Calibration of piezoelectric bimorphs for experiments in a surface forces apparatus

Sung Chul Bae and Steve Granick[a)]
Departments of Materials Science, Chemical Engineering and Chemistry, University of Illinois, Urbana, Illinois 61801

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A simple interferometric method is described to measure the time-dependent deformation of piezoelectric bimorphs driven by ac voltage. Applying this method to a bimorph assembly used to measure viscoelastic forces in a surface forces apparatus, we find that a sinusoidal-shaped harmonic drive voltage generates sinusoidal deformation but that a triangular-shaped harmonic drive voltage fails to produce triangular-shaped deformation if the drive frequency exceeds 1/100 of the resonance frequency. Sinusoidal displacement amplitudes as small as 0.1 nm were resolved.
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The ability of piezoelectric bimorphs to produce controlled displacements over a wide range of amplitudes, from sub-angstrom to micrometers, is invaluable in scanning probe microscopies such as scanning tunneling microscopy (STM), atomic force microscopy (AFM), and the surface forces apparatus (SFA).[1–4] A frequently adopted calibration strategy is to image a crystalline lattice whose lattice dimensions are known. Since this strategy does not apply to SFA experiments, which do not image laterally, it has been customary to calibrate these devices by measuring the deflection produced by an applied dc voltage. Usually the dc voltage is chosen to be sufficiently large to produce deflections visible in an optical microscope.[4] The assumption is that, in response to a time-varying input voltage $V(t)$, the output deformation, $D(t)$, is $D(t) = \alpha V(t)$.

There are two difficulties with this traditional method of calibration. First, since these voltages are typically 1–2 orders of magnitude larger than would be employed in an experiment designed to probe displacements on the angstrom and nanometer length scales, it is fair to question linearity of response. Second, since the measurements are typically dynamic but the calibration is static, it is fair to question whether the calibration might itself depend on frequency. Here we describe a simple alterative calibration method that responds to both concerns.

A schematic diagram of the optics used for interferometric calibration is shown in Fig. 1. This Twyman–Green interferometer is a variation of the traditional Michelson interferometer.[5] A 2 mW He–Ne laser (Melles Griot 05LHP121) was used as the light source. It had a linear polarization and the beam size was 0.59 mm at $1/e^2$ intensity. A spatial filter (Thorlabs, KT300-B) was used to expand the beam size and produce a clean Gaussian beam. It was composed of an aspheric lens whose focal length was 11 mm, a 25 μm pinhole, and a collimating lens whose focal length was 50 mm. The beam size was expanded ~4.5 times using these components. A beamsplitter (CVI, BS1-633-50-1037-45P) divided the incoming beam into two, one segment traveling to the fixed mirror M1 and one to the mirror M2 attached to the bimorph whose calibration was intended. The bimorph assembly has been described elsewhere;[4] in brief, a specimen hangs as a ‘‘boat’’ from two piezoelectric bimorphs.

The two beams were reflected by mirrors and returned to the beamsplitter, the beam from M1 passing through the beamsplitter and the beam from M2 being deflected by the beamsplitter toward the detector. Here the two beams met and the resulting interference pattern was imaged, as shown schematically in Fig. 1.

A 200 μm slit was positioned at maximum interference irradiance and a Si photodiode detector (Thorlabs, PDA55) was used to monitor the irradiance changes caused by the displacement of mirror M2 attached to the moving bimorph. Provided that the two beams are coherent and have equal irradiances I_0, the interference irradiance I at this position can be written as[5]

$$I = 4I_0 \cos^2 \frac{2\pi(2D)}{2\lambda} = 2I_0 \left\{ 1 + \cos\left(\frac{4\pi D}{\lambda} \right) \right\}, \qquad (1)$$

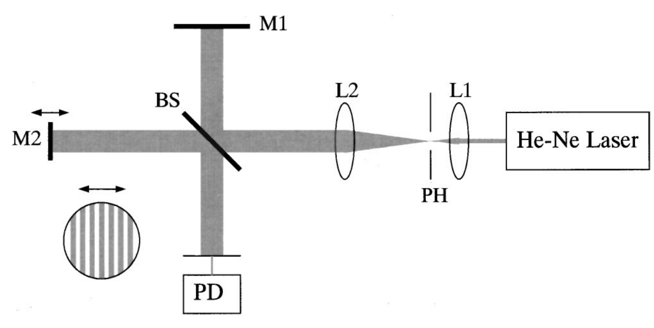

FIG. 1. Schematic diagram of the interferometric setup for bimorph calibration. Laser light passed through an aspheric lens L1 (focal length 11 mm), a pinhole (PH) (diameter 25 μm), a collimating lens L2 (focal length 50 mm), and was separated by a beamsplitter (BS). One portion passed to a fixed mirror M1, another portion to a moving mirror M2 rigidly attached to the moving bimorph, and the interference fringes produced by the reflection recombined beams was imaged on a photodiode (PD). The interference fringes oscillated with the bimorph motion as sketched in the bottom left of this figure.

