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For a piezoelectric device with multiple electrodes, it should be possible to quantitatively and conveniently measure the piezoelectric coefficient d_{31} by use of the double piezoelectric effect, without the need for any unusual apparatus or a calibration sample. One pair of electrodes is used to excite the piezo, and another is used to measure the response. For example, for a piezoelectric tube this should allow measurement of d_{31} as a function of temperature or of lateral offset voltage. An important correction to the current theory is described. Measurements on two piezo tubes are presented for excitation voltages in the range of 0.5–110 V_{pp}. An inductive proximity sensor was used to measure the actual piezo motion. It is shown that the current theory disagrees with this and previous experiments by a simple factor of 2 for symmetric excitations. However, for asymmetric excitations the disagreement with theory is more complex, and the current theory does not accurately predict the effects of varying tube geometry.
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I. BACKGROUND

A material is piezoelectric if the application of an external mechanical stress induces an internal dielectric displacement. The internal dielectric displacement creates an external surface charge (the direct piezoelectric effect). The reverse process is also possible; an imposed external surface charge (or electric field) induces a mechanical stress in piezoelectric materials (the converse piezoelectric effect).[1]

It is relatively easy to make actuators from piezoelectric ceramics so that a 1 V change in the applied voltage causes a converse piezoelectric deflection of less than 10 nm. Thus the converse piezoelectric effect is well suited to provide the fine control needed for a scanned probe microscope (SPM). Unfortunately, piezoelectric ceramics exhibit a wide variety of undesired effects, including creep, hysteresis, nonlinearity, and aging. Further, the magnitude of the converse piezoelectric effect varies with temperature and frequency. Thus, at a minimum it is usually necessary to regularly check the calibration of the SPM piezo actuator using a sample with known dimensions.

In 1992, Julian Chen[2] suggested a method for *in situ* calibration of the piezo actuator by using one electrode to create a deflection (with the converse piezoelectric effect) and a second to measure the deflection (with the direct piezoelectric effect). This combination is referred to as the "double piezoelectric effect." In practice, an ac excitation is applied, and the charge developed on the sensing electrodes is measured with a current meter which holds the sensing electrode(s) at virtual ground.

The most common actuator for SPM use[3] is a hollow piezoceramic tube with longitudinally quartered electrodes on the outside and a continuous electrode on the inside. If the voltages on all four outer electrodes ($+x$, $-x$, $+y$, and $-y$) are increased by the same amount ΔV, the length of the tube decreases by[4]

$$\Delta z=\frac{L}{h}d_{31}\Delta V, \tag{1}$$

where L is the tube length, h is the wall thickness, and d_{31} is the piezoelectric coefficient. This uniform application of voltages is used by the feedback circuitry to regulate the spacing between tip and sample. (Here we have assumed the usual poling direction for the ceramic.)

When a positive ΔV is applied to the $+x$ electrode only, with the other voltages held constant, the $+x$ side of the tube tends to contract, causing bending of the tube and lateral translation of the tube end. By simultaneously applying a negative ΔV to the $-x$ electrode, the lateral translation can be doubled. This is the mode used to raster the scanned probe tip over the sample, in order to generate an image. Chen[4] has shown that if one end of the tube is kept fixed, the resulting displacement of the other end is given by

$$\Delta x,\Delta y=\frac{2\sqrt{2}L^2}{\pi Dh}d_{31}\Delta V, \tag{2}$$

where D is the tube diameter.

Chen[2] has analyzed three different configurations for the double piezoelectric effect. In the "symmetric" configuration, equal voltages are applied to the $+y$ and $-y$ electrodes and the current is measured from one of the x electrodes, with the other x electrode connected to ground. In the "adjacent" configuration, the excitation voltage is applied to a y electrode and the current is measured from an x electrode, with the other electrodes grounded. Finally, in the "opposite" configuration, the voltage is applied to a y electrode and the current is measured from the opposite y electrode, with the other electrodes grounded. (Of course, it is possible to interchange the roles of x and y for any of these configurations.)

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He assumes that the wall thickness h is much smaller than the tube diameter D. For the opposite and adjacent configurations, for which the excitation voltage is applied to only one electrode (the $+y$ electrode, for example), Chen assumes that the magnitude of the stress depends linearly on the corresponding spatial coordinate (for example, stress depends linearly on y).

