness mode of a stepped piezoelectric block in conjunction with a pair of fundamental flexural modes of a pair of slanted beams—each slightly differs in configuration—gives the ability to generate silent bidirectional motion at an excitation frequency of about 1.7 MHz. In addition to offering forces at least one order of magnitude larger than those of the other methods, the system also serves as a platform for studying nonlinear frictional phenomena on the nanoscale and its manipulation through acoustic irradiation of the contact interface for propulsion.
[DOI: 10.1063/1.2814044]

Generating useful and controlled motion at small scales is surprisingly difficult to achieve. Despite the many approaches explored, using forces generated by electrostatics,[1] electromagnetics,[2] thermal expansion,[3] surface tension,[4] and van der Waals,[5] few if any of these may be exploited to generate large-scale motion under controlled speeds and forces in a package small enough to be useful for micro/nanorobotics.[6,7] Using piezoelectric materials for actuation is a familiar approach, especially on the millimeter scale of motors for cameras, watches, and other consumer devices.[8,9] These devices almost universally use resonance, amplifying the miniscule output strain of the piezoelectric materials enough to obtain bulk motion. Given the favorable scaling characteristics of piezoelectric actuation,[10] there have been attempts to shrink these devices to smaller scales by Flynn and others.[11] Here, we explore the use of ultrasonic piezoelectric actuation for a linear micromotor able to fit into a cube 400 μm on a side, within Feynman's original 1/64th-in. challenge made in 1959 (Ref. 12) and only forty-seven years behind McLellan's winning design.[13] Presumably, ours is more useful for applications on these scales, with linear speeds of up to 40 mm/s and forces of over 30 mN obtained in either direction. The actuation technique is similar to the one used by Friend *et al.*,[14] but at a far smaller scale.

By using resonance to amplify the strain available from the piezoelectric material, significant motion in the structure—the *stator*—may be obtained on the order of 1 m/s particle velocity. At the frequencies of the device in this study, over 1 MHz, the amplitude of vibration is on the order of tens of nanometers. From a physical perspective, much of what is interesting about the operating mechanism of ultrasonic motors, in general, and this high-frequency device, in particular, is its uniquely powerful method of controlling interface friction to obtain motion, a topic of recent and intense study.[15]

The key difficulty in designing an ultrasonic motor is obtaining oscillatory motion along the contact interface between the stator and rotor or slider in a form that will efficiently generate an oriented motion. The unique approach here combines the use of a stepped piezoelectric element to amplify the output displacement with the use of flexural resonances in a pair of slanted beams mounted atop the element, as shown in Fig. 1. Circular cylindrical shapes are cut about the tips of the beams to form masses that effectively lower their flexural resonance frequencies. Further, one of the cylindrical shapes has a different diameter than the other, causing the resonance frequencies between the two beams to be different. The beam lengths are adjusted so that a slider placed atop them remains parallel to the horizontal plane of the stator. Placed at an angle, the beams' flexural vibration combined with the vertical vibration from the piezoelectric element gives elliptical vibration of one beam tip or the

