УДК 681.2

INFLUENCE OF ADDITIONAL MASS ON QUARTZ TUNING FORK IN DYNAMIC OPERATION MODE

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An atomic force microscopy (AFM) with quartz tuning fork (QTF) is described. Key elements of shear force detector are the tuning fork element, the attached tip, and the glue for tip fixing. The results of connections were found to improve the Q factor of the shear-force sensor as well as to facilitate the replacement of the AFM cantilever tip and other parts. We present approach curves and images that researching the influence of the additional mass and selecting stability factors of the system on quartz tuning fork in dynamic operation mode.

Introduction

After their first application as a force sensor by Guethner et al. in acoustic microscopy [1], piezoelectric shear-force sensors are widely used for probe-sample distance control in scanning near-field optical microscopy (SNOM) [2,3], atomic force microscopy (AFM) [4] and other scanning probe techniques.

In atomic force microscopy, researchers have tried to achieve higher-resolution images by improving force sensor properties and tip characteristics. Recently, a technique based on the properties of piezoelectric tuning fork quartz oscillators, of the type used in watches, has been used in scanning force microscopy (SFM) [4]. In all of the applications where quartz tuning forks are used as a force sensor, an appropriate probe is attached to one of the tuning fork prongs. The interaction of the probe with the surface induces a shift of the tuning fork's resonance frequency. This shift or the resulting impedance change can be used for distance control by means of feedback mechanism acting on the so-called *z* piezo.

In this paper, however, we only present measurements with the tuning fork system that allow an investigation of the influence of the additional factors of attaching additional mass to quartz tuning fork on characteristics, as resonance frequency f and quality factor Q.

Theory calculation

Before experiments, calibration of the tuning fork was performed. The theoretical spring constant is obtained from the formula $k = \frac{E}{4} w \left(\frac{t}{l} \right)^3$ [5] where $E = 7,87.10^{10}\ {}^{N}\!/\!_{m^2}$ is the Young modulus of quartz. We have measured for our tuning fork w ≈ 0,38mm is the width of the fork, t ≈ 0.60mm is the thickness of the fork, and l ≈ 5,00mm is the length of one arm of the fork. Using these parameters we obtain k ≈ 12kN/m, which

ISBN 985645653-3

agrees reasonably well with our experimental result.

If the interaction of the tip with the surface is described by a potential energy function $U_i(z)$, the shift in the resonant frequency for small oscillations can be ascribed to a change in the spring constant of the tuning fork, k. The interaction produces an effective spring constant $k_{eff} = k + \left.\frac{d^2U_i}{dz^2}\right|_{z_0}$ where z_0 is the equilibrium distance of the tip from the surface. When the probe is far from the surface (large z_0) the interaction is weakly attractive and diminishing, leading to a small reduction of k_{eff} below k. An increasing repulsive interaction when the tip nears or contacts the surface increases k_{eff}.

Since the resonant frequency of an oscillator can be written as:

$$w_{resonance} = w_0 = \sqrt{\frac{k_{eff}}{m}}$$

the frequency should rise when the tip is near or contacting the surface. In practice the oscillation amplitudes are not always small compared to z_0 and the interaction should be averaged over the oscillation cycle, but the essential behavior remains.

A common used parameter is the quality factor Q. The quality factor is a measure of the ratio between the amplitude and the effective drive when driven at resonance. If there is no damping then the quality factor becomes infinite.

$$Q_{factor} = \frac{w_0}{\gamma},\ \gamma \text{ is the total viscosity}$$

For practical reasons, the quality factor is commonly defined in the following manner:

$$Q_{factor} = \frac{w_0}{w_1 - w_2} \qquad w_1 - w_2 \text{ is the full width at } 1/\sqrt{2} \text{ maximum.}$$

Experimental setup

The commercially available quartz tuning forks used to measure have a fundamental resonant frequency 2^{15}Hz (~32768Hz), with a spring constant k ≈ 12kN/m, calculated from the measured dimensions of the tuning fork. The QTF was modeled in a standard way as a series R-L-C circuit. The R-L-C model provides a convenient electrical analog of the mechanical properties of the tuning fork. (Its mass m, stiffness or spring constant k, and damping due to internal and external dissipative forces are represented by L, C, and R respectively.) This model is usually further improved by the inclusion of a parallel shunt capacitance Co corresponding to the package capacitance. A schematic diagram of our experiment is shown in Fig. 1.

