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Calibrating a tuning fork for use as a scanning probe microscope force sensor

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Quartz tuning forks mounted with sharp tips provide an alternate method to silicon microcantilevers for probing the tip-substrate interaction in scanning probe microscopy. The high quality factor and stable resonant frequency of the tuning fork allow accurate measurements of small shifts in the resonant frequency as the tip approaches the substrate. To permit an accurate measure of surface interaction forces, the electrical and piezoelectromechanical properties of a tuning fork have been characterized using a fiber optical interferometer. © 2007 American Institute of Physics.

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I. INTRODUCTION

Originally designed for high precision frequency control, ¹⁻⁴ quartz tuning forks are widely used in clocks, watches, and other frequency standards. Most of the commercial tuning forks have a standard resonant frequency of 2¹⁵ Hz=32.768 kHz. Recently, it has been shown that quartz tuning forks can be used with great advantage as force detectors in scanning probe microscopes (SPMs). They are robust and extremely stable in frequency compared to conventional SPM cantilevers. Their high mechanical quality factor makes them sensitive to piconewton shear and normal forces. The piezoelectric effect of quartz crystals, which yields an electrical signal proportional to deformation, makes the measurement of the amplitude of oscillation very simple compared to an optical beam bounce measurement scheme. In addition, they can be directly excited to vibrate by applying an ac voltage to the tuning fork electrodes. Hence the need for a separate dither piezodriver, commonly found in microcantilever-based SPMs, is unnecessary. Due to these advantages over conventional SPM force probes, tuning forks have been successfully used as force sensors in SPM, yielding atomic resolution images at low temperature and ultrahigh vacuum.^{5–7}

To measure the tip-substrate interaction force accurately, it is critical to accurately calibrate the oscillation amplitude of a tuning fork force sensor. In prior studies, this was done by immobilizing one prong of the tuning fork, essentially turning the tuning fork into a cantilevered bar. This approach is often difficult to implement, since a large decrease in the probe's Q factor results if the immobilization of the one prong is not performed correctly. An alternate and somewhat simpler approach is to use a commercially available quartz tuning fork without the immobilization of any prongs, thus inherently retaining the high Q factor of the probe. In what follows, we further explore this latter possibility and describe a reliable calibration procedure.

In this article, we use an optical fiber interferometer to calibrate the oscillation amplitude of each prong of the tuning fork. In this way, a calibration can be performed on both prongs of the tuning fork which is valid even when a scanning probe tip attached to one prong breaks the symmetry. This technique allows an accurate determination of the amplitude of oscillation of the probe tip from a measurement of the current generated by the tuning fork. Furthermore, the mass manufacture of tuning forks guarantees an inexpensive (about \$0.25 per tuning fork) source of identical force sensors. Because of the high fidelity standards adopted during the fabrication of quartz tuning forks, our approach offers the promise of an inexpensive SPM resonator that can be used as a standardized force sensor between different laboratories.

II. THE QUARTZ TUNING FORK

An as-received quartz tuning fork is encased in a vacuum-sealed canister for commercial use; its quality factor can be as high as 40 000-50 000. When used as a SPM force sensor under ambient conditions, the metallic protective canister must be removed and the two prongs are exposed to air. To be useful as a force sensor, a sharp SPM probe tip must be attached to the end of one prong. Even when operating in air, a quartz tuning fork has two main advantages when compared to a conventional silicon microcantilever: (i) a high quality factor, which is still 8000-10 000 under ambient conditions and (ii) a high stiffness, which is on the order of 10³ N/m. The high quality factor allows the tuning fork to detect subhertz shifts in the resonant frequency; the high stiffness prevents the jump to contact of the tip when it approaches the substrate. While the high stiffness produces a large tip-substrate force, the tremendous improvement in frequency resolution enabled by the high Q factor leads to unprecedented force resolution even under ambient conditions.