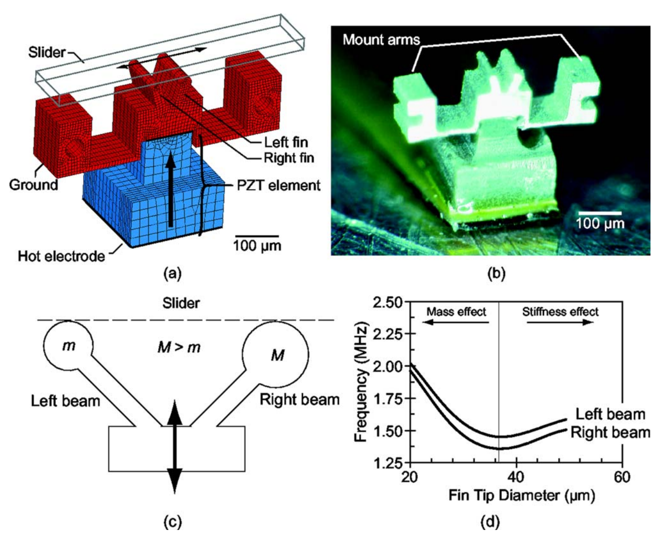

FIG. 1. (Color online) The (a) oblique view of a finite element mesh used to model the stator for the motor alongside (b) a completed prototype stator. Notice the slider sits atop the pair of fins; the fins are a pair of cantilever beams mounted at an angle with asymmetry and have different fundamental flexural resonances if (c) the end masses are different. Depending on the relative size of the tip masses to the beams' length, they either (d) reduce the resonance frequency (mass effect) or increase it (stiffness effect).

[a]Electronic mail: james.friend@eng.monash.edu.au

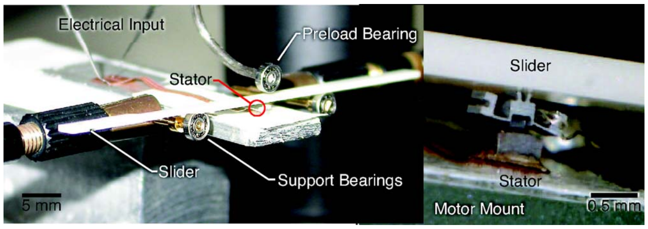

FIG. 2. (Color online) The experimental setup to test the performance of the motor system.

other, depending on the driving frequency and on the relative phase of the axial and flexural vibrations. The control of the phase defines the shape of the motion; a 90° phase shift between the flexural and axial vibration generates elliptical output motion at the beam tip. Such an arrangement is achieved here by designing the actuator so that the piezoelectric element's axial and the beams' flexural resonance frequencies are slightly different. By switching between the resonance frequencies of the two beams, the excitation of flexural vibration may be controlled between the two beams and, therefore, the direction of sliding may be reversed. Since the beams are short in comparison to their width and depth, the complexity of motion introduced by the mounting technique, and the short piezoelectric element structure, finite element analysis was used from the beginning to analyze and parametrically design the stator complete with harmonic behavior, piezoelectric and damping losses, and anisotropic piezoelectric material modeling. The mesh used in ANSYS (ANSYS, Inc., Canonsburg, PA USA) is shown in Fig. 1 for the final design; 322 iterations were made to reach this final design, including numerous modifications to the mounted arms, fins, and piezoelectric element.[16]

The stepped piezoelectric elements were fabricated by Taiheiyo Cement (Tokyo, Japan) using a 400-μm-thick, face-electroded disk of their hard lead zirconate titanate, type NA, using an automated diamond wafer dicing saw system in a two-step process: first machining the $200\times200\times200$ μm^3 narrow sections of the element followed by dicing out the $200\times400\times400$ μm^3 base from the wafer. Using microelectrodischarge machining (Mitsubishi DIAX PA05S, Shin-Yokohama, Japan), the 200-μm-thick stator structure was cut from heat-annealed 2024T6 aluminum with 25 μm minimum feature size, as shown in Fig. 1(b), representing an aspect ratio of 1:9.5. Annealing the aluminum eliminated stress-release distortion of the cut structure. A 23 g, $0.57\times2.07\times50$ mm^3 slider was machined from alumina and polished to a sub-nanometer flatness on its largest two faces for contact against the stator.

