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Note: Seesaw actuation of atomic force microscope probes for improved imaging bandwidth and displacement range

H. Torun,[1] D. Torello,[2] and F. L. Degertekin[2]
[1]*Department of Electrical and Electronics Engineering, Bogazici University, Bebek, TR-34342 Istanbul, Turkey*
[2]*G. W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, USA*

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The authors describe a method of actuation for atomic force microscope (AFM) probes to improve imaging speed and displacement range simultaneously. Unlike conventional piezoelectric tube actuation, the proposed method involves a lever and fulcrum "seesaw" like actuation mechanism that uses a small, fast piezoelectric transducer. The lever arm of the seesaw mechanism increases the apparent displacement range by an adjustable gain factor, overcoming the standard tradeoff between imaging speed and displacement range. Experimental characterization of a cantilever holder implementing the method is provided together with comparative line scans obtained with contact mode imaging. An imaging bandwidth of 30 kHz in air with the current setup was demonstrated. © *2011 American Institute of Physics*. [doi:10.1063/1.3622748]

Bulk piezoelectric (piezo tube) actuators are commonly used in conventional AFM systems for z-actuation because they provide several microns of displacement range, which is suitable for many applications, such as topographic imaging or bio-molecular characterization. However, these actuators also have limited actuation bandwidths typically on the order of a few kHz, limiting the imaging speed of the AFM setup. To increase the speed of the piezo tube, or z-piezo, substantially, smaller piezo actuators have been used at the expense of reduced displacement ranges. These actuators may provide up to a few hundred kHz bandwidth with a displacement range on the order of a few hundred nm to 1 μm. Ando *et al*. demonstrated a z-scanner bandwidth of ~500 kHz with a range of 250 nm in fluid.[1] In another work, Schitter *et al*. showed relatively more balanced optimization between displacement range (4.3 μm) and z-piezo speed (22 kHz).[2] Miniaturized flexural stages are employed in both of these systems to couple piezo actuators to the cantilevers. Previous research for fast AFM development also includes alternative driving methods for microcantilevers, such as micromachined piezoelectric transducers,[3] electrostatic actuators,[4] and electromagnetic actuators.[5] The aim is to directly actuate the microcantilever so that the coupled mass to the actuator is minimal.

Given the trade-off between the speed and the displacement range, the use of these actuators is limited to the applications where the imaged substrate is relatively smooth. However, semiconductor and MEMS fabrication industries need in-line fabrication metrology tools that can quickly image over high aspect ratio trenches. Moreover, many applications of AFM in biology such as protein unfolding experiments with large proteins and cellular applications with large cells require large displacement ranges on the order of several microns. In one study, Lehenkari *et al*. assembled two piezo tubes in series so that the net displacement in z-direction is doubled.[6] This work addresses the need for larger displacement ranges without increasing the operating speed.

Increasing both the speed and the displacement range has previously been addressed by using two separate actuators. Sulchek *et al*. approached this question by combining a fast piezoelectric transducer and a slower thermal actuator.[7] Similar approaches have been followed in different studies where dual piezo transducers were used.[8,9] This method of actuation improves system dynamics at the expense of increasing system complexity, and the large displacement piezo is still a limiting factor when large feature imaging is required, although smaller piezo increases imaging bandwidth for smaller feature sizes. There is thus a need for a large displacement, high bandwidth system that is not bandwidth limited through its entire displacement range.

In this work a method of actuation for AFM cantilevers is presented that provides both high actuation bandwidth and large displacement range. In a conventional AFM, the z-piezo actuates the cantilever by translating it along the z-direction as in Fig. 1(a). In contrast, the proposed method relies on rotating the cantilever along an axis perpendicular to its plane of motion, which is shown conceptually in Fig. 1(b). Here, the piezo actuator translates the end of the cantilever chip and the cantilever is free to rotate along a support, forming a seesaw type mechanism. The clamping force ensures the contact between the cantilever and the piezo actuator during the operation. By moving the fulcrum point along the cantilever chip, the displacement gain, $G = L_2/L_1$, can be controlled. For $G > 1$, the seesaw actuation method increases the apparent displacement range by a factor of G at the cantilever tip. This simple configuration allows us to use a small, high bandwidth piezo actuator without worrying about its limited displacement range. A practical way of implementing a seesaw actuator for commercial AFM systems is shown in Fig. 1(c). The cantilever is mounted on a fulcrum and the backside of the cantilever chip is held in contact with a small, high bandwidth piezo actuator attached to the holder.

A prototype holder based on this design was machined using stereolithography (Viper 7510 SLA, 3D Systems, Rock Hill, South Carolina, USA) and it was characterized experimentally. The optical characterization setup is shown schematically in Fig. 2(a). The piezo actuator on the holder

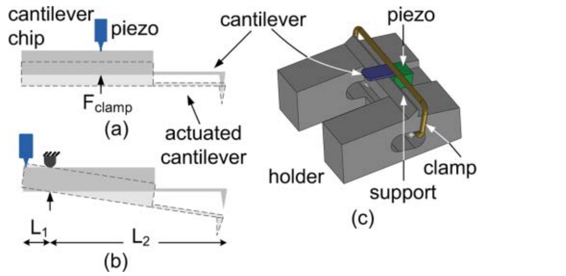

FIG. 1. (Color online) (a) Schematic view of a conventional method of actuating an AFM cantilever. Piezo actuator simply translates the cantilever in vertical direction. (b) Schematic view of proposed method of actuation. Piezo actuator translates the end of the cantilever chip. The chip is free to rotate along the out-of-plane axis passing through the support point. (c) 3D model of a cantilever holder employing seesaw actuation method.