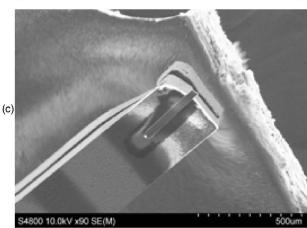


FIG. 1. (a) A schematic diagram of the quartz tuning fork used in this experiment illustrating the electrode arrangement. (b) A SEM photo useful for determining the dimension of the tuning fork. The placement of electrodes can also be inferred from this photo. The bright regions at the end of the tuning fork are due to e-beam charging effects. (c) A SEM image illustrating the placement of a SPM microcantilever on one end of the tuning fork prong.

A. Mechanical properties

The quartz tuning fork is conveniently viewed as two identical cantilevered bars coupled by a low-loss quartz bridge, as pictured schematically in Fig. 1(a). The normal mode vibrations of these two bars can be classified as in phase (symmetric) and out of phase (antisymmetric). The two eigenstates are an out-of-phase mode in which the oscillation of the two bars opposes one another and an in-phase mode in which the two bars oscillate together in unison. In the limit of zero coupling between the two bars, these two modes have degenerate eigenfrequencies. Coupling produced

TABLE I. Dimensions and nominal calculated mechanical values for a cantilevered bar from the Raltron model R26 tuning fork used in this study.

Raltron model R26 quartz tuning fork ^a					
Length (mm)	3.20 ± 0.05	Effective mass of bar	$2.72 \times 10^{-7} \text{ kg}$		
Thickness (mm)	0.40 ± 0.01	Spring constant of bar	12.7 kN/m		
Width (mm)	0.33 ± 0.01	$f_{\rm bar}$	34.39 kHz		
Density (kg/m³)	2650	Young's modulus (Pa)	7.87×10^{10}		

^aReference 8.

by the low-loss quartz bridge splits this degeneracy, pushing the antisymmetric eigenfrequency above its symmetric counterpart. A small mass added to one of the two bars reduces the symmetric eigenfrequency faster than the antisymmetric one. In the fabrication of quartz tuning forks, the asymmetric placement of the conducting electrodes [see Fig. 1(a)] prevents excitation of the in-phase resonance. In what follows, we will focus on the out-of-phase resonance which is of most interest for SPM applications.

The resonant frequency of a cantilevered bar can be calculated from the effective mass of the beam defined by $m_{\rm eff}$ =0.2427 $\rho \times Lwt$, where ρ is the density of quartz and L, w, and t are the length, width, and thickness of the beam. The spring constant k is given by $k = \frac{1}{4}Yw(t/L)^3$, where Y is Young's modulus for quartz. The calculated resonant frequency is then given by

$$f_{\text{bar}} = \frac{1}{2\pi} \sqrt{\frac{k}{m_{\text{eff}}}} = 1.015 \frac{t}{2\pi L^2} \sqrt{\frac{Y}{\rho}}.$$
 (1)

A Raltron model R26 tuning fork was chosen for this study. A series of scanning electron microscope (SEM) photos after removing the tuning fork from its protective canister [see Fig. 1(b)] were used to estimate the bar dimensions L, w, and t. Combinging these values with standard values for ρ and Y of quartz allows estimates for the relevant parameters (see Table I) characterizing this mechanical bar. Note that the influence of the mass added by the tuning fork electrodes is not included in these estimates.

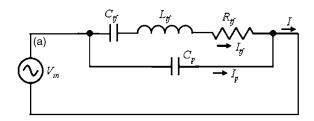
B. Electrical properties

Because of the piezoelectric properties of quartz, any mechanical oscillation of a bar (or prong) produces an electric potential difference across the prong. Equivalently, by applying a potential difference between the two prongs, a mechanical oscillation is produced. For the case of a tuning fork, the electrical properties of the antisymmetric mode of oscillation can be modeled by an energy equivalent electronic circuit shown in Fig. 2(a). Such a circuit is useful to understand the electrical properties of a tuning fork as a function of the drive frequency ω . 9,10