To make full use of advantages of tuning fork in force measurements, a good quantity tip very important. In all of the applications, an appropriate probe is attached to one of the tuning fork prongs. In AFM, tip fabrication requires special attention, in particular, the actual sharpness of the tip. Typically, for tip fabrication, one uses a very thin (i.e. a few microns in diameter) metallic wire (e.g. Au, PtIr or W). However, for comparing in experiments, the AFM tips (commercial Contact silicon cantilever

ISBN 985645653-3

CSC21/15 chips produced by MicroMasch Company [6] that have two or six straight cantilevers of different lengths) or diamond tip were used. In addition, in the case of tunings fork, the mass of the glue used to attach probe to the tuning fork can radically alter the resonance properties and quality factor of the tuning fork. And the standard methods of connecting a tip to the tuning fork are gluing with epoxy two systems or cyanoacrylate glue (super glue). Cyanoacrylate glue could be chosen because of its strong adhesive properties, and the added mass of the glue was negligibly small, however its drying rate is very rapidly. For our experiment, therefore, the epoxy [7] was chosen for its high mechanical stiffness, the added mass could be researched, and especially, because of its drying rate not fast.

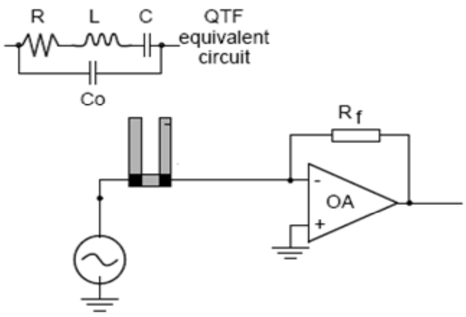

Fig. 1. Essential features of tuning fork sensing system and the equivalent circuit. Current through the tuning fork is converted to a voltage by an OpAmp (OA)

For attaching the tip to the quartz tuning fork, we glue a cantilever from chip to the end of the tuning fork with glue. The cantilever tip was placed on the tuning fork using an optical microscope equipped with a micropositioning stage. After the glue became dry, it was easy to break the tip from the rest of the cantilever chip by gently moving the chip up and down with respect to the tuning fork. Figure 2 shows the result of this process, with a very sharp tip only a few tens of micro across attached to one prong of the tuning fork.

Fig. 2. Image of commercial cantilever tip attached to tuning fork face surface

Results and conclusions

After uncovering from the packaging lid, the tuning fork will undergo a frequency shift because of air damping. The resonant frequency is about 32,758–32,960 Hz. The vibration spectrum of the fork working in the air is shown in Fig. 3 a. The quality factor of tuning fork will also decrease and can be abstracted from Fig. 3 a.

Fig. 3 b shows the resonance curves in air for a tuning fork before and after it is mounted with a commercial AFM cantilever tip on one prong, as described earlier. The

ISBN 985645653-3

tip is selected from AFM cantilevers that have six straight cantilevers of different lengths, and mass of glue is not significant. The resonance frequency reduces by about 52 Hz, and the amplitude of the oscillation or Q changed not much (about ~ 1 %).

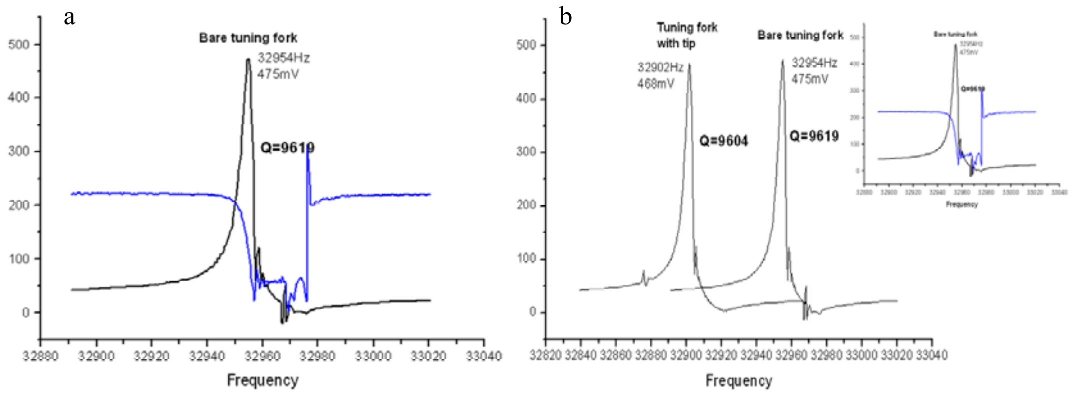

Fig. 3. Resonant frequency curve of bare tuning fork (a) and Spectrum comparison between bare tuning fork and tuning fork with tip AFM (b)