Chen calculates that, for an applied sinusoidal voltage at frequency f with amplitude V_{p-p}, the double piezoelectric current is given by

$$I_{p-p}=\gamma\frac{DLY}{h}(d_{31})^2 f V_{p-p}, \tag{3}$$

where Y is the Young's modulus of the ceramic, L is the tube length, d_{31} is the piezoelectric coefficient, and γ is a constant which depends on the configuration:

$$\begin{aligned} &\text{symmetric: } \gamma=\pi^2/4,\\ &\text{adjacent: } \gamma=\pi^2/8, \\ &\text{opposite: } \gamma=\pi/2-\pi^2/8\cong 0.337. \end{aligned} \tag{4}$$

However, there is a calculational error in Ref. 2 for the opposite configuration. The correct values given the above assumptions are

$$\begin{aligned} &\text{symmetric: } \gamma=\pi^2/4,\\ &\text{adjacent: } \gamma=\pi^2/8, \\ &\text{opposite: } \gamma=2-\pi^2/8\cong 0.766. \end{aligned} \tag{5}$$

In previous work,[5,6] the double piezoelectric effect has been used qualitatively to measure the resonant frequency of piezo tubes. Additionally, Chen[2] performed quantitative experiments at low excitation voltages (1 V excitation), using a PZT-4 tube with L=25.4 mm, D=12.7 mm, and h=0.50 mm. He found the linear dependence on frequency predicted by Eq. (3). However, there is a significant discrepancy between the magnitude of the current he measured and the theoretical prediction. For the symmetric configuration with a 1 kHz excitation, he measured an average double piezo current which was 51% of the theoretical value. For the adjacent configuration, he measured 52% of the predicted current. For the opposite configuration, he measured only 22% of the current predicted by the corrected theory [Eqs. (3) and (5)].

II. EXPERIMENTAL METHODS

We performed measurements on two different piezo tubes (Stavely Sensors), both made from the ceramic PZT-4. The "small" tube had outer diameter D=6.3 mm, length L=14.6 mm, and wall thickness h=0.51 mm. The "large" tube had outer diameter D=12.7 mm, length L=24.6 mm, and wall thickness h=0.76 mm. (This is very similar to the tube used by Chen, but with 50% larger wall thickness.)

The theory also assumes no deformation of the mouth shape of the free tube end. To ensure this condition, we securely epoxied this end to a 1.5-mm-thick alumina plate, cut slightly larger than the tube o.d.

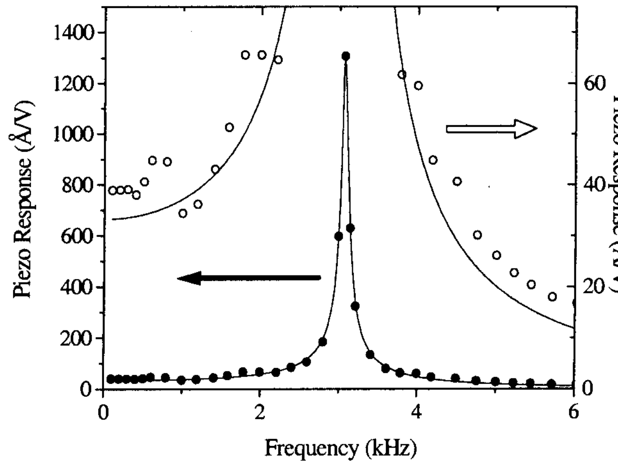

FIG. 1. Solid circles (left vertical axis): measured lateral deflection for the large tube as a function of frequency for an 80 V_{pp} drive voltage applied to the $+y$ electrode with all other electrodes grounded. The solid line is a fit to a damped driven harmonic oscillator with resonant frequency of 3069 Hz and Q=39. Hollow circles (right vertical axis): same data replotted to show the behavior away from resonance.

The theory assumes that the other end of the tube remains fixed. We found that to achieve reproducible results, it was essential to anchor this end extremely firmly. Each tube in turn was securely epoxied to the top of a much more massive stainless steel cylinder (5 cm diameter, 3.8 cm length), which in turn was tightly clamped to a small platform. The platform was suspended from latex tubing for vibration isolation.

For the large tube, numerous resonances persisted despite these measures, preventing the observation of a clear double piezoelectric current at the drive frequency. To eliminate these resonances, we epoxied stainless steel washers with a mass of 7.13 g to the alumina plate on the free end, and filled the interior of the piezo with silicone adhesive. These measures also reduced the fundamental resonant frequency, as discussed below.