[a)]Electronic mail: sgranick@uiuc.edu

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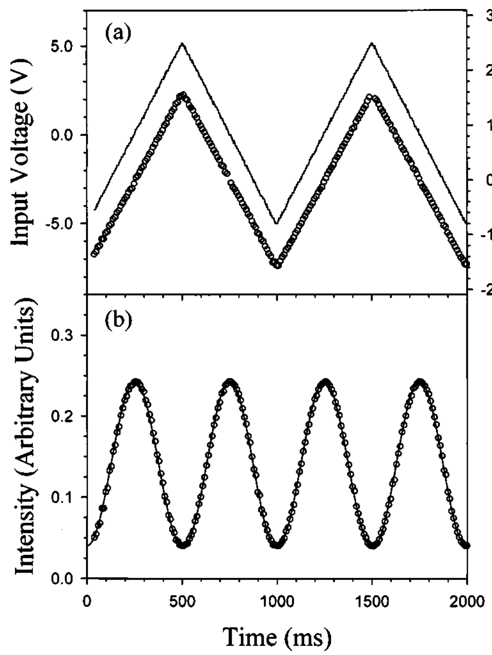

FIG. 2. Examples of photodiode signal and bimorph motion at 1 Hz. A triangular-shaped input voltage was applied (a, left ordinate axis), producing modulation of interference fringes that was sensed as a sinusoidally varying intensity of signal at the photodiode. Using Eq. (3), the bimorph deflection was calculated (a, right ordinate axis).

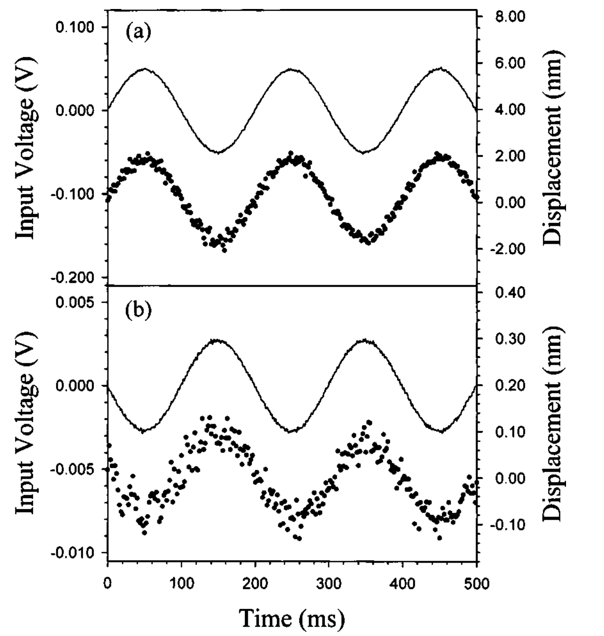

FIG. 3. Bimorph response to 5 Hz sinusoidal input voltage of 50 (panel a) and 2.5 mV (panel b) after averaging for 20 and 300 cycles, respectively. The input waveform is plotted on the left ordinate and the resulting bimorph deflection, calculated from the photodiode signal (not shown) using Eq. (3), is plotted on the right ordinate. Displacements of 2.0 and 0.1 nm were easily resolved.

where D is the displacement of M2 from the position it takes in the absence of driving voltage, and λ is the wavelength of the laser beam, 632.8 nm. Considering the offset and the gain of the photodiode detector, the photodiode signal intensity S can be written as

$$S=S_0+GI=S_0+2GI_0+2GI_0\cos\left(\frac{4\pi D}{\lambda}\right)$$
$$=a+b\cos\left(\frac{4\pi D}{\lambda}\right), \tag{2}$$

where S_0 is the signal offset and G is the gain of the photodiode. Then the temporal oscillation period of the signal corresponds to a displacement of amplitude $\lambda/2$.