For comparison, we show the results of similar when increasing mass of the glue or using AFM cantilevers that have only two triangular cantilevers. In this case, the resonance frequency is shifted by about ~ 300Hz, and the amplitude of the oscillation and especially, quality factor Q are significantly reduced (more 10%). It is evident that the increase in mass loading with glue or tip gradually lower the resonant frequency. In addition to influence the amplitude and quality factor, the symmetry property of resonant curve of quartz tuning fork is broken because of its balance. The breaking of the symmetric shape of the main resonance peak creates two or more resonance peaks of the tuning fork (Fig. 4 a). It can affect the stability and measurement results of tuning fork with atomic force microscope. Furthermore, the balancing design of the tuning fork provides the high quality factor Q and is therefore responsible for the high force sensitivity. For making balance, generally, we stick with approximate mass (epoxy glue is used in our experiment) in another prong of tuning fork. The curve in Fig. 4 b illustrates the result of additional mass in two prongs. The amplitude and resonant frequency decrease, however the quality factor Q increase significant.

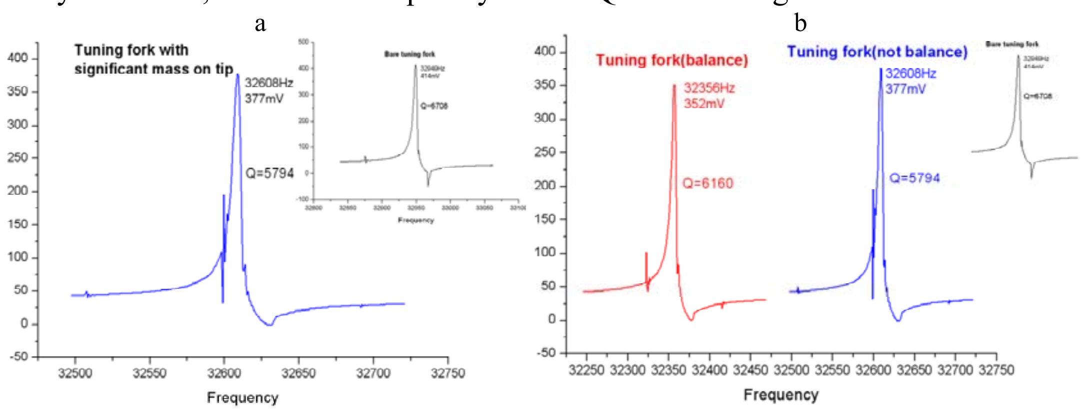

Fig. 4. Spectrum resonance of tuning fork with significant mass in the one and two prongs

ISBN 985645653-3
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In order to test again the influence of the added mass, we used the diamond tip glue in the prong of tuning fork and selected the tuning fork with large quality factor Q. The diamond tip has remarkable mass. In this case, similar to above result, the resonance frequency is shifted a large amount (about ~800 Hz), and the amplitude of the oscillation and especially, quality factor Q are significantly reduced (about 10 %). Fig. 5

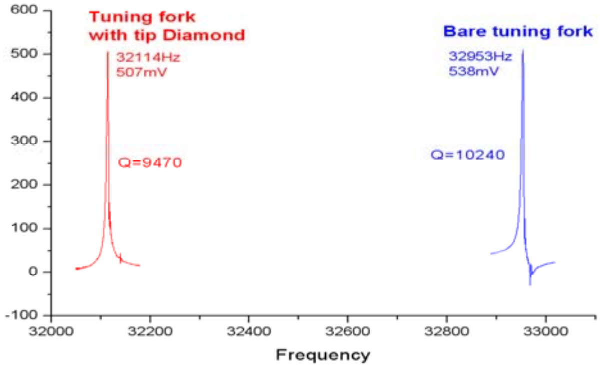

Fig. 5. Spectrum resonance curve of tuning fork with diamond tip (large mass) in the one prong

It is evident therefore that the quality factor Q, resonant frequency and the sensitivity for the interaction with the sample are decreased considerably by the additional mass to one prong of tuning fork. Especially, the symmetry property of the resonant curve is disappearing when additional mass in the prong is significant. However, this disadvantage can almost be cancelled by an equivalent additional mass as counter balance attached to the other prong. Therefore, depend on the purpose of applications and experiment, one can select which tip probes, glue, quartz tuning fork with correlative properties, in order to obtain comparable results.

Acknowledgements

The authors would like to thank Professor Jonathan Maps and Professor Tran Xuan Hoai for helpful discussions.

The work was carried out in the frame of the Belarusian Project 1.9 of SSTP «Scientific Equipment».

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ISBN 985645653-3