We measured deflections of the end of the piezo tube using an inductive proximity sensor (Bentley Nevada model 3300) with a bandwidth of 8 kHz, which was also mounted on the vibration isolation platform. Figure 1 shows the results for an asymmetrical (voltage applied to $+y$ electrode only) excitation of 80 V_{pp} for the large tube, showing the main resonance at 3.1 kHz. Similar measurements for the small tube gave a main resonance frequency of 6.2 kHz. Since the double piezoelectric effect theory is intended to be used only at frequencies well below resonance, we limited our measurements of the double piezoelectric current to frequencies of 1.6 kHz and below. Clearly, this is not "well below resonance" for the large tube, and some deviations are apparent in the upper end of our measured frequency range. However, the qualitative trends are consistent at all frequencies.

We used the proximity sensor to measure d_{31} for longitudinal (same voltage applied to all outer electrodes) and asymmetrical (voltage applied to $+y$ electrode only) excitations. We performed these measurements over a frequency range of 250 Hz–1.6 kHz, using excitation voltages over the range 20–110 V_{pp}. We found little variation of d_{31} for lon-

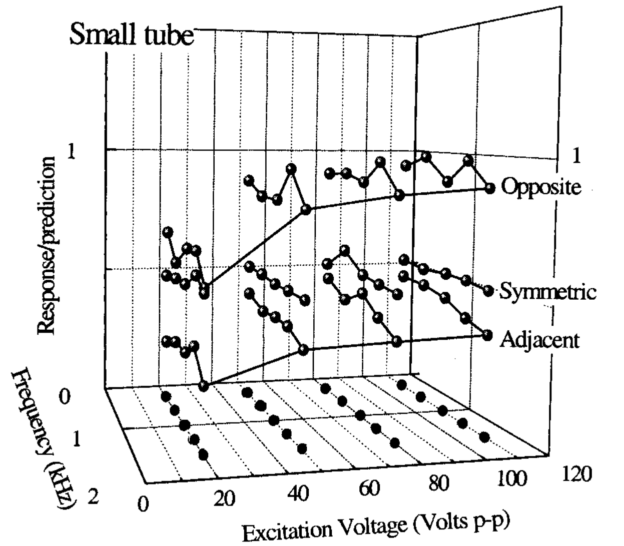

FIG. 2. Measured double piezoelectric current divided by the theoretical prediction for the *small* tube as a function of excitation frequency for excitation voltages of 20, 50, 80, and 110 V_{pp}. Measurements were taken at frequencies of 295 Hz, 655 Hz, 1.0 kHz, 1.3 kHz, and 1.6 kHz. The theoretical prediction is calculated using Eqs. (3) and (5) and the value measured experimentally for d_{31} at each frequency and drive amplitude. The dark circles at the bottom show the projections of the data points onto the bottom plane.

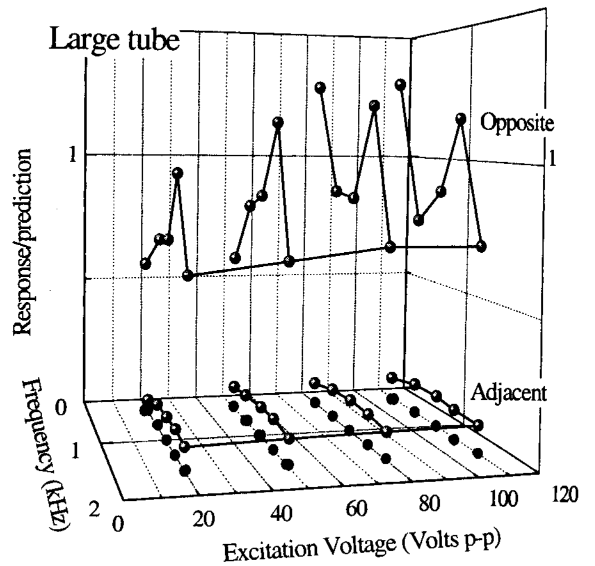

FIG. 3. Measured double piezoelectric current divided by the theoretical prediction for the *large* tube as a function of excitation frequency and excitation voltage. (Measurements were taken at the same voltage and frequency values as for Fig. 2.) The variations are much larger than the system noise, which is typically ±15%.

gitudinal excitations within these ranges. For the small tube, we found $d_{31}=1.23$ Å /V excitation [using Eq. (1)], which is quite close to the nominal value of 1.27 Å /V quoted by the manufacturer. For asymmetrical excitations, the variation with drive frequency and amplitude was much larger, ranging from 1.1 to 1.5 Å /V for the small tube and 1.1 to 1.8 Å /V for the large tube. [Equation (2) was used to calculate d_{31} from the measured displacements.] Some of this variation may be due to mechanical resonances, although it is difficult to understand why the variation is so large at these relatively low frequencies. These measured frequency- and amplitude-dependent values of d_{31}, together with the manufacturer's quoted value for the Young's modulus ($Y=8.1\times10^{10}$ N/m^2), were used for comparison with theory (Figs. 2 and 3).