Figure 2 shows an example of operation of this device. A triangular-shaped waveform was applied with amplitude 5 V and frequency 1 Hz. The photodiode signal [Fig. 2(a)] showed the expected sinusoidal waveform and this was fit to Eq. (2). The fit yielded a period of 0.488 s. During this period, the displacement of M2 should be $\lambda/2=316.4$ nm with corresponding voltage change 9.76 V, from which we deduce that the voltage constant for this bimorph assembly was $\alpha=32.4$ nm/V. The voltage constant obtained from a conventional calibration[4] (100 V_{dc} input and using an optical microscope to measure resulting deflection) was 30.8 nm/V. Our result agrees with this value within 5%, showing that the bimorph assembly is remarkably linear up to very high voltage.

One of the advantages of this interferometric method is that it shows directly the bimorph's motion. From Eq. (2), the bimorph displacement can be written as

$$D=\frac{\lambda}{4\pi}\arccos\left(\frac{S-a}{b}\right). \tag{3}$$

From the data in Fig. 2, the constants a and b were found to be 0.1417 and 0.1013, respectively. Using these constants,

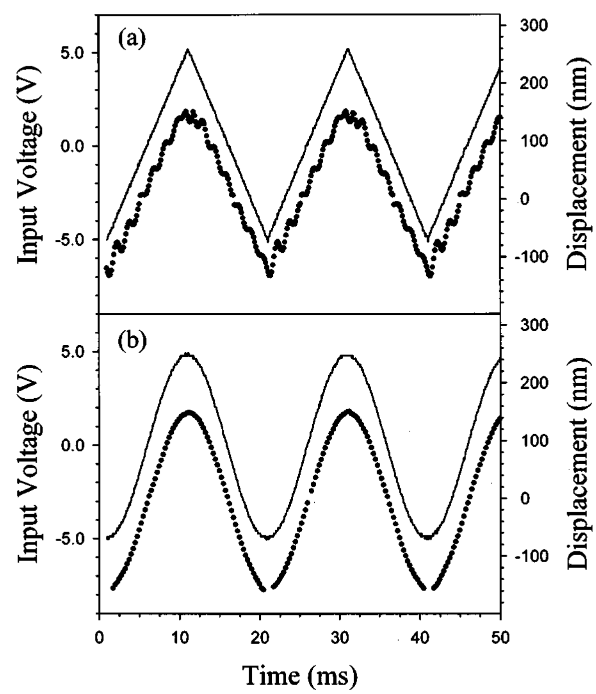

FIG. 4. Comparison of bimorph response to sinusoidal and triangle-shaped waveforms at 50 Hz, which is closer to the apparatus resonance of 660 Hz. (a) A triangle-shaped waveform, (b) a sinusoidal waveform. For both, the input waveform is plotted on the left ordinate and the resulting bimorph deflection, calculated from the photodiode signal (not shown) using Eq. (3), is plotted on the right ordinate.

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we calculated the displacement of the bimorph, with results included in Fig. 2(a). (Similar results were obtained using sinusoidal input voltages.) It is evident that the traditional assumption, $D(t) = \alpha V(t)$, was satisfied in this instance.

In order to check the sensitivity of this method, we applied progressively smaller sinusoidal input voltages, with amplitude as small as 2.5 mV. After averaging over 300 cycles, sinusoidal shear displacements as small as 0.1 nm could be resolved, as illustrated in Fig. 3.

Figure 4 compares the response at higher frequency, 50 Hz, which is closer to the resonance frequency, 660 Hz, of this bimorph assembly. In this case a large difference was observed when comparing sinusoidal and triangular-shaped waveforms. In the former case [Fig. 4(a)] the motion of the bimorph was smooth and followed the same sinusoidal function as the input voltage, but in the latter case the motion was jittery. Jitter can be explained by the discontinuity of applied force at the turning point of a triangular waveform; the discontinuity induces vibrations within the moving bimorph. In Fig. 4(b), one observes that the frequency of jitter is the resonance frequency of this bimorph assembly. Other experiments confirmed that the magnitude of jitter increased with drive frequency (as can be expected since the force discontinuity at the turning point increases with frequency). Other parts of the device had a bandwidth sufficient to not affect the results presented.

It is conceivable that jitter of the kind illustrated in Fig. 4 might also be a concern in scanning AFM measurements and in SFA experiments that employ triangular-shaped voltage waveforms. The magnitude of the effect would be damped, however, if the tip were in sliding contact with a solid surface.

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