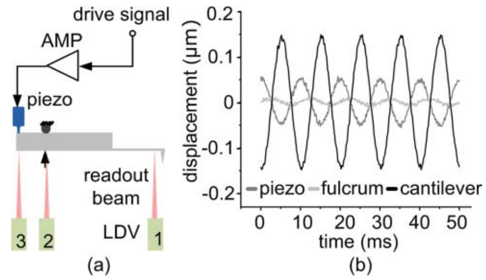

FIG. 2. (Color online) (a) Schematic view of the optical setup using a laser Doppler vibrometer (LDV) to characterize the seesaw actuation holder. *Point 1* represents the piezo readout location, *Point 2* represents the fulcrum readout location, and *Point 3* represents the cantilever readout location. (b) Displacement data measured by LDV at three different positions along the cantilever chip at a Vp-p signal of 5 V.

is a cube-shaped chip actuator with a side length of 2 mm (PL022 PICMA Chip Actuator, Physik Instrumente GmbH & Co.KG, Karlsruhe, Germany), which is capable of providing a displacement range of 2.2 μm at 100 V (measured values indicated that this was closer to 2.2 μm at 110 V) and has an unloaded resonant frequency of 300 kHz. A rectangular silicon cantilever (FESP, Veeco Instruments Inc.) was placed in the holder and the piezo driver was implemented using a high-voltage OPAMP (PA78, Apex Microtechnology Corp.). Using 150 V peak-drive signals, a driver bandwidth of 500 kHz and a 500 ns rise time was recorded. The displacement characterization was carried out using a laser Doppler vibrometer (LDV) (PDV-100 Polytec, Karlsruhe, Germany) by driving the piezo actuator with a 100 Hz sine wave and measuring the displacement on three different points along the cantilever chip: at the cantilever end, the piezo actuator end, and above the fulcrum. The drive signal amplitude was adjusted such that the piezo followed the signal with a peak-to-peak displacement amplitude of 0.1 μm as shown in Fig. 2(b). During the operation, the displacement near the tip of the cantilever was measured 0.3 μm peak-to-peak, indicating a seesaw gain of 3 with this particular fulcrum placement. In addition, the displacement signals measured at the piezo and the cantilever are out-of-phase as expected for a seesaw mechanism. The displacement at a point along the fulcrum axis is also shown in Fig. 2(b), where the relatively low (0.015 μm peak-to-peak) displacement amplitude indicates that the cantilever is rotating along the fulcrum axis as opposed to translating vertically as in a conventional system. It is reasonable to assume that the finite spot size of the laser prevented a zero displacement measurement at the fulcrum point. Because the cantilever is manually mounted on this holder prototype, spatial variations and limitations due to the geometry of the cantilever and the chip and human error define the achievable displacement gain. Nevertheless, using the current holder and mounting methods, the measured displacement range of the specific piezo used was extended from 2.2 μm to 6.6 μm at a maximum driving voltage of 110 V.

Next, the imaging bandwidth of the cantilever mounted in the holder was measured in order to confirm high speeds for the entire displacement range. The holder was mounted to a commercial AFM system (Dimension 3100, Veeco Instruments Inc.) to obtain the frequency response. Figure 3(a) shows both the amplitude and the phase response of the cantilever chip actuated by the seesaw piezo driven with white noise. The longitudinal displacement signal was generated by collecting laser light reflected off the chip near the cantilever. Using the optical lever detector of the AFM system, the displacement spectrum was obtained through a digital spectrum analyzer (SR780, Stanford Research Systems, CA). The displacement signal with no piezo actuation (ambient and system noise actuated) is also provided in Fig. 3(a). The experimentally identified bandwidth for the actuated system is 30 kHz, which corresponds to a phase lag of 45° from observation of the phase response. The resonant frequency for the unloaded piezo is reported to be near 300 kHz, and the resonant frequency for a free cantilever chip was calculated to be 264 kHz using the method presented by Leissa.[10] A finite-element model was constructed using the COMSOL software (COSMOL MULTIPHYSICS v.3.5) to assess the effect of mass loading due to the cantilever chip on the piezo and the finite clamping force. A 2D structural model with varying point masses for eigenfrequency analysis was used to verify the measured bandwidth.

After characterizing the actuator, the frequency response of the cantilever on the chip (MLCT-C, Veeco Instruments Inc.) was also measured. Figure 3(b) shows the frequency response of the cantilever obtained while the piezo was actuated with a white noise signal (labeled *on*) and with thermal noise (labeled *off*) recorded from the longitudinal displacement signal component of the optical lever detector. The peaks on the response curves correspond to the first longitudinal and torsional resonance modes of the cantilever, respectively, indicating that both of these modes would be excited by the piezo.