The conductance of this circuit can be written as

$$Y(\omega) = j\omega C_p + \frac{1}{R_{tf} + j\omega L_{tf} + 1/j\omega C_{tf}} = j\omega C_p + \frac{\omega^2 C_{tf}^2 R_{tf} + j(1 - \omega^2/\omega_0^2)\omega C_{tf}}{(1 - \omega^2/\omega_0^2)^2 + \omega^2 R_{tf}^2 C_{tf}^2},$$
(2)

where C_{tf} is the motional capacitance of the tuning fork, R_{tf} is the equivalent series resistance, and L_{tf} is the equivalent



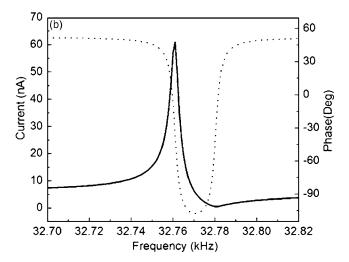


FIG. 2. (a) Electrical model of a quartz tuning fork. (b) The measured frequency response for the admittance (both phase and amplitude) of a quartz tuning fork in air after removal from vacuum-sealed canister when driven through resonance.

inductance. The circuit model of the tuning fork has a resonant frequency of $\omega_0 = 2\pi f_0 = 1/\sqrt{L_{tf}C_{tf}}$.

The capacitor C_p accounts for any parasitic capacitance from electrical contacts and connecting wires. Current through C_p breaks the symmetry of the frequency response curve, causing a noticeably asymmetric resonance response as measured in Fig. 2(b). Note that the resonant frequency of the tuning fork in air is measured to be 32.761 kHz rather than the 2^{15} Hz=32.768 kHz applicable when the tuning fork is housed in its vacuum-sealed canister. Although the current though a tuning fork accurately reflects the amplitude of oscillation of the tuning fork prongs, this quantity is often difficult to measure accurately because of the parasitic current through C_p .

When driven at a frequency away from resonance, the tuning fork's response is dominated by the parasitic capacitor C_p which has impedance $Z_p = (j2\pi f C_p)^{-1}$. The current through the parasitic capacitance produces a minimum in the admittance located at $f_p = f_0 \sqrt{1 + C_{tf}/C_p}$ and directly accounts for the lack of symmetry in the frequency response curve [see Fig. 2(b)].

The magnitude of the conductance given in Eq. (2) can be used to obtain explicit equations that describe the conditions for a maximum and a minimum in current. By measuring the frequencies and amplitudes at which these two conditions occur, four equations can be written to determine the four electrical parameters of the tuning fork under ambient conditions.

C. Piezoelectric properties

The piezoelectric properties of quartz provide a very convenient method to resonantly vibrate the tuning fork with an external voltage. For use as a force sensor in SPM, it is important to know the oscillation amplitude from the measured current generated by the tuning fork. For small amplitude of oscillation, the current produced by the tuning fork is linearly proportional to the amplitude of oscillation of the prongs because of the piezoelectric effect of quartz. To calibrate the tuning fork, an independent measure of the amplitude of oscillation of each prong is required. However, it is difficult to measure such small oscillation amplitudes (on the order of nanometers) directly. In a previous study, we attempted this calibration using a microcantilever of known spring constant. In what follows, we describe a more accurate and complete method involving optical interferometry.

When a quartz bar oscillates with an amplitude x at a frequency ω , the current is given by 9

$$i_{\text{bar}}(\omega) = \alpha \omega x(\omega),$$
 (3)

where α is the piezoelectromechanical coupling constant that describes the charge induced on the piezomaterial for a given mechanical deflection. ¹⁰ This constant is an intrinsic parameter of the quartz bar once the geometric size and crystal orientation of the bar are fixed. It will not change if a small additional mass, for instance, a SPM probe tip, is attached. ¹⁰ As indicated by Eq. (3), the constant α can be determined by measuring the current flowing through the bar while the mechanical oscillation amplitude is independently measured.

