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A simple and accurate method for calibrating the oscillation amplitude of tuning-fork based AFM sensors

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ABSTRACT

We have developed a simple and accurate method for calibrating the amplitude of vibration of quartz tuning fork sensors commonly used in atomic force- and near field optical-microscopy. Unlike interferometric methods, which require a complex optical setup, the method we present requires only a simple measurement of the electro-mechanical properties of the tuning-fork oscillator and can be performed in a matter of minutes without disturbing the experimental setup. Comparison with interferometric methods shows that an accuracy of better than few percent can be routinely achieved.

0. Introduction

Quartz tuning-fork oscillators of the type commonly found in watches are widely used as force sensors in scanning-probe microscopy experiments. In a typical scheme, an AFM tip is mounted at the end of one of the tuning-fork prongs and the tuning fork is piezo-electrically excited at its resonant frequency with a constant amplitude sinusoidal current (which corresponds to a constant amplitude of vibration of the tuning fork). The amplitude of the driving voltage required is then a measure of the interaction of the tip with the sample under investigation. Various other schemes exist, all relying on the measurement of the fork excitation voltage and current to determine the fork vibration amplitude and the tip interaction with the sample. For quantitative applications it is necessary to know as accurately as possible the absolute amplitude of the mechanical oscillation corresponding to a given driving current, and interferometric measurements are normally required for this calibration [1,2]. Unfortunately, interferometric methods require a relatively complex optical setup, which is not always practical to implement, especially in AFM experiments that do not make use of a laser. Furthermore, even when an interferometric method can be implemented, it typically requires inconvenient modifications of the instrument's routine configuration and tedious alignment procedures.

We present here a simple method for performing this calibration, requiring only the measurement of a few mechanical properties of the fork (dimensions and Q factor), which can be easily obtained in a matter of minutes, and without changing the experimental setup. Briefly, we use the (known) electrical energy absorbed by the system, and the Q-factor, to derive the elasto-mechanical energy stored in the tuning fork, and from this, we use the elastic constants of the system to derive the amplitude of motion.

1. Theory

In the following we will consider that the tuning fork is excited at or near its nth natural frequency (typically, the lowest, $n = 1$), and that the corresponding mode has a large Q factor. Hence, the dominant contribution to the motion of the fork prongs comes from the resonant mode and all non-resonant modes can be neglected. Further, we assume that the fork behaves as a linear system. Let $a(t) = a_0 \cos(\omega_n t)$ be the amplitude of motion of the end of the tuning fork where the tip is mounted. Neglecting the small mass added by the tip, the two prongs are equivalent, each prong stores an elasto-mechanical energy $k_n a_0^2/2$, and the total energy stored by the fork is

$$\mathscr{E}_m = k_n a_0^2. \tag{1}$$

The elastic constant k_n (derived in Appendix A), depends only on known or easily measurable properties of the prong: length (L), width (W), thickness (T), and Young modulus (E). In particular, for

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the first vibrational mode, it reads

$$k_1 = 0.2575\frac{TW^3E}{L^3}. \quad (2)$$

A fraction $2\pi/Q$ of the stored mechanical energy is lost during each oscillation cycle, hence the energy loss per unit time is

$$\left.\frac{\mathrm{d}\mathscr{E}_m}{\mathrm{d}t}\right|_{\mathrm{loss}} = -\frac{\omega_n\mathscr{E}_m}{Q} = -\frac{\omega_n k_n a_0^2}{Q}. \quad (3)$$

This energy loss is compensated by the electrical circuit driving the oscillation at the same frequency ω_n, with a voltage v_{rms} and current i_{rms}

$$\left.\frac{\mathrm{d}\mathscr{E}_m}{\mathrm{d}t}\right|_{\mathrm{drive}} = v_{\mathrm{rms}}i_{\mathrm{rms}}. \quad (4)$$

Taken together, Eqs. (3) and (4) give the sought after result:

$$a_0 = \sqrt{\frac{Qv_{\mathrm{rms}}i_{\mathrm{rms}}}{k_n\omega_n}}. \quad (5)$$

The Q factor and ω_n are determined by fitting the frequency-dependent current drawn by the tuning fork when excited at constant voltage near its resonance frequency ω_n. We use the pseudo-Lorentzian

$$i(\omega) = \frac{i_n}{\sqrt{1+Q^2(\omega/\omega_n - \omega_n/\omega)^2}}. \quad (6)$$

Once the tuning fork has been thus characterized, Eq. (5) defines the relationship between the driving voltage v_{rms} and current i_{rms}, on one hand, and the amplitude of oscillation, a_0 on the other hand.