For voltages below 20 V_{pp}, the proximity sensor was not able to accurately measure the deflection. Therefore, to analyze the data we acquired at these smaller voltages we used the d_{31} measured at 20 V_{pp}.

III. RESULTS

For the symmetric configuration, our findings match well with the experimental results of Ref. 2: the measured double piezo response is approximately half that predicted by theory over the entire range of voltage (0.5 V_{pp}–110 V_{pp}) and frequency (300–1600 Hz), as shown by the middle set of curves in Fig. 2.

For the adjacent configuration, Chen[2] measured 52% of the theoretical current. For the small tube, our results are qualitatively similar (Fig. 2), although we find a significantly smaller value at low excitation voltages (average of 25% of prediction for voltages from 0.5–20 V_{pp}). For the large tube, however, we measure only about 7% of the predicted current (Fig. 3). For both tubes, the response versus voltage increases slightly faster than the predicted $I\propto V$.

For the opposite configuration at the lower voltages (0.5–20 V_{pp}), we measure an average of 60% of the predicted current for the small tube, in contrast to Chen's measurement of 22%. As the excitation voltage is increased, we again find a stronger than linear dependence of the double piezoelectric current. At the highest voltage (110 V_{pp}), we measure an average of 95% of the predicted current for the small tube.

For the large tube, the opposite configuration shows a large variation in the current (Fig. 3, top set of traces). This variation is not due to experimental noise, which is typically ±15% (95% confidence limits). It is likely that some of the variation, especially that at 1.6 kHz, is associated with mechanical resonances, however the degree of variation at 1 kHz and below is surprising.

IV. DISCUSSION

The *qualitative* behavior of our data is well described by the theory; the measured double piezoelectric current increases proportionally with the applied excitation voltage, and generally increases with frequency. However, there are significant quantitative discrepancies for all three measurement geometries. It seems likely that the assumptions made in deriving[2] Eqs. (3)–(5) about the elastic behavior of the piezo tube may not be accurate.

Our data for the adjacent configuration, and also that of Chen, suggest that when the excitation is applied the stress distribution on the adjacent electrodes is surprisingly symmetrical, leading to a smaller than expected response current. Our results, combined with those of Chen, make it clear that the theory does not adequately account for the effects of tube geometry for the adjacent and opposite configurations. For the opposite configuration, we find similar results (in comparison to theory) for the small and large tubes. However, although our large tube has virtually the same dimensions as that used by Chen (ours has a 50% thicker wall), Chen measures a dramatically *lower* current (as compared to theory) for the opposite geometry. For the adjacent geometry, Chen measures a much *higher* current (as compared to theory) than we do. These comparisons show clearly that the effect of variations in the wall thickness is not accurately treated by the theory.

For the symmetric configuration, the theory accurately treats the variations caused by tube geometry, although it consistently predicts a current twice as high as that measured. Our experimental results, together with those of Chen, suggest that the correct value of γ for the symmetric configuration is $\pi^2/8$, rather than $\pi^2/4$.

For many applications, use of the symmetrical configuration should provide a convenient and reliable method for *in situ* measurement of d_{31}, using the empirically determined value of $\gamma=\pi^2/8$. For example, the variation as a function of temperature could be measured easily. Our results show that the theory in this case is correct even for relatively high drive voltages.

However, it should also be possible to use the double piezoelectric effect to measure the nonlinearity of the piezo for lateral deflections. (For example, a dc offset would be applied to $+x$, a corresponding negative offset to $-x$, and then the double piezoelectric effect used to measure d_{31} as a function of the offset.) Our experiments clearly indicate that the current theory does not adequately describe the double piezoelectric effect for such deflections. Further experimental work is needed to ascertain the functional form of the variations with tube geometry, and further theoretical work is needed to describe the experimental results accurately.

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