To use the tuning fork as a force sensor, a sharp SPM probe tip must be attached to one prong of the tuning fork. This additional mass breaks the symmetry of the coupled oscillation and the amplitudes of the two prongs will not be equal anymore. Suppose that prong B has a SPM cantilever (with tip) attached and is slightly heavier than prong A. As a result of this asymmetry, let the amplitudes of each prong be represented as $x_A(\omega)$ and $x_B(\omega)$, respectively. The total current generated is then given by

$$i_{\text{tot}}(\omega) = i_A(\omega) + i_B(\omega) = \alpha \omega [x_A(\omega) + x_B(\omega)].$$
 (4)

To accurately measure $x_B(\omega)$, one has to independently measure the oscillation amplitudes of *both* prongs which are still assumed to oscillate out of phase.

Once the coupling constant α of a quartz tuning fork has been determined, the electrical parameters (L_{tf}, C_{tf}, R_{tf}) of the tuning fork can be related to the mechanical properties (m, k, γ) using the following relations:

$$m = L_{tf} 2\alpha^2$$
, $k = 2\alpha^2/C_{tf}$, $\gamma = 2\alpha^2 R_{tf}$. (5)

III. EXPERIMENTAL DETAILS

Optical fiber interferometers have been used in SPM to detect the deflection of cantilevers for many years. ^{12–14} It has been proved that fiber optical interferometry is an ideal technique to measure small vibrations with subangstrom resolution.

The fiber optical interferometer used in this study consists of a laser diode with a wavelength of 1310 nm, a 2×2 optic fiber coupler, and a photodiode detector which is

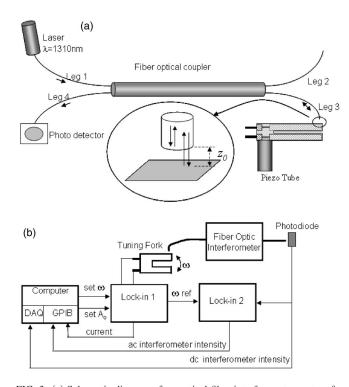


FIG. 3. (a) Schematic diagram of an optical fiber interferometer system for measuring the oscillation amplitude of a quartz tuning fork. The tuning fork is mounted on a standard piezotube which is used as a fine adjustment when setting the spacing between the end of the fiber optic and the top surface of the tuning fork prong. (b) The schematic diagram of the electronics used in the calibration experiments. The two lock-ins are EG&G model 7260. The DAQ card is an NI-6062E. The computer controlled data acquisition software was written in LABVIEW code.

sensitive to light with the wavelength of 1310 nm, as shown in Fig. 3(a). The optical fiber has a diameter of 8.2 μ m. The fiber optical coupler acts as a beam splitter, splits the incident laser beam from leg 1 into two-halves, and sends them to leg 2 and leg 3, respectively. At the end of leg 3, the fiber is cleaved at an angle of 0° to reflect some amount of beam back at the fiber vacuum-air interface. The transmitted beam leaves leg 3 and is reflected off the surface of the tuning fork located at a distance z_0 before it reenters leg 3 again. The two reflected beams interfere. After the intensity is reduced by half due to the coupler, the interfered beam travels to leg 4 and its intensity is measured by a photodiode.

A schematic of the electronics required to implement this interferometer scheme to calibrate quartz tuning forks is given in Fig. 3(b). A standard piezotube is used to vary the separation distance z_0 between the fiber optic end and one prong of the tuning fork. This variation in z_0 produces a periodic change in the reflected light intensity at the photodiode, giving a periodic signal, as plotted in Fig. 4.