A pair of resonance frequencies at 1.733 and 1.823 MHz was found for the *slider-loaded* stator (preload of 0.45 N) using an impedance analyzer (Agilent 4294A, Waltham, MA, USA), which corresponded to the finite element analysis design: 1.69 and 1.71 MHz for the fundamental flexural resonance of each beam and 1.70 MHz for the axial resonance of the piezoelectric element; scanning laser Doppler vibrometer (MSA-400, Polytec, Waldbrunn, Germany) results (not shown) indicated that these modes were the ones desired. Using a signal generator and an amplifier (WF1946 and HSA4101, NF Corporation, Tokyo, Japan), the actuator was driven with a 35 $V_{p\text{-}p}$ sinusoidal signal at these two frequencies using the experimental setup shown in Fig. 2 with a 0.45 N preload on the contact interface. Using a single point laser Doppler vibrometer with steady-state displacement measurement capability (LDV, AT0023+0070, GRAPHTEC, Yokohama, Japan) to illuminate the end of the slider, the velocity of the slider was measured with respect to time, as shown for leftward and rightward [see Fig. 1(a)] sliding over time in Fig. 3. From the velocity data and the mass of the slider, the force that the motor can deliver may be calculated using the method of Nakamura *et al.*,[17] as shown in Fig. 4. Though some motors exhibit force-velocity responses inappropriate for the assumptions made in forming the exponential-linear model of Nakamura *et al.*, the velocity versus time data taken from the LDV—the small dots in Fig. 3—correspond well to the exponential-linear curve represented by the solid lines and indicate the assumptions are sound for this motor. The asymmetry in the velocity curves

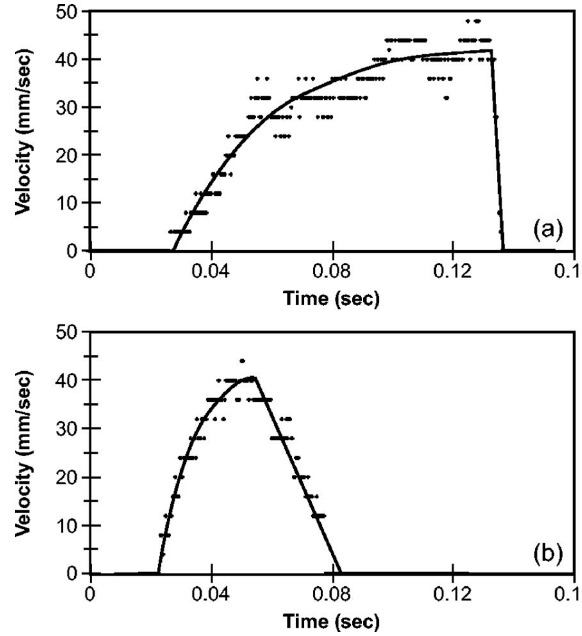

FIG. 3. Velocity vs time for a single run: (a) leftward, 1.733 MHz, and (b) rightward, 1.823 MHz.

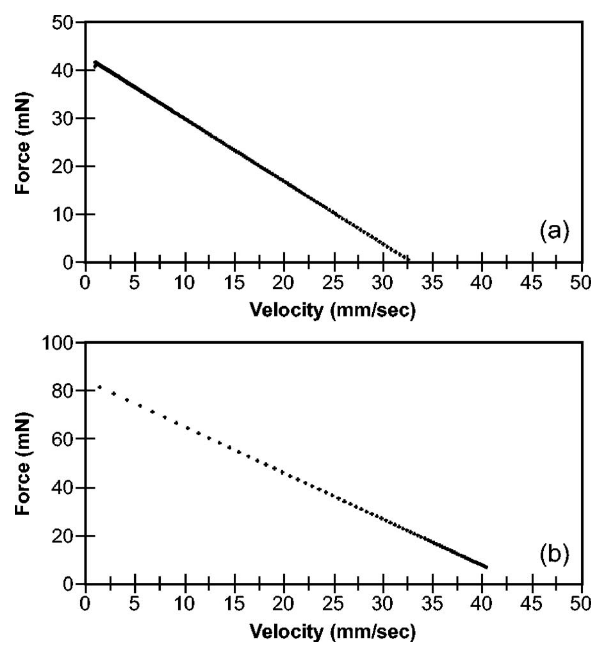

FIG. 4. Sliding force vs velocity: (a) leftward and (b) rightward.

in Fig. 3 results from the asymmetry in the fin configuration; the higher frequency, rightward motion reaches the maximum speed much quicker [Fig. 3(b)] than the leftward direction [Fig. 3(a)], and the 80 mN maximum rightward force, almost double the 42 mN maximum leftward force, illustrates the difference in performance. This is opposite of the larger version of this actuator reported earlier;[14] in the new actuator, the right-hand, lower resonance frequency beam continues to vibrate at the higher excitation frequency, unlike the larger version, due to improvements in the design gleaned from experience with the prior actuator. Given the large, 23 g mass of the slider in comparison to the stator, a 1000:1 ratio, the long 100 ms time to reach full (no-load) speed in comparison to larger ultrasonic motors is not especially surprising.