After the static and dynamic characterization of the seesaw actuated system, topographic images were acquired with the holder in the commercial AFM. One inherent difficulty encountered when imaging with this actuation method is that the displacement signal has two components: cantilever bending due to the sample-tip interaction forces and the cantilever bending due to the chip rotation. So, a deflection signal is recorded by the photodiode even when there is no actual deflection from a tip-surface interaction. This problem was previously addressed for piezoelectric driven cantilevers by subtracting a signal proportional to the actuation signal from the deflection signal in the feedback loop.[3] This method was implemented in the seesaw imaging setup. To demonstrate topographic imaging capabilities, a calibration sample

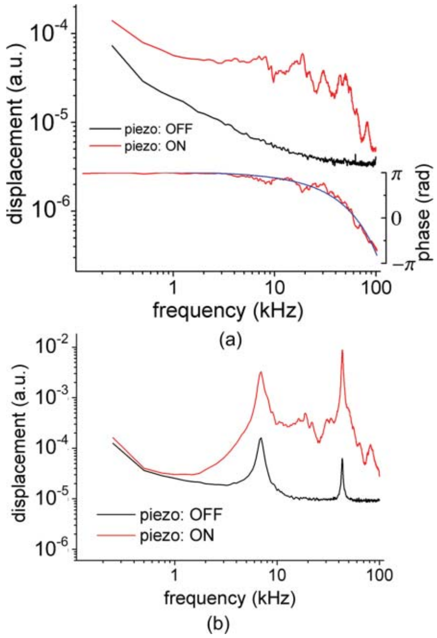

FIG. 3. (Color online) Frequency response of (a) a cantilever chip (b) a cantilever (Veeco MLCT-C) measured using an AFM system (Veeco Dimension 3100). The seesaw holder was put onto the pins of the AFM head. The optical lever sensor of the AFM system was used to gather data when the seesaw holder's piezo was turned off and on. The piezo actuator was driven with a white noise.

(APCS-0001, Veeco Instruments Inc.) was used with 100-nm-deep artifacts and a period of 1 μm. Figure 4(a) shows the line scans obtained with the conventional piezo scanner of the dimension AFM in contact mode. We optimized the feedback parameters for each method of actuation and for different scan rates. Distortion can easily be observed when the scan rate is larger than 20 Hz with the slow piezo scanner. There are also distortions on the sample imaged using the seesaw actuator with optimized feedback parameters as shown in Fig. 4(b); however, the seesaw actuator was able to follow the steps even at 30 and 60 Hz scan rates with acceptable accuracy based upon visual inspection.

There are many ways to improve upon the design of the seesaw-actuated system in order to improve imaging quality and bandwidth. Compliance issues in the holder due to the relatively soft nature of the SLA resins used in the fabrication of the holder can be removed by machining a holder out of steel or some other easily machined metal using electric discharge machining (EDM) or other such high resolution technologies. A more rigid holder reduces the dissipation of energy from the actuation piezo into the holder itself, allowing for cleaner displacement of the cantilever chip. Alignment of the cantilever chip in the holder is another serious issue that needs to be addressed with further design iterations. A significant corrective step would be to use micromachining to implement cantilever and chip structures that decouple tip-sample interactions from the cantilever actuation, thereby avoiding electronic correction in the feedback loop as mentioned earlier. An example of these structures has been implemented by Beyder and Sachs for in-fluidic applications.[11] The key to this design is the hinged structure upon which the tip is fabricated. The axis of actuation is perpendicular to the axis

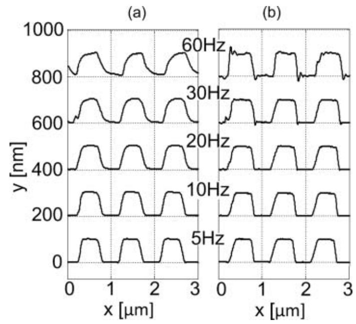

FIG. 4. Contact-mode line scans of a calibration sample obtained at different speeds. The sample was imaged using (a) the z-piezo of the commercial AFM system and (b) the seesaw holder with the same feedback settings. The calibration sample is a 100-nm-thick diffraction grating with a period of 1 μm.

of detection that effectively decouples the dynamics of the tip from the actuator, allowing for the separate measurement of the motion of each of these components. A batch microfabricated version of the seesaw actuated cantilever would allow for the implementation of a similar structural element to decouple the tip/actuator motions, would make alignment of the structure more controllable and repeatable, and would provide larger displacement gains because of the lithographically determined hinge location as opposed to the operator alignment setting the gain as in the current design.

In summary, a method for fast cantilever actuation in AFM with large displacement range is demonstrated. In contrast to the standard piezo tube combined with tapping piezo approach, this method uses fast piezo transducers and a seesaw mechanism to provide the range necessary for large scale displacements with high actuation bandwidths. A prototype holder was machined that demonstrated the described concept and allowed us to use this system in a conventional AFM setup. Characterization results that were obtained with the holder were presented and topographic images were gathered using the seesaw actuation method.

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