To detect a small deflection of the tuning fork, the fiber-reflector separation z_0 should be adjusted to a value where the slope |dI(z)/dz| is a maximum to optimize the sensitivity. This operating point is designated by the point P shown in Fig. 4. When a small deflection δz of the cantilever occurs about the separation z_0 (assuming that the deflection satisfies $\delta z \ll \lambda$), the detected intensity will be given by

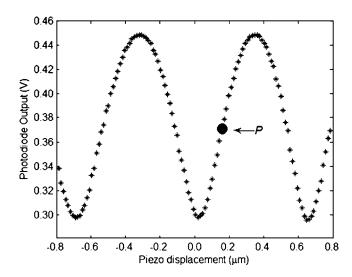


FIG. 4. The intensity of interfering optical beam oscillates with the separation between the fiber end and the reflector attached to the surface of a tuning fork prong. The working point should be located at point P where the slope is steepest.

$$I(z) = I(z_0) + \delta I(z) = I(z_0) + \left. \frac{dI(z)}{dz} \right|_{z=z_0} \delta z. \tag{6}$$

Therefore, for a sinusoidal vibration of the tuning fork prong,

$$A(\omega, t) = A_0 \sin(\omega t) \quad (A_0 \le \lambda), \tag{7}$$

the intensity will oscillate at frequency ω and the amplitude of its ac component will be given by

$$I_{\rm ac}(\omega) = \left[\left. \frac{dI(z)}{dz} \right|_{z=z_0} \right] A_0(\omega). \tag{8}$$

Using Eq. (8), one can then obtain the amplitude of oscillation A_0 by measuring the intensity with a phase sensitive detector.

IV. RESULTS

In order to increase the reflection of the laser light from each prong of a Raltron model R26-32.768 kHz, ± 5 ppm quartz tuning fork, identical silicon microcantilevers (ultrasharp μ Masch cantilever model CSC12/Cr-Au/50-E, $l=350~\mu\text{m},~w=35~\mu\text{m},~t=1~\mu\text{m};~\text{mass}~\cong 2.85\times 10^{-11}~\text{kg})$ were attached to the outermost surface of each prong using epoxy. The current measured for a 10 mV (rms) excitation under ambient conditions was measured, as shown in Fig. 5. Note that the resonant frequency of the tuning fork has shifted from 32.761 down to 32.566 kHz due to the attachment of the two microcantilevers.

These data can be used to accurately determine the electrical parameters of the energy equivalent circuit shown in Fig. 2(a). The results for R_{tf} , L_{tf} , C_{tf} , and C_p are summarized in Table II below, and the resulting fit to the experimental data is plotted as the solid black line in Fig. 5. Once the electrical parameters are known, it becomes possible to calculate the current through the tuning fork and through the parasitic capacitor. These results are also plotted in Fig. 5. As expected, once the effect of the parasitic capacitance is properly taken into account, the current through the tuning fork

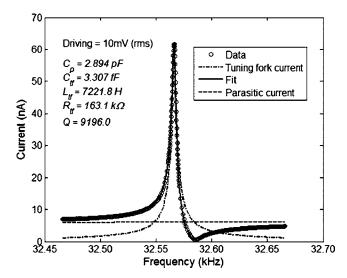


FIG. 5. An experimentally measured current as a function of frequency near resonance along with a fit to the data. A plot of the current through the parasitic capacitance and the current through the tuning fork calculated from the fitting parameters is also plotted.

reveals a symmetric resonance that can be directly related to the amplitude of oscillation of the two prongs of the tuning fork.

In order to determine the coupling constant α , the oscillation amplitude of each prong as well as the current through the tuning fork were measured using the setup shown in Fig. 3(b). The resonance curves measured for each prong using a 10 mV (rms) driving signal are essentially identical and are plotted in Fig. 6(a). As can be inferred from these data, $x_A(\omega)$ and $x_B(\omega)$ are essentially the same.

Using Eq. (4), the piezoelectromechanical coupling constant can be calculated at each frequency by comparing the sum of the measured oscillation amplitude from each prong to the current through the tuning fork within the frequency bandwidth [see Fig. 6(b)]. A histogram of the values obtained in this way is given in Fig. 6(c) and allows an estimate for α of 4.90±0.11 μ C/m.

The ultimate goal of this research is to use the freely oscillating tuning fork as a SPM force sensor. In order to achieve this goal, it is useful to eliminate in real time the

TABLE II. Nominal electrical values and inferred mechanical values measured for a Raltron model R26 tuning fork equipped with a microcantilever on each prong (Ref. 8).

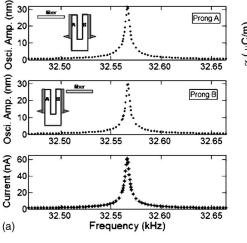
C_p (pF)	2.89	m (kg)	3.46×10^{-7}
C_{tf} (pF)	3.31×10^{-3}	k (kN/m)	14.52
$R(k\Omega)$	163	γ (kg/s)	7.83×10^{-6}
L_{tf} (kH)	7.222	Q	9196
f_0 (kHz)	32.566	Coupling constant α (μ C/m)	4.90 ± 0.11

asymmetry caused by the parasitic capacitance. If this is done, then the current through the tuning fork even when driven off-resonance can be used to accurately infer the tip oscillation amplitude.

To meet this goal, a circuit was designed, as shown in Fig. 7(a). The driving signal of the tuning fork has 180° phase difference from the voltage source applied to the compensating capacitor C. By adjusting the variable capacitor C to the proper value, the current through it exactly cancels the current through the parasitic capacitance and a symmetric resonance curve can be obtained, as plotted in Fig. 7(b). It is evident that the circuit effectively eliminates the asymmetric conductance due to the parasitic capacitance. By incorporating this circuit directly into any SPM head, it becomes possible to directly measure the symmetric current resonance of a driven quartz tuning fork and using the values of α obtained in this study, the amplitude of oscillation of each prong can be inferred from the tuning fork current.

Finally, to establish whether the above calibration applies for any tuning fork of the same make and model, five additional quartz tuning forks (labeled 2–6) chosen randomly from a shipment of 50 were carefully calibrated as discussed above. A microcantilever was again attached to each prong of the tuning fork to allow a measurable signal from the fiber optic interferometer. During this sequence of experiments, an effort was made to apply a minute amount of epoxy when compared to the results presented for tuning fork 1 above [see Fig. 1(c)]. With practice, this procedure only required ~5 min per tuning fork and produced considerably smaller frequency shifts than observed for the first tuning fork studied.

Following the procedure discussed above, the results for



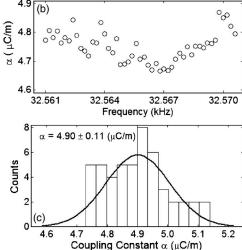


FIG. 6. (a) The oscillation amplitude of each prong of a quartz tuning fork with a Si microcantilever attached to each prong. The current flowing through the tuning fork as a function of drive frequency is also plotted. For clarity, only every fourth data point acquired is plotted. (b) The point-bypoint determination of the coupling constant α over the bandwidth of the resonance. (c) A histogram plot of the piezoelectromechanical coupling constant deduced from these data. A Gaussian fit enables a reliable estimate for the coupling constant α .

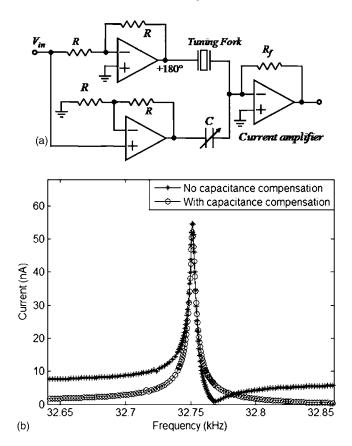


FIG. 7. (a) The detection circuit for a tuning fork force sensor to eliminate the asymmetry in the resonance curve. (b) The frequency response of the current through a quartz tuning fork with an applied driving signal $V_{\rm in}$ of 10 mV (rms). The curve with stars shows the current through tuning fork without the parasitic capacitance compensation circuit. The curve with open circles shows the current fed into the current-voltage amplifier shown in Fig. 8(a). The current is only due to the oscillation of the quartz tuning fork.

all six tuning forks investigated during this study are collected in Table III. This table indicates that the calibration is reproducible between different tuning forks of the same make and model.

V. AN UNBALANCED FORCE SENSOR

Undoubtedly, the great benefit of the tuning fork geometry is the high Q factor which is inherent in the mechanical

design of the device. To utilize the high Q, it is usually assumed that both prongs must be precisely matched. For use in scanning probe microscopes, a tip must be attached to one prong and this tip must then interact with the substrate, resulting in a small force imbalance between the two prongs. The mass of the tip mounted on one prong and the interaction of this tip with a sample break the symmetry of tuning fork geometry, allowing some uncertainty in its use. By firmly fixing one of the two prongs to a massive baseplate, Giessibl has pioneered one way to circumvent this problem, effectively transforming the tuning fork symmetry into a cantilevered beam. 6

However, using the results above, it is possible to use a tuning fork as a calibrated force sensor with a tip attached to one prong. To demonstrate this possibility, a number of tests were performed in which an additional microcantilever was added to one prong (prong B in what follows) of the tuning fork, essentially breaking the mass symmetry between the two prongs. For these tests, we estimate that the mass of the microcantilever plus glue is $\sim 10^{-10}$ kg and we anticipate a corresponding shift in the resonant frequency that is larger than encountered in the studies summarized in Table III.

For a given applied voltage $V_{\rm in}(\omega)$, the current measured through the tuning fork as a function of frequency will be given by Eq. (4) above,

$$i_{\text{tot}}(\omega) = i_A(\omega) + i_B(\omega) = \alpha \omega [x_A(\omega) + x_B(\omega)]$$

. If the tuning fork is to be of any use in SPM, we need to infer an accurate value for $x_B(\omega_o)$ when only values for the resonance frequency ω_o and the total in-phase tuning fork current $i_{\rm tot}(\omega_o)$ are experimentally measured. At resonance, the conductance of the tuning fork is just $1/R_{tf}$ and the amplitude $x_B(\omega_o)$ can be estimated from

$$x_B(\omega_o) = \frac{1}{\langle \alpha \rangle 2 \pi f_o} \left[i_{\text{tot}}(\omega_o) - \frac{1}{2} \frac{V_{\text{in}}(\omega_o)}{\langle R_{tf} \rangle} \right], \tag{9}$$

where the values of $\langle \alpha \rangle$ and $\langle R_{tf} \rangle$ are the average values listed in Table III. The relevant results of this test using an unbalanced tuning fork are summarized in Table IV which tracks the changes measured after mounting the additional cantilever. As expected, the shift in the resonant frequency is

TABLE III. Relevant parameters for six different Raltron model R26 tuning forks with microcantilevers attached to each prong, measured under ambient conditions. The first row tabulates the resonance frequency under ambient conditions for the tuning fork after it is removed from the metallic canister. All other rows are values that were measured when nominally identical microcantilevers were attached to each prong of the tuning fork.

	1	2	3	4	5	6	Average
f ₀ (kHz) (ambient)	32.761	32.753	32.755	32.754	32.761	32.754	32.756±0.003
f_0 (kHz)	32.566	32.715	32.740	32.744	32.740	32.726	32.705 ± 0.063
$\alpha (\mu \text{C/m})$	4.90	4.90	4.76	4.89	4.74	4.87	4.843 ± 0.067
Q	9196	10 007	9961	9204	9841	9611	9637 ± 333
C_p (pF)	2.89	2.57	2.37	2.56	2.85	2.49	2.62 ± 0.19
C_{tf} (fF)	3.31	3.37	2.87	3.35	3.27	3.14	3.22 ± 0.17
R_{tf} (k Ω)	163	147	173	161	154	164	160.3 ± 8.1
L_{tf} (kH)	7222	7 034	8249	7056	7229	7542	7390 ± 420
$m(10^{-7} \text{ kg})$	3.46	3.36	3.94	3.38	3.46	3.62	3.54 ± 0.20
k (kN/m)	14.52	14.22	16.70	14.28	14.64	15.24	14.93 ± 0.86
γ (kg/s)	7.83	7.06	7.84	7.70	6.92	7.78	7.52 ± 0.38

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TABLE IV. Using average values for the calibration constants for a balanced tuning, the amplitude of oscillation for one prong of an unbalanced tuning fork can be accurately inferred.

	Nominally balanced (measured)		Unbalanced [calculated from Eq. (9)]
f_o (kHz)	32.57	32.14	•••
$i_{\text{tot}}(\omega_o)$ (nA)	60.9	57.7	•••
$x_A(\omega_o)$ (nm)	31.6	30.8	31.9
$x_B(\omega_o)$ (nm)	29.6	26.8	27.1

 \sim 400 Hz (as compared to the \sim 50 Hz shift measured in Table III). The corresponding measured values of $x_A(\omega)$ and $x_B(\omega)$ for the unbalanced fork using the fiber optic interferometer are plotted in Fig. 8.

We conclude that using Eq. (9) to infer the amplitude of oscillation for the unbalanced tuning fork gives an estimate for the tip amplitude that is accurate to $\sim 1\%$. At frequencies off-resonance, the measured in-phase current is not an accurate measure of deflection, and the circuit in Fig. 7 must then be used to cancel out the current through the parasitic capacitance. Taken together, these two results indicate that a modestly unbalanced tuning fork might have a broad application in SPM studies requiring high Q resonances.

VI. DISCUSSIONS

An optical fiber interferometer has been used to calibrate the piezoelectromechanical coupling constant of a quartz tuning fork (Raltron model R26-32.768 kHz, ±5 ppm) force sensor. Once this calibration is complete, the oscillation amplitude of each prong can be independently deduced by measuring the total current generated by the tuning fork when

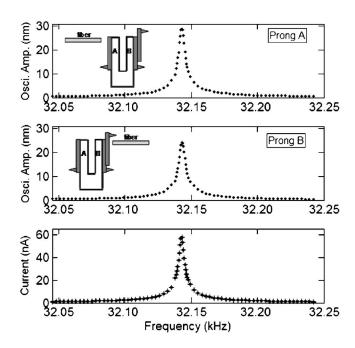


FIG. 8. The optical interferometer is used to measure the oscillation amplitude of each prong of a quartz tuning fork when an additional Si microcantilever is attached to prong B, intentionally breaking the symmetry. The current flowing through the tuning fork as a function of drive frequency is also plotted. For clarity, only every fourth data point acquired is plotted.

driven by a small (10 mV) applied ac voltage. Experiment shows that when the symmetry between prongs is intentionally broken by attaching an extra SPM microcantilever to one prong, the prong without the microcantilever oscillates essentially unchanged while the prong with the microcantilever suffers a reduction in amplitude, hence contributing a smaller current. Experiments have shown that the calibration is valid for a number of different tuning forks of the same make and model. Taken together, these results provide a first step in identifying an inexpensive and reproducible force sensor not requiring optical alignment that can be used across laboratories for standardized SPM force calibration experiments.

The high Q of the tuning fork (\sim 9000) under ambient conditions makes the tuning fork an ideal tool for measuring small frequency shifts due to interaction forces between a tip attached to one prong and a substrate under ambient conditions. Knowing both the frequency shift and amplitude variation as a tip approaches a substrate, it now becomes possible to calculate the interaction force versus distance under ambient conditions using established algorithms that appear in the literature. 15 SPM imaging is also possible using the quartz tuning fork in a dynamic SPM mode, but unacceptably slow scans are required because of the high Q factor. However, artificially and reversibly reducing the Q factor by introducing a reversible damping between the two prongs should restore rapid topographic scanning. Removing the damping will enable accurate frequency shift measurements at selected locations above the substrate. By equipping the standardized tuning fork described above with a sharp probe tip of choice, both SPM topography and SPM force (frequency shift) measurements under ambient conditions should result.

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