At over 30 mN in either direction, this actuator offers axial forces at least an order of magnitude larger than those of the other actuation methods at these scales, even with the crude testing arrangement pictured in Fig. 2 an illustration of the favorable scaling of piezoelectric materials and ultrasonic vibration in actuation. Indeed, the numerous approaches used in trying to obtain micro- and nanoactuation illustrate the potential that researchers perceive in the development of these devices. Again, Feynman's prescience helped lead the discussion with ideas such as "swallowing the surgeon"[12] as one of many useful outcomes enabled by such technology: machines composed of such actuators could treat illnesses not possible by other means, long a children's fantasy.[18] Since then, progress has been made on molecular motors[19] and indeed fascinating combinations of biological and man-made systems,[20] though there remains a gap between the millimeter and molecular scales that lacks useful actuators for micro- and nanorobotics, a gap that ostensibly meets Feynman's original challenge.[21] This actuator is a step toward filling this gap and fulfilling Feynman's original vision.

[1]A. Fennimore, T. Yuzvinsky, W. Han, M. Fuhrer, J. Cumings, and A. Zetti, Nature (London) **424**, 408 (2003).
[2]C. Malek and V. Saile, Microelectron. J. **35**, 131 (2004).
[3]A. Geisberger, D. Kadylak, and M. Ellis, J. Micromech. Microeng. **16**, 1943 (2006).
[4]J. Lee and C. Kim, J. Microelectromech. Syst. **9**, 171 (2000).
[5]K. Autumn, M. Sitti, Y. Liang, A. Peattie, W. Hansen, S. Sponberg, T. Kenny, R. Fearing, J. Israelachvili, and R. Full, Proc. Natl. Acad. Sci. U.S.A. **99**, 12252 (2002).
[6]A. Requicha, Proc. IEEE **91**, 1922 (2003).
[7]J. Friend, K. Nakamura, and S. Ueha, IEEE/ASME Trans. Mechatron. **9**, 467 (2004).
[8]N. Goldberg, *Camera Technology: The Dark Side of the Lens* (Elsevier, Burlington, MA, 1992).
[9]S. Ueha and Y. Tomikawa, *Ultrasonic Motors: Theory and Applications* (Clarendon, Oxford, UK, 1993).
[10]Z. Wang, Adv. Mater. (Weinheim, Ger.) **19**, 889 (2007).
[11]T. Morita, Sens. Actuators, A **103**, 300 (2003).
[12]R. Feynman, Engineering and Science Magazine (Caltech)0013–7812 **4**, 23 (1960).
[13]T. Hey, Contemp. Phys. **40**, 257 (1999).
[14]J. Friend, Y. Gouda, K. Nakamura, and S. Ueha, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **53**, 1160 (2006).
[15]M. Urbakh, J. Klafter, D. Gourdon, and J. Israelachvili, Nature (London) **430**, 525 (2004).
[16]See EPAPS Document No. E-APPLAB-91-034747 for a pair of animations illustrating the two vibrational mode shapes as driven by the harmonic excitation of the piezoelectric element via an sinusoidal input through the electrodes. This document can be reached through a direct link in the online article's HTML reference section or via the EPAPS homepage (http://www.aip.org/pubservs/epaps.html).
[17]K. Nakamura, M. Kurosawa, and S. Ueha, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **38**, 481 (1991).
[18]R. Heinlein, *Waldo and Magic, Inc.* (New English Library, London, 1986).
[19]J. Howard and R. Clark, Appl. Mech. Rev. **55**, B39 (2002).
[20]B. Behkam and M. Sitti, Appl. Phys. Lett. **90**, 023902 (2007).
[21]A. Junk and F. Riess, Am. J. Phys. **74**, 825 (2006).