2. Experiment

To test the validity of the above approach, and to assess its accuracy, we have measured the oscillation amplitude of a commercial tuning fork using an interferometric technique, and we have compared it with the results of Eq. (5). The method and the experimental setup (Fig. 1) are very similar to those described in Ref. [1]; briefly, a phase locked loop (PLL) excites the tuning fork at its fundamental vibrational frequency ($f = 2\pi\omega_1$); the tuning fork is mounted on an inverted microscope, and a low power diode laser is focused onto the end of one of the prongs through a low magnification objective. The same microscope objective is used to collect the light reflected by the prong end and send it to a photodiode detector (D_1). In close proximity to the prong end is located a glass cover slide, which acts as a beam-splitter, and reflects part of the incoming light onto the same detector D_1; the two reflected beams interfere at the detector D_1, and the amount of interference is modulated by tuning-fork vibration. Accordingly, the detector output signal contains components at the oscillation frequency f and its higher harmonics $2f, 3f, \ldots$. The amplitude of each component depends on the amplitude of vibration of the tuning fork, and also on the relative position of the tuning fork and the glass slide. The latter is mounted on a closed-loop piezo translator, which allows to move it with nanometer precision while recording the signals of interest. We use two lock-in amplifiers to measure simultaneously the components I_1 at frequency f and I_2 at frequency $2f$ as the relative position of the fork and the glass slide is changed. Control, data acquisition and PLL operations are performed with commercial electronics (Nanonis GmbH). A typical oscillatory behavior is observed when scanning the glass slide position, as shown in Fig. 2.

According to Ref. [1], I_1 and I_2 have the form

$$I_1 = C_1\sin(\phi_0) - A_1\sin[\phi_2 + 4\pi/\lambda\cdot\Delta z], \quad (7)$$
$$I_2 = C_2\cos(\phi_0) - A_2\cos[\phi_2 + 4\pi/\lambda\cdot\Delta z], \quad (8)$$

where C_1, C_2, ϕ_0, and ϕ_2, are constants which depend on the experimental setup, λ is the laser wavelength, and A_1, A_2 contain the information required to determine the fork vibrational amplitude. The expressions given in Ref. [1] for A_1 and A_2 are valid only in the limit of small vibrational amplitudes, and we prefer, for sake of generality to use the expressions

$$A_1 = 2B_{\mathrm{FS}}J_1(4a_0\pi/\lambda), \quad (9)$$
$$A_2 = 2B_{\mathrm{FS}}J_2(4a_0\pi/\lambda) \quad (10)$$

(derived in Appendix A) which are valid for arbitrary amplitudes.

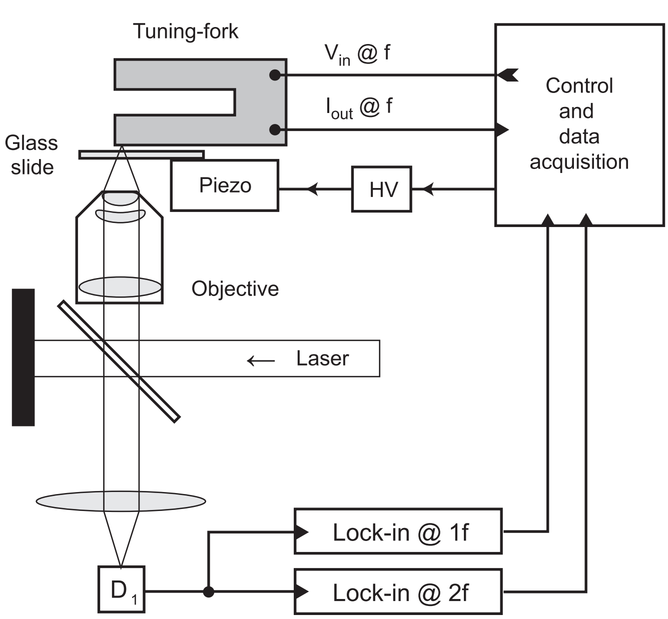

Fig. 1. Schematic of the experimental setup. Components not to scale.

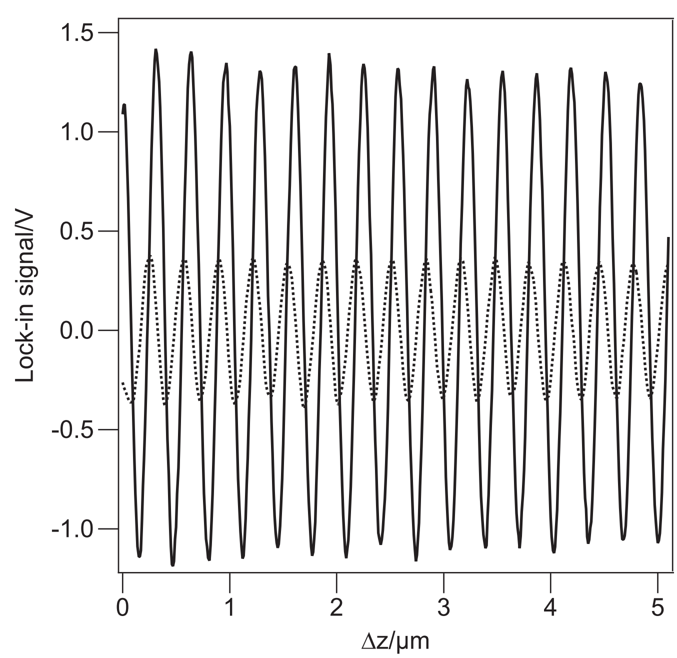

Fig. 2. Interference pattern observed at the detector D_1 of Fig. 1, as the glass slide position is changed by Δz. Solid line: signal demodulated at the first harmonic of the mechanical oscillation frequency (f). Dashed line: signal demodulated at the second harmonic of the mechanical oscillation frequency